Fragmentation uncertainties in hadronic observables for top-quark mass measurements

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Abstract

We study the Monte Carlo uncertainties due to modeling of hadronization and showering in the extraction of the top-quark mass from observables that use exclusive hadronic final states in top decays, such as $t \rightarrow$ anything $+ J/\psi$ or $t \rightarrow$ anything $+ (B \rightarrow$ charged tracks), where B is a B-hadron. To this end, we investigate the sensitivity of the top-quark mass, determined by means of a few observables already proposed in the literature as well as some new proposals, to the relevant parameters of event generators, such as HERWIG 6 and PYTHIA 8. We find that constraining those parameters at $\mathcal{O}(1\%–10\%)$ is required to avoid a Monte Carlo uncertainty on m_t greater than 500 MeV. For the sake of achieving the needed accuracy on such parameters, we examine the sensitivity of the top-quark mass measured from spectral features, such as peaks, endpoints and distributions of E_B, $m_{B\ell}$, and some m_{T2}-like variables. We find that restricting oneself to regions sufficiently close to the endpoints enables one to substantially decrease the dependence on the Monte Carlo parameters, but at the price of inflating significantly the statistical uncertainties. To ameliorate this situation we study how well the data on top-quark production and decay at the LHC can be utilized to constrain the showering and hadronization variables. We find that a global exploration of several calibration observables, sensitive to the Monte Carlo parameters but very mildly to m_t, can offer useful constraints on the parameters, as long as such quantities are measured with a 1% precision.

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1. Introduction

The top quark mass (m_t) is a fundamental parameter of the Standard Model which, together with the W mass, constrained the Higgs mass even before its discovery. It plays a crucial role in the determination of the Standard Model vacuum life-time, which has been recently found to be at the border between stability and metastability [1,2]. It is therefore of paramount importance to measure m_t with the highest possible accuracy and provide a reliable determination of the error on m_t. Furthermore, much work has been lately carried out in order to estimate the uncertainty on m_t, once it is interpreted in terms of well-defined theoretical quantities, such as the pole mass [3–5].

In fact, standard measurements, based on the template, matrix-element and ideogram methods (see, *e.g.*, the analyses in [6–8]), rely on parton shower generators such as HERWIG [9] or PYTHIA [10]. They simulate the hard scattering at leading order (LO) and multiple radiation in the soft or collinear approximation, with phenomenological models for hadronization and underlying events. By contrast, so-called alternative methods use other observables, *e.g.,* total cross sections or kinematic endpoints, which, besides Monte Carlo simulations, can be compared directly with fixed-order and possibly resummed QCD calculations, thus allowing a straightforward theoretical interpretation of the extracted mass (see, for example, Ref. [11] on the pole mass extraction from the total $t\bar{t}$ production cross section).

More recent NLO + shower programs such as aMC@NLO [12] and POWHEG [13] implement NLO hard-scattering amplitudes, but still rely on HERWIG and PYTHIA for parton cascades and non-perturbative phenomena. NLO corrections to top quark production have been available in both aMC@NLO and POWHEG for some time, while much effort has been later devoted to improve the treatment of top quark decays. In the aMC@NLO code, NLO top decays are implemented for single-top events [14]; in $t\bar{t}$ production, the decays are still on shell, but spin correlations and part of the off-shell contributions are included via MadSpin [15]. In the POWHEG framework, NLO corrections to top decays were implemented first in Ref. [16], with an approximate treatment of top-width effects, and more recently, in Ref. [17], the interference between top production and decay, as well as non-resonant contributions have been included. Furthermore, the SHERPA code [18] implements $t\bar{t}$ production in conjunction with up to three jets at NLO, merged to parton showers along the lines of Ref. [19]. Top decays in SHERPA include spin correlations and are accounted for in the LO approximation [20].

At present, since most standard m_t determinations rely on the reconstruction of b-flavored jets in top decays ($t \to bW$), one of the main uncertainties is from the b-jet energy scale (bJES), which amounts to about 250 MeV of the overall 700 MeV in the world average determination [21]. Therefore, several attempts have been made so far to overcome the difficulties of such standard methods, in particular to calibrate the jet energies to very high accuracy. Some strategies use the W-boson mass as a constraint to calibrate *in-situ* the jet reconstruction [7]: this method, however, cannot account for the differences between b-jets and light-flavored jets, as the W decays mostly into light or charm quarks. In other attempts the jet energy scale has been effectively constrained by exploiting the anti-correlation of the b-jet energy and angular variables [8] imposed by the $V - A$ matrix element that in the Standard Model describes top-quark decay.

Despite all these efforts, the jet energy scale keeps being a bottleneck for the improvement of standard mass measurements; therefore, new methods have been conceived to go around this uncertainty. Among the earliest attempts, we recall those based on the exclusive fragmentation of the b-quark to J/ψ [6,22] and studies of the decay length of B hadrons [23,24]. In the J/ψ method, leptonic decays of the J/ψ are used to identify the resonance. The distribution in the