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Top-mass determination from leptonic final states

Gennaro Corcella[1,*]

[1]INFN, Laboratori Nazionali di Frascati, Via E. Fermi 54, I-00044 Frascati (RM), Italy

Abstract. The top-quark mass is a fundamental parameter of the Standard Model, as it plays a crucial role in the electroweak precision tests, stability of the vacuum and inflation. I review the method and the main results contained in a recent ATLAS analysis which measures the top mass by using the invariant mass of the leptons coming from W and B-hadron decays. The extracted top mass turns out to be the most precise single measurement by ATLAS.

1 Introduction

The mass of the top quark (m_t) is a fundamental quantity of the Standard Model of strong and electroweak interactions, which enters in the electroweak precision tests and constrained the value of the Higgs boson mass even before its discovery. Furthermore, it is of paramount importance in inflation and in the determination of the stability of the universe.

Since the top quark is the only quark which decays before hadronization, the interpretation of the top-mass measurements has been the subject of a long-standing debate, since the most accurate measurements have been obtained by using Monte Carlo event generators, which are not exact QCD calculationss. Much work has been carried out in addressing the uncertainty/discrepancy of the extracted mass when expressed in terms of well-defined field theory definitions, such as the pole mass (see, e.g., [1–3] for reviews). It is well understood that the mass obtained from direct measurements relying on top decays ($t \to bW$) must be close to the pole mass, up to corrections which depend on the top width or non-pertubative effects, such as colour reconnection or underlying event. Having in mind this discussion on the nature of the measured top mass, this contribution deals with a recent top-mass measurement carried out at the LHC by the ATLAS Collaboration [4] at a centre-of-mass energy $\sqrt{s} = 13$ TeV and integrated luminosity $\mathcal{L} = 36$ fb^{-1}. This analysis uses leptonic final states in top decays and the so-called soft-muon tagging (SMT), i.e., it exploits the invariant mass $m_{\ell\mu}$, where ℓ is a charged lepton from the W and μ comes from the decay of a b-flavoured hadron. The advantage of this method is that, as it is based on fully-leptonic final states, it exhibits a mild sensitivity to jet calibration and to the $t\bar{t}$ production phase; on the other hand, one should expect a major dependence on b-quark fragmentation, as it relies on the description of the hadronization of a b into a B-hadron, eventually decaying into a muon. Nevertheless, as will be detailed, such an analyis yields the most precise single m_t measurement by ATLAS.

In the following section, I will give some insight on the analysis [4], paying special attention to the Monte Carlo modelling and uncertainties in the top mass measurement. I will finally make some concluding remarks.

*e-mail: gennaro.corcella@lnf.infn.it

2 Measuring the top mass using the soft-muon tagging

The analysis presented hereafter makes use of data collected in 2015 and 2016 by the ATLAS Collaboration at the LHC, namely centre-of-mass energy $\sqrt{s} = 13$ TeV and integrated luminosity $\mathcal{L} = 36.1$ fb^{-1}. The selected $t\bar{t}$ events feature lepton+jets final states, i.e. one W decays leptonically ($W \to \ell\nu$) and the other one into jets ($W \to jj'$). At parton level, one has a final state $b\ell\nu\bar{b}jj'$, i.e. four jets, one charged lepton and missing energy due to the neutrino. Furthermore, as pointed out in the introduction, at least one of the b-flavoured jets in $t \to bW$ is required to yield a muon μ, coming from the semileptonic decay of a B-hadron. The invariant mass $m_{\ell\mu}$ is then employed to extract m_t.

Final-state jets are clustered according to the anti-k_T algorithm [5] with a radius parameter $R = 0.4$ and must have rapidity $|\eta_j| < 2.5$ and transverse momentum $p_{T,j} > 25$ GeV. As for primary leptons, i.e. those coming from W decays, the corresponding cuts are $p_{T,\ell} > 27$ GeV and $|\eta_\ell| < 2.5$. One also sets an invariant opening angle between jets and primary leptons $\Delta R_{j\ell} > 0.4$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, ϕ being the azimuthal angle. In the selected sample each event must have at least one SMT, namely a b-jet where the B-hadron decays into a soft muon. The cuts applied on such a muon are $p_{T,\mu} > 8$ GeV, $|\eta_\mu| < 2.5$ and an angular distance $\Delta R_{j\mu} < 0.4$ from its own jet candidate. Furthermore, one requires $\Delta R_{\ell\mu} < 2$ between primary leptons and soft muons, in such a way to enhance the probability that both leptons come from the same top and minimize the fraction of events where they instead originate from two different top quarks.

The simulation of the $t\bar{t}$ samples is carried out by using the *hvq* setup of POWHEG [6] with the NLO NNPDF3.0 parton distribution functions [7]. Off-shell and width effects are included in the MADSPIN approximation, based on Ref. [8], while showers, underlying event and hadronization are modelled by the PYTHIA 8.2 code [9]. HERWIG 7.1.3 [22] is instead used for the sake of comparison and estimating the Monte Carlo systematics. Bottom- and charm-hadron decays and mixing are handled by the EVTGEN 1.2.0 program [10], with the production fractions and branching ratios rescaled to agree with the PDG values [12]. In the *hvq* POWHEG framework, NLO QCD corrections are applied to $t\bar{t}$ production, while gluon radiation in top decays is completely handled by the PYTHIA shower. Matrix-element corrections to parton showers in top decays, namely NLO tree-level corrections $t \to bWg$, are included along the lines of [11]. The $h_{\rm damp}$ parameter in POWHEG, ruling the transverse momentum of the first emission, is set to $h_{\rm damp} = 1.5\, m_t$; moreover, the total $t\bar{t}$ cross section is rescaled to the NNLO value computed by the Top++ code [13], i.e. $\sigma_{t\bar{t}} \simeq (832^{+46}_{-51})$ pb. Backgrounds to $t\bar{t}$ production are simulated by SHERPA 2.2.1 [14] or POWHEG itself: the details of the background simulation are discussed in [4] and are not reported here for the sake of brevity.

The specific PYTHIA tuning employed in this analysis deserves some thorough discussion. The ATLAS Collaboration released the A14 tuning [15], based on LEP and Tevatron data, as well as on a few ATLAS measurements at $\sqrt{s} = 7$ TeV, in order to account for effects which are relevant at hadron colliders, such as underlying event, colour reconnection or multiple interactions. However, since this top-mass determination crucially depends on the fragmentation of b quarks into B-hadrons, the ATLAS Collaboration decided to retune the PYTHIA b-fragmentation parameters, for the sake of a reliable measurement. In PYTHIA, b-quark hadronization is described according to the so-called Lund-Bowler non-perturbative fragmentation function [16, 17]:

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp\left(-bm_T^2/z\right). \tag{1}$$

In Eq. (1) m_b is the b-quark mass, m_T the B-hadron transverse mass, i.e. $m_T = \sqrt{p_T^2 + m_B^2}$, z the hadron longitudinal energy fraction with respect to the parent quark. a, b and r_b are instead free parameters which must be tuned to experimental data. However, while a and b are sensitive to light-hadron production, r_b is specific to b-quark fragmentation. Therefore, in [4] a and b are kept to their default values, while r_b, whose default is $r_b = 0.85$ in A14, is instead retuned to data from LEP (ALEPH [18], DELPHI [19] and OPAL [20] experiments) and SLD [21] on B-hadron production in e^+e^- annihilation at the Z pole [1]. The details of the fit are described in [4] and lead to the value $r_b = 1.05 \pm 0.02$: the obtained setting is referred to as A14-r_b. The comparison of the tuned PYTHIA simulation with the e^+e^- data is presented in Fig. 2, which also contains the predictions of the HERWIG 7.1.3 event generator [22]: the improvement of the A14-r_b setup with respect to the default one is well visible. Before presenting the results on the top-mass extraction, it should be pointed out that, in principle, using in pp collisions a Monte Carlo fit to e^+e^- data may be arguable, since in a hadron environment one has effects like initial-state radiation, underlying event or colour reconnection between initial and final state, which do not have a counterpart in lepton colliders. From this point of view, a fit to precise pp data would be preferable. However, the analysis setup of [4] indeed minimizes such effects, as one just deals with leptonic final states, and the standalone A14 fit includes information coming from LHC data. Furthermore, in the narrow-width approximation for the top quark, shower and hadronization of b quarks in $t \to bW$ are expected to be similar to $Z \to b\bar{b}$, and hence a tuning of r_b to LEP and SLD is expected to be reliable even for b-quark fragmentation in top decays.

The top mass is then extracted by comparing the POWHEG+PYTHIA prediction, based on the A14-r_b tuning, with the data on the $m_{\ell\mu}$ invariant mass, as displayed in Fig. 2, for distributions obtained after the fit. In [4], checks are carried out fitting separately the electron and muon channels, as well as the samples where the leptons from W and B have the same (SS) or opposite (OS) signs. The fit yields the following result:

$$m_t = 174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil}). \tag{2}$$

While for a discussion on the determination of the systematic and statistical errors one can refer to [4], the so-called recoil uncertainty quoted in (2) deserves further comments. In fact, in the treatment of the PYTHIA parton shower off the b quark in $t \to bW$, one has the option to change the gluon recoil scheme from recoiling against the b (often labelled as RTB), which is the default setting, to recoiling against the W (RTW) or the top (RTT). The RTW and RTT options typically lead to wide-angle radiation in top decay and deposits of energy out of the clustered b-jet, while the RTB one is more consistent with the shower collinear approximation. As a matter of fact, in [4] the change of the recoil modelling is assumed to be another source of uncertainty. Some hints on the reliability of the various options can be obtained by comparing the PYTHIA results for the B-hadron energy fraction in top decays, defined in an equivalent way to x_B in Fig. 1, with the NLO+NLL resummed calculation of Ref. [23], which uses the Kartvelishvili non-perturbative fragmentation function [24], tuned to ALEPH data [18] to model hadronization. Ref. [23] also investigates bottom-quark fragmentation in top decays in Mellin moment space, including the non-perturbative information by means of a fit to DELPHI data in N-space [19]. Overall, it is found that the RTB setting data gives the best comparison with [23], while the RTT and RTW options lead to a shift in the extracted mass of about 0.25 GeV. Therefore, Ref. [4] quotes a recoil uncertainty of 0.25 GeV, as in Eq. (2), in the measured top mass with the SMT method.

[1] b-quark fragmentation in Refs. [18–21] is described in terms of the energy fraction $x_B = 2p_B \dot p_Z / m_Z^2$, p_B and p_Z being the four-momenta of the B-hadron and of the Z boson, respectively.

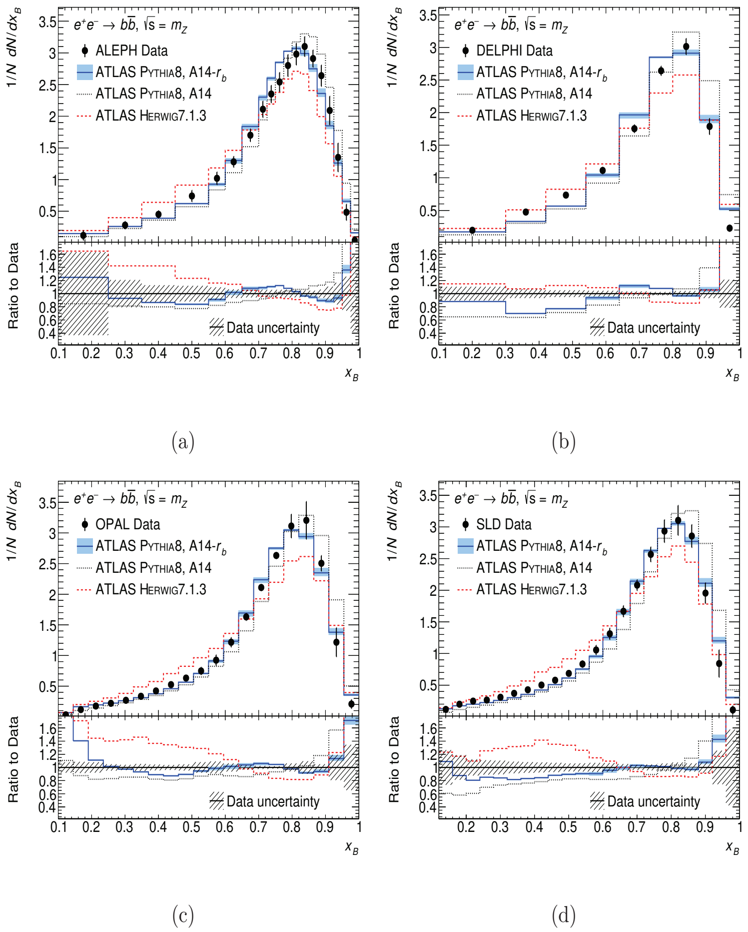

Figure 1. Comparison of the x_B data from LEP and SLD at the Z pole with PYTHIA and HERWIG simulations. As for PYTHIA, both A14 and A14-r_b setups are employed. Figures taken from [4].

3 Conclusions

I reviewed a recent analysis undertaken by the ATLAS Collaboration on the top-mass determination by using the invariant mass of a lepton and a soft muon, coming from a W and a B-hadron in top decays, respectively. This measurements fully relies on leptonic final states in top decays, which minimizes uncertainties due to the $t\bar{t}$ production stage and

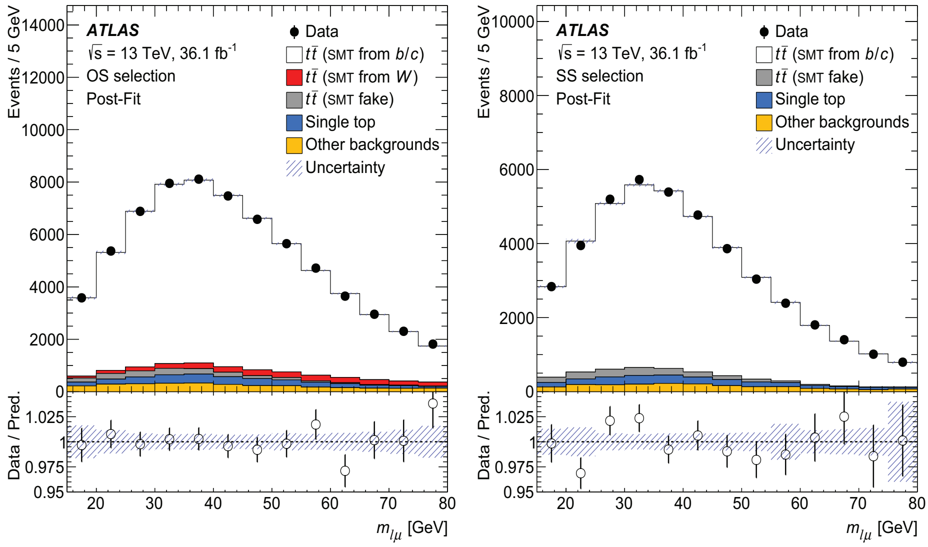

Figure 2. Data on the invariant mass $m_{\ell\mu}$ compared with tuned POWHEG+PYTHIA for $t\bar{t}$ signal and background as discussed in [4]. The OS and SS labels refer to whether the lepton from the W and the soft muon from the B-hadron have opposite (OS) or same (SS) sign. The uncertainty band includes statistical and systematic uncertainties. Figures taken from [4].

jet energy scale and calibration. For the sake of a reliable measurement, the bottom-quark fragmentation parameter r_b in the PYTHIA event generator was retuned to LEP and SLD data. As a matter of fact, for the time being, this top-mass extraction turns out to be the most precise single measurement from the reconstruction of the top-decay products, i.e. $m_t = 174.41 \pm 0.39$ (stat.) $\pm$ 0.66 (syst.) $\pm$ 0.25 (recoil). While the determination of the systematic and statistical uncertainties is rather standard, particular care was taken about the assessment of the one due to the choice of the PYTHIA recoil scheme for gluon radiation in top decays. For this purpose, the comparison with a resummed calculation for b-quark fragmentation in top decays turned out to be very useful to address the best option for the recoil scheme and give a meaningful estimate of the uncertainty. Overall, the presented top-mass measurement is in agreement with other determination and, thanks to the negligible error due to the jet activity, it is expected to play a relevant role in the future combinations.

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