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Top mass at the LHC

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Abstract

With about 10 millions top-pairs event per year at low luminosity, the LHC will be a top-factory. Among all precision measurements that will be performed in the top quark sector, the determination of its mass is probably the most important and will help in constraining the Standard Model (SM). A brief review of the direct and indirect measurements of the top quark mass will be given, with indications about the potential of ATLAS and CMS in different luminosity scenarios.

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1   Introduction

Top-pair production at the LHC is important for several reasons: it will allow to precisely measure the top quark quantum numbers, to perform tests of QCD and, thanks to its large mass and coupling to the Higgs boson, to investigate possible presence of new physics, both in production and in decay mechanisms. Moreover, top-pair events are important as main background to many search channels and as an excellent environment for calibration of the jet energy scales and the b-tagging algorithm. Among all precision measurement in the top sector, the top mass has a key role in the constraining of the SM. Indeed, the Higgs boson mass is related to the other parameters of the model via loop corrections; since m_t is still the one with the largest experimental uncertainty, an improvement of its measurement will greatly reduce the allowed range for m_H and eventually discriminate between the SM and the presence of new physics.

The studies presented in this report will give an indication about the realistic potential of CMS and ATLAS in the determination of the top quark mass and are largely based on full detector simulations and on up-to-date generation tools. They are documented in detail in the CMS physics TDR [1] and in several notes updating the ATLAS physics TDR [2].

2   Top mass determination

Top-pair production at the LHC happens mainly via gluon fusion. Final states result from the decay of two top quarks into Wb, with a branching ratio close to unity, and the subsequent decay of the W boson. The resulting channels are therefore called fully hadronic ($\approx$46%), semileptonic ($\approx$44%) and fully leptonic ($\approx$10%), depending on the type of W decay. Triggering top-pair events is relatively straightforward in the (semi)leptonic cases, where the inclusive triggers of single isolated lepton or di-leptons can be used, whereas it is more complex for the fully hadronic final state because of the large component of QCD background. In this case the trigger selection is based on the inclusive jet trigger, where the thresholds depend on the number of jets and are lowered with respect to reference [3] in order to increase the efficiency, and on a fast b-jet tagging algorithm.

There are two main approaches to determine the top quark mass: the first one uses the direct reconstruction of the invariant mass via the detection of the $t\bar{t}$ final state, the second one infers the value of m_t by measuring quantites which are correlated to it. The use of different approaches in determining the top quark mass is essential to reduce, in combination, the contribution of the correlated systematic errors, dominating the error on the measurement.

2.1   Direct measurements

Direct measurements are based on the reconstruction of the invariant mass from the detected decay products. The simplest final states are the (semi)leptonic ones, where the trigger and the selection are made simpler by the presence of at least an isolated lepton. In semileptonic events the top mass is reconstructed from the hadronic decay of the Wb system, after proper calibration of the light and b jet energies. Both ATLAS [4] and CMS [5] have investigated the possibility of fitting the resulting spectrum by using kinematic constraints imposing the value of the W boson in the decay and additionally the equality of the two top masses in the event. This procedure results in a substantial improvement in the resolution and a reduced sensitivity to systematics due to radiation. Figure 1 shows the two expected mass spectrum for CMS with only 1/fb of integrated luminosity.

Direct reconstruction can be applied also for the fully leptonic channel. In this case it is necessary to use a constrained fit imposing the W boson masses and the equality of the two decaying top quark masses to a test mass (6 constraints) to cope with the missing information from the undetected neutrinos (6 unknowns). Each fit may have a solution to which a weight can be associated. The mass test value which maximizes the weight will provide the value of m_t which is the most compatible with the kinematics of the event. The dominating contribution to the error in this channel comes from the b jet energy scale calibration [4, 6].

The top mass can also be directly reconstructed in the fully hadronic channel, but the sensitivity is quite reduced because of the enormous QCD background and the combinatorial background coming from the wrong pairing of jets to form the two top quarks. The measurement is expected to be dominated by systematic errors coming from the jet energy scale and the control of the background.

Another interesting approach consists in using only high transverse momentum top-pair semileptonic candidates (with p_T >200 GeV/c), determining the mass by collecting all the energy in a cone around the flight direction of the candidate "hadronic" top quark. The advantage of this method is that it is much less sensitive to combinatorial backgrounds and to jet calibration. However, it is very sensitive to the description of the underlying event, whose
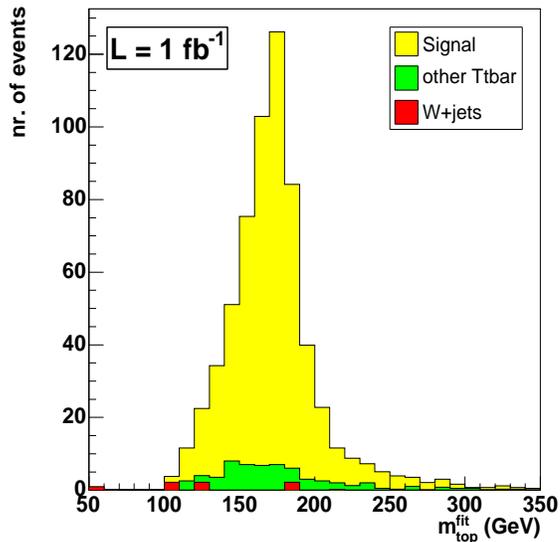
Figure 1: Top quark mass spectrum for the semileptonic channel for 1/fb. Both signal and expected backgrounds are indicated.

energy must be properly subtracted and whose description represents the main source of error.

2.2 Indirect measurements

There are ways to determine the top mass indirectly. The most promising consists in using exclusive semileptonic final states with the production of a J/Ψ meson from the hadronization of the b quark. The meson is identified by its decay into two light leptons and the top mass is inferred from its correlation with the invariant mass of the three leptons in the event [7, 8], as shown in figure 2. The selection is affected by a very low background contribution, mostly coming from combinatorial in top-pair events. The advantage of this method is that the top mass is reconstructed without b-tagging and with a limited use of jet reconstruction, making it insensitive to the most relevant systematics sources in the direct reconstruction methods. On the other hand, the branching ratio for the final state is so low that it will be necessary to use a few years of data taking before approaching a statistical error competitive with the systematic one.

Another possibility is to exploit the large dependence of the top-pair cross-section to the value of the top quark mass. A 5% uncertainty in the measurement of the cross-section would already give an error on the top quark mass of $2\,\mathrm{GeV/c^2}$, with a systematic breakdown largely uncorrelated to direct measurements. In practice, however, the cross-section itself will suffer from large errors from the knowledge of the proton p.d.f.s and the error on the luminosity, which make this analysis extremely difficult.

3 Error on the top mass

At the LHC the measurement of the top quark mass will soon be dominated by systematic uncertainties, the precise determination of which is currently under study. It is interesting, however, to already have an estimate of the ones expected to give major contributions. They can be divided into two broad categories: instrumental ones and theoretical ones. The former include the jet and lepton energy scale and resolution, the b-tagging efficiency and fake rate and the luminosity measurement. Preliminary studies [9] show that the jet energy calibration using external samples like Z(γ)+jet or the W mass constraint in top-pair events can bring the uncertainty on the jet energy scale to a level of a few percent and that the use of top events can also assure an internal calibration of the b-tagging at the level of 4-5%. Theoretical uncertainties, on the other hand, reflect our poor understanding of the reality of a p-p collision and the imperfect way in which it is implemented in our Monte Carlo (MC) simulation. This category include the description of the quarks and gluons p.d.f.s in the proton, the underlying event and the minimum bias, and the description of the radiation and fragmentation. It is difficult to assess today the magnitude of the systematics effects due to MC modelling; nevertheless recipes already exist [10], though entirely based on simulation, and are currently used by the analyses to quantify these errors in the absence of data. When the
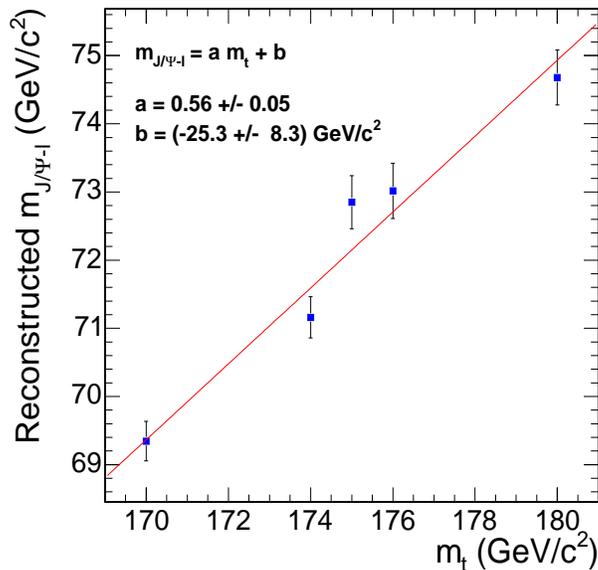
Figure 2: Correlation plot at full simulation between the top quark mass and the three-lepton invariant mass in the exclusive J/Ψ decays method (CMS). Only final states with electrons or muons are used.

data will be available many more constraints and MC tuning, especially with QCD data, will help in reduce quite significantly these uncertainties.

Table 1 shows the approximate expected error contributions on the top quark mass in the different analyses that have been briefly described and with the present knowledge of simulations and tools. The systematic error is

Method	δm_t (stat.)	δm_t (syst. instr.)	δm_t (syst. theory)	δm_t
bbqq$\ell\nu$	0.2	1.0	0.6	1.1
bbqq$\ell\nu$ (high p_T)	0.2	0.9	1.4	1.7
bb$\ell\nu\ell\nu$	0.5	1.0	0.3	1.2
bbqbbq	0.2	2.3	3.5	4.2
J/Ψ decays	0.5	0.5	1.4	1.5
Via σ_{tt}	0.1	0.7	4.0	4.1

Table 1: Expected top mass error breakdown for different analyses. The second column presents the expected statistical error after one year of data taking at low luminosity, with exception of the J/Ψ channel, where full LHC statistics is considered. The third and fourth columns present the expected systematic error split into instrumental and theory components, whereas the last column summarizes the experimental error. All numbers are expressed in GeV/c^2.

decomposed into purely instrumental contribution and theory contribution; it is evident that the combination of several analysis will greatly help in reducing the error, and that particular care will have to be taken for a complete understanding of the totally correlated systematic errors, especially when coming from MC modelling. The possibility of having a final LHC combined error of about 1 GeV/c^2 seems very well in reach.

4   Top mass determination as a commissioning tool

Studying the top mass is not only interesting per se, but also an invaluable tool for commissioning detector and tools. In a study performed with only 100/pb of luminosity, corresponding to few days of nominal LHC operation, and with the additional hypothesis of non-availability of any b-tagging, the ATLAS collaboration [11] showed that it is already possible to clearly separate a top signal in the three-jets invariant mass in semileptonic events, as shown in figure 3, by simply selecting those events where two of the three jets are close to the nominal W mass. This exercise can help having top enriched samples with which it will be possible to perform a first light jet energy calibration and an estimate of the b-tagging efficiency using the fourth jet in the event. This analysis could also
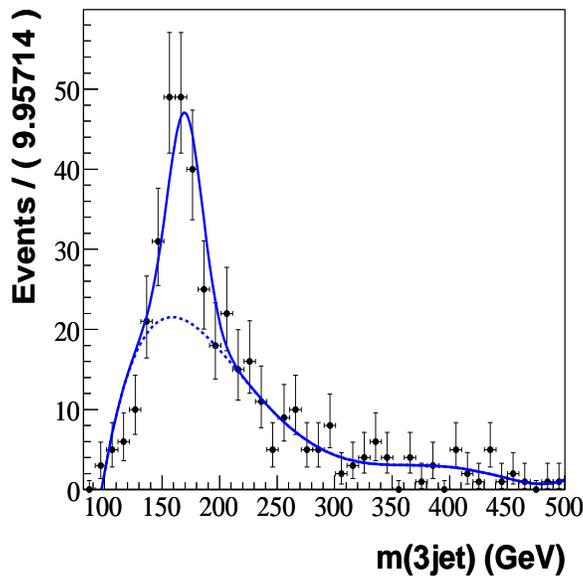
Figure 3: Three jets invariant mass after selection and 100/pb luminosity in ATLAS without use of b-tagging.

lead to the first physics measurements at the LHC.

5   Conclusions

The sector of top quark physics in general and the top quark mass determination in particular are extremely important to understand both physics and detector at the LHC. Moreover, m_t will be essential to constrain the validity of the SM or of new physics. Both ATLAS and CMS collaborations are very active in studying the realistic potential of the experiments in this measurement, which can be performed with the use of very different methods and that can achieve a final combined error of 1 GeV/c^2 or less.

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