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Top-quark mass measurements: Review and perspectives

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ABSTRACT

The top quark is the heaviest elementary particle known and its mass ($m_{\rm top}$) is a fundamental parameter of the Standard Model (SM). The $m_{\rm top}$ value affects theory predictions of particle production cross-sections required for exploring Higgs-boson properties and searching for New Physics (NP). Its precise determination is essential for testing the overall consistency of the SM, to constrain NP models, through precision electroweak fits, and has an extraordinary impact on the Higgs sector, and on the SM extrapolation to high-energies. The methodologies, the results, and the main theoretical and experimental challenges related to the $m_{\rm top}$ measurements and combinations at the Large Hadron Collider (LHC) and at the Tevatron are reviewed and discussed. Finally, the prospects for the improvement of the $m_{\rm top}$ precision during the upcoming LHC runs are briefly outlined.

1. Introduction

Naturally complementing direct searches for new physics (NP) phenomena, precision measurements of the properties of the fundamental particles constitute an extremely successful path to refine our knowledge of high-energy physics and of its implications on the evolution of the Universe. In this context, the top quark plays a special role: its lifetime is extremely short ($\approx 10^{-25}$ s) and inhibits top-quark bound states and top-quark flavoured hadrons to be formed, offering a unique possibility to study the properties of the particle as a quasi-free quark (see Refs. [1,2] for recent reviews on the subject). The top quark is the heaviest elementary particle currently known and its mass ($m_{\rm top}$) plays a fundamental role in high-energy physics. The value of $m_{\rm top}$ affects theory predictions of particle production cross-sections required for exploring Higgs-boson properties and searching for NP phenomena. Due to top-quark induced quantum-loop corrections, which modify the theory predictions for several physics observables, the precise determination of $m_{\rm top}$ is essential for testing the overall consistency of the Standard Model (SM) and to constrain NP models through precision electroweak fits. Fig. 1(a), from Ref. [3], displays the 68% and 95% confidence level (CL) contours for the indirect determination of the mass of the W boson (m_W) and $m_{\rm top}$ from global SM fits to electroweak precision data. The blue (grey) areas illustrate the fit results when including (excluding) the direct Higgs-boson mass measurements [4,5]. The contours are compared with the direct measurements of m_W and $m_{\rm top}$, shown by the horizontal and vertical green bands, that are excluded from the fits.

In addition, owing to its large value, of the order of the electroweak symmetry breaking energy scale, $m_{\rm top}$ has a direct impact on the Higgs sector of the SM, and on extrapolations of the SM to high-energy scales [6,7]. With the discovery of a Higgs boson [4,5] at the Large Hadron Collider (LHC) with a mass of $m_{\rm H} = 125.09 \pm 0.24$ GeV [8], precision measurements of the top-quark mass take a central role in answering the question of the stability of the electroweak vacuum: top-quark

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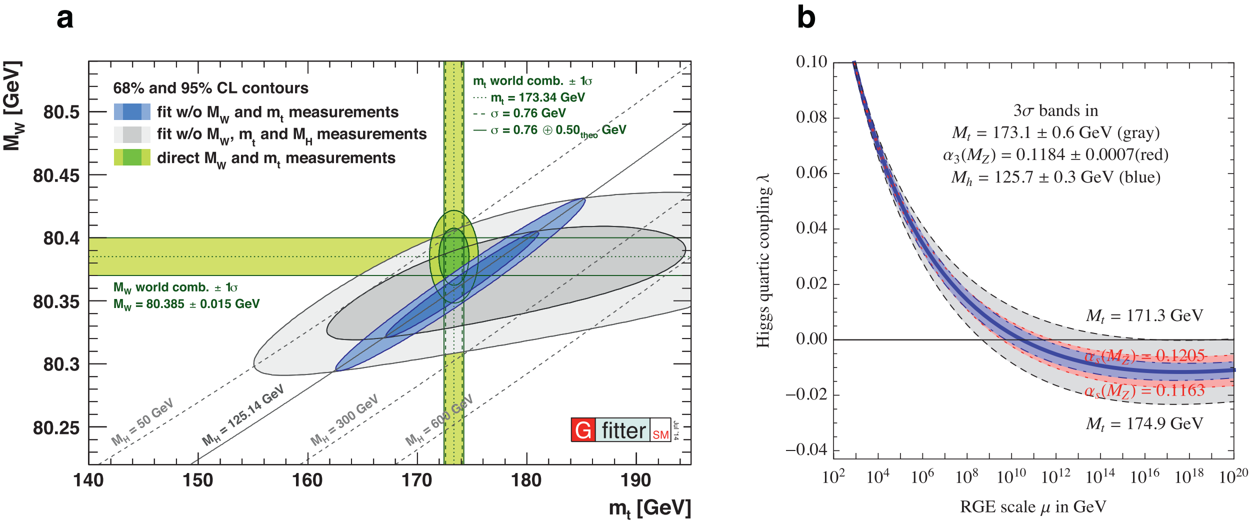

Fig. 1. (a) The 68% and 95% CL contours for the indirect determination of m_W and $m_{\rm top}$ from global SM fits to electroweak precision data (from Ref. [3]). (b) Evolution of the Higgs-boson self-coupling λ, within the renormalisation group equation (RGE), for the central values of $m_{\rm H} = 125.7$ GeV, $m_{\rm top} = 173.1$ GeV and $\alpha_S(m_Z) = 0.1184$ (solid curve), and variation of these central values by $\pm\, 3\sigma$ for the blue, grey and red, dashed curves, respectively (from Ref. [6]).

radiative corrections can drive the Higgs-boson self-coupling (λ) towards negative values, potentially leading to an unstable vacuum. The determination of the energy scale (μ) at which this happens, possibly requiring new physics at lower or comparable energies, is strongly influenced by the precision of the top-quark mass measurement and by the interpretation of $m_{\rm top}$ in a clear theoretical framework (μ varies by several orders of magnitude under a ± 1.8 GeV variation of $m_{\rm top}$, as shown in Fig. 1(b), from Ref. [6]).

Currently, the most precise measurements of $m_{\rm top}$ are obtained from direct reconstruction of the top-quark decay final states and use calibrations based on Monte Carlo (MC) simulation to determine the top-quark mass value that best describes the data. In this approach, the measured top-quark mass corresponds to the parameter implemented in the MC ($m_{\rm top}^{\rm MC}$) which formally is not a renormalised field theory parameter, and must be used with care as input for precise theoretical predictions [9–11]. The top quark is colour charged and does not exist as an asymptotic state: the value of $m_{\rm top}$, extracted from the experiments, depends on the theoretical definition of the mass, which varies according to the renormalisation scheme adopted: pole mass ($m_{\rm top}^{\rm pole}$) or running mass. As a result, the identification of $m_{\rm top}^{\rm MC}$ with $m_{\rm top}^{\rm pole}$ is currently subject to an uncertainty of the order of 1 GeV [10], comparable to the present experimental precision (see also Refs. [12,13] for previous recent reviews on $m_{\rm top}$).

2. Top-quark pair production and signatures at the Tevatron and LHC

At Tevatron and LHC hadron colliders top quarks are mainly produced in pairs, through strong interactions, via gluon fusion and quark-antiquark annihilation processes. Depending on the collider centre-of-mass-energy ($\sqrt{s}$), and on the type of particle beams being utilised (proton-antiproton, $p\bar{p}$, or proton-proton, pp), the relative importance of the two processes varies. At the Tevatron $p\bar{p}$ collider, operating at $\sqrt{s} = 1.8 - 1.96$ TeV, approximately 85% of the top-quark pairs ($t\bar{t}$) are produced through quark-antiquark annihilation, whereas at all centre-of-mass-energies explored by the LHC pp collider, gluon fusion processes are dominant (80–90% for $\sqrt{s} = 7 - 14$ TeV). The top-quark pair production cross-section varies from $7.16^{+0.20}_{-0.23}$ pb at the Tevatron, to $172.0^{+6.4}_{-7.5}$ pb ($\sqrt{s} = 7$ TeV), $245.8^{+8.8}_{-10.6}$ pb ($\sqrt{s} = 8$ TeV) and $953.6^{+27.9}_{-38.3}$ pb ($\sqrt{s} = 14$ TeV) at the LHC [14]. The production of single-top quarks occurs via electroweak interactions and relates to a significantly lower (about one half) production cross-section than that for top-quark pairs.

After the discovery of the top quark in 1995 [15,16], the CDF and D0 experiments, operating at the Tevatron, have collected about 10 fb^{-1} of $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions. The LHC experiments, ATLAS and CMS, in operation since 2010, have collected 5 fb^{-1} and 20 fb^{-1} of pp collisions data at the centre-of-mass-energies of 7 and 8 TeV, respectively (LHC Run-1). Within the planned LHC programme, about 100 fb^{-1} of $\sqrt{s} = 13 - 14$ TeV (LHC Run-2) and 200 fb^{-1} of $\sqrt{s} = 14$ TeV (LHC Run-3) pp collision data will be collected in the time period 2015–2022. An additional ten-fold increase of the integrated luminosity is expected within the LHC high-luminosity upgrade [17]. Correspondingly, the expected number of $t\bar{t}$ events that will be produced by the end of LHC Run-3 amount to about 300 Million, compared to 6 Million produced during the LHC operations at $\sqrt{s} = 7$ and 8 TeV, and 70k produced at the Tevatron at $\sqrt{s} = 1.96$ TeV. As we shall see in the following, this will open unprecedented opportunities for precise measurements of the properties of the top quark, and in particular of $m_{\rm top}$.