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A top-quark mass measurement feasibility study in the $t\bar{t}$ dilepton channel at LHC and at future hadronic colliders

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Summary. — This contribution documents the first efforts being taken to study the feasibility of a measurement of the top-quark mass at the Large Hadron Collider and future hadron colliders in pair production events in the dilepton channel.

1. – Introduction

The top-quark is the only fundamental fermion within the Standard Model (SM) having a mass of the order of the typical energy scale of electroweak interactions [1]. Beside other important implications, from this follows the well-known argument that, having a large Yukawa coupling, its interaction with the Higgs Boson must have a role in stabilising its mass at the electroweak scale against heavy New Physics scales, if present. Another consequence of the large top-quark Yukawa coupling is that, even in the case in which the SM is taken as the theory of Nature up to Planck scales, its mass is a sensible parameter entering the calculation of the effective potential of the Higgs boson, which can develop a second minimum aside from where our Universe is standing, possibly affecting the stability of the electroweak vacuum [2,3]. These are only few among other compelling reasons for having a precise determination of the top-quark mass, and explain the huge amount of work being done by both the theoretical and experimental community to develop and improve independent techniques with this aim [4]. Here initial steps toward a correct implementation of the method presented in [5] are presented.

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TABLE I. – *Coefficients parametrizing the dependence of the first Mellin moment on the top-mass as computed, at LO accuracy, by* MADGRAPH5_aMC@NLO *and their dependence on the PDF sets choice.*

Obs.	α	β	α^{up}	α^{low}	β^{up}	β^{low}
$p_T(l^+)$	0.133	0.226	0.137	0.128	0.230	0.223
$p_T(l^+ + l^-)$	0.119	0.311	0.141	0.096	0.333	0.289
$M(l^+l^-)$	0.293	0.396	0.303	0.283	0.404	0.389
$E(l^+) + E(l^-)$	0.562	0.680	0.582	0.542	0.695	0.664
$p_T(l^+) + p_T(l^-)$	0.254	0.462	0.270	0.239	0.477	0.447
$\|\eta^+ - \eta^-\|$	-0.0002	0.0002	0.0001	-0.0006	0.0006	0.0003
$p_T(l^+ - l^-)$	0.189	0.379	0.199	0.180	0.389	0.370

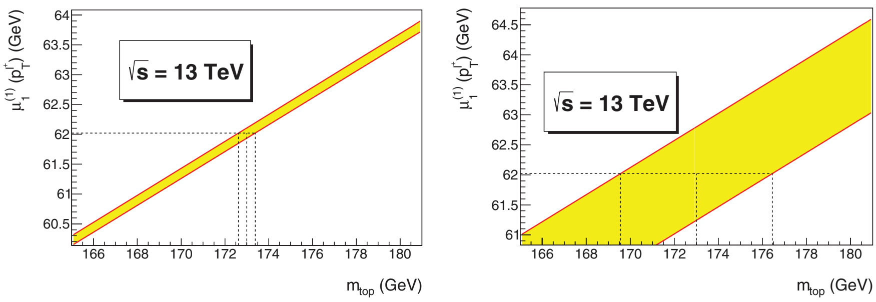
2. – Top mass determination using Mellin moments

The normalised i-th Mellin moment of an observable O is defined as

$$\mu^{O}_{(i)} = \frac{1}{\sigma}\int \mathrm{d}\sigma O^i \qquad (1)$$

and it is by construction independent of factorizable overall normalization-related effects affecting the prediction of O_i, while keeping track of its shape features. The method here presented consists in computing the dependence of Mellin moments of some particular observable correlated to the top-quark mass value. Within the set of observables $\{O_i\}$ of this kind, one should try to pick the ones with possibly stronger dependence on the top-quark mass([1]), while less affected by systematic experimental and theoretical uncertainties. This second argument leads naturally to select $t\bar{t}$ events in the *dilepton* channel, and to rely solely on variables related to the two leptons present in the event, being in this way less sensitive to intrinsic nonperturbative QCD effects. We therefore compute the first four moments of the variables related to the lepton system collected in table I, to be able to validate the method by comparing results to [5]. In addition, for future reference, it has been studied also the dependence on the top-quark mass of the difference of the momenta of the two charged leptons and of their absolute difference in rapidities (being aware to have in this way one variable more than the independent degrees of freedom of the lepton system). For each mass assumption in $m_{top} = \{165, 167, 169, 171, 173, 175, 177, 179\}$ GeV, a total amount of 310000 events have been generated with MADGRAPH5_aMC@NLO [6] at leading-order (LO) accuracy. Parton-showering and hadronisation effects have been simulated using Pythia8 [7]. The detector simulation has been performed using the fast simulation software Delphes 3 [8]. Realistic kinematical cuts have been applied to leptons: $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$. Mellin moments have been computed using four different Parton Density Function (PDF) sets, to assess their LO dependence on this theoretical systematics (fig. 1), even if this has to be intended as an introductory step to a foreseen NLO reimplementation of this study. The central values in table I which can be compared with [5] are in good agreement with it. Using the procedure outlined in [5], the resulting combination of the

([1]) Top-quark mass mildly dependent observables can be considered if needed when used to constrain systematic uncertainties.



(a) (b)

Fig. 1. – Representative theory uncertainties at LO accuracy on the first Mellin moment of the positively charged lepton p_T in $t\bar{t}$ pair production in the dilepton channel and schematical view of the corresponding uncertainty on the top quark mass. (a) Detector level reconstruction effects. (b) PDF sets choice. The resulting large uncertainty is expected, and must not be understood as a theoretical error intrinsic to the method, being related to the Leading Order approximation used in the simulation.

TABLE II. – *Correlation matrix between the first Mellin moments of the observables dependent on the top-quark mass introduced in table I.*

	$\mu_1^{(1)}$	$\mu_2^{(1)}$	$\mu_3^{(1)}$	$\mu_4^{(1)}$	$\mu_5^{(1)}$	$\mu_6^{(1)}$
$\mu_1^{(1)}$	1	0.396	0.598	0.538	0.776	0.719
$\mu_2^{(1)}$	0.396	1	0.114	0.334	0.504	0.218
$\mu_3^{(1)}$	0.598	0.114	1	0.663	0.774	0.823
$\mu_4^{(1)}$	0.538	0.334	0.663	1	0.694	0.648
$\mu_5^{(1)}$	0.776	0.504	0.774	0.694	1	0.926
$\mu_6^{(1)}$	0.719	0.218	0.823	0.648	0.926	1

four-Mellin-moments LO theoretical uncertainty on the top mass using the six variables here considered is of 3.1 GeV (table II). Given the LO accuracy of this preliminary stage of the study, this is a good check that the method has been correctly applied.

3. – Conclusions and outlook

This study represents an important contribution toward the correct implementation of the top-quark mass measurement presented in [5]. In its preliminar stage, it shows that a NLO predicton for the kinematical distributions being considered, expecially the transverse momentum of the charged leptons, is vital for a reliable measurement. On the other hand, this same sensibility clearly proves that the method is able to identify the presence of theoretical biases in the measurement, which is of extreme importance for the top-quark mass extraction and for the consequent interpretation within theoretical related arguments. The LO prediction for the Mellin moments of $p_T(l^+ - l^-)$ and its correlations among the other variables have been computed here for the first time. Some first insights on the PDF set choice related systematics have been given. Inclusion of background effects and other dominant systematics is under investigation and will be part of a separate work.

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