# Top-quark mass measurements at LHC: a new approach

**S. Alioli**[1]**, P. Fernández**[2]**, J. Fuster**[2]**, A. Irles**[2]**, S. Moch**[3 4]**, P. Uwer**[5]**, M. Vos**[2]

[1] LBNL & UC Berkeley, 1 Cyclotron Road, Berkeley, CA 94720, USA
[2] IFIC, Universitat de València and CSIC, Catedrático Jose Beltrán 2, E-46980 Paterna, Spain
[3] II. Inst. für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
[4] DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[5] Humboldt-Universität zu Berlin, Newtonstrasse 15, D-12489 Berlin, Germany

E-mail: adrian.irles@ific.uv.es

**Abstract.** We present a new method to measure the top-quark mass in high energetic hadron collisions at the LHC. We study the mass dependence of the production of top-quark pairs in association with an additional jet. The cross section of tt+1Jet production is sensitive to the top-quark mass since gluon radiation depends on the top-quark mass through threshold and cone effects. In particular we study the normalised tt +1Jet cross section differential in the invariant mass of the final state jets. We have investigated the sensitivity of the method together with the impact of various theoretical and experimental uncertainties. We find that the method has the potential to be competitive with existing methods. We emphasize that in the proposed method the mass parameter can be uniquely defined through one-loop renormalization.

## 1. Introduction

The top quark is the heaviest elementary particle with a mass of $173.2 \pm 0.9$ [1]. Due to its large mass the top quarks present the strongest coupling to the Higgs boson within the framework of the Standard Model (SM). For that, the top quark become an ideal laboratory for detailed tests of the Higgs mechanisms and of many alternative explanations of spontaneous symmetry breaking (EWSB) in Beyond Standard Models (BSM) theories. Top-quark mass comparison with the mass of the recently observed resonance [2, 3] —assuming that the resonance is the long-sought Higgs boson—can be used to test the validity of the Standard Model [4] and the structure of the electroweak vacuum [5, 6].

Quarks, in contrast to leptons, are colored objects that feel the strong interactions. As a consequence, quarks doesn't exist as free particles as they are confined into hadrons. Since quark masses are in general not observables by themselves their precise values depend on the renormalization scheme used to define them. In the case of heavy quark masses the most commonly used definitions are the pole mass $m_q^{\text{pole}}$ and the running mass $\overline{m}_q(\mu_r)$.

The top-quark mass is presently inferred by the kinematical reconstruction of the invariant mass of its decay products (see e.g., Ref. [7]) or by its relation to NLO defined observables like the inclusive top-quark pair production cross section [8]. The extracted mass from kinematical measurements reach to precisions of $\sim 1$ GeV. Mass determinations using the inclusive cross section Ref. [8] presents a weak sensitivity on the top-quark mass $\frac{\Delta\sigma}{\sigma} \sim -5\frac{\Delta m_t}{m_t}$ but in this measurement the renormalization scheme is unambiguously defined in difference with the determination based on the kinematical reconstruction.

In this work we advocate a new method to measure the top-quark mass in high energetic hadron collisions at the LHC looking for a high precision measurement with a renormalization scheme

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unambiguously defined. The mass dependence of the production of top-quark pairs in association with an additional jet is exploited.

## 2. Top-quark pair production in association with a hard jet at NLO accuracy in QCD

The NLO QCD corrections for $t\bar{t}+1\text{-jet}+X$ have been presented in Refs. [9, 10] for Tevatron and LHC (14 TeV) conditions. The results share all the attractive features of theoretical predictions including radiative corrections at higher orders. The cross section for $t\bar{t}+1\text{-jet}+X$ is theoretically very well under control and well suited for precision measurements.

In this document we have updated the results of Refs. [9, 10] to 7 TeV proton proton collisions: see Table 1

**Table 1.** The $t\bar{t}+1\text{-jet}+X$ cross section using LO and NLO calculations [9, 10] for proton-proton collisions at 7 TeV and for different $m_t^{\text{pole}}$ values. Jets are defined using the anti-kt algorithm [11] with R=0.4 as implemented in the FASTJET package [12]. The additional jet is required to have $p_T > 50$ GeV and $|\eta| < 2.5$. The uncertainty due to the limited statistics of the numerical calculation is indicated in parenthesis affecting the last digit. The scale uncertainty is also shown for some top-quark mass values ($\mu = m_t^{\text{pole}}/2 < \mu < \mu = 2m_t^{\text{pole}}$). The CTEQ6.6 [13] (CT09MC1 [14]) PDF set has been used to obtain the NLO (LO) results.

| | $\sigma_{t\bar{t}+1\text{-jet}}$ [pb] | |
|---|---|---|
| $m_t^{\text{pole}}$ [GeV] | LO | NLO |
| 165 | 57.615(4) | 52.25(9) |
| 170 | $49.910(3)^{+30}_{-17}$ | $45.45(6)^{+1}_{-6}$ |
| 175 | 45.372(3) | 39.46(6) |

Finally, the uncertainties originating from the PDFs have been studied by comparing the results obtained with the PDF sets CTEQ6.6 and MSTW2008nlo90cl [15]. For $m_t^{\text{pole}} = 170$ GeV we find, for example $\sigma_{t\bar{t}+1\text{-jet}}^{\text{NLO, MSTW08}} = 49.21$ pb

Very recently predictions for $t\bar{t}+1$-jet productions matched with parton shower predictions (PS) have been provided [16, 17]. We have used the results from Refs. [18, 17] to investigate the effect of the parton shower and allowing for a more realistic study closer to what will be done in the experimental analysis. The obtained results are in good agreement with the previously mentioned.

The various studies mentioned above show, that the theoretical description of the process $t\bar{t}+1$-jet based predictions at NLO accuracy in QCD is well under control.

## 3. Top-quark mass measurements with $t\bar{t}+1$-jet events

The mass sensitivity of the $t\bar{t}+1$-jet cross section $\sigma_{t\bar{t}+1\text{-jet}}$ is very similar to the inclusive $t\bar{t}$ cross section as it is illustrated on Table 1 and a measurement of the top quark mass from it not lead to any significant improvement. Since inclusive cross sections are in general difficult to measure, we propose to study normalized differential distributions. Evidently distributions contain more information and may be more sensitive to the mass parameter. Furthermore, due to the normalization many experimental and theoretical uncertainties cancel between numerator and denominator. In order to enhance the mass sensitivity of $t\bar{t}+1$-jet events we need to focus on specific kinematical configurations. A natural observable to look at is the (normalized) differential distribution of the $t\bar{t}+1$-jet cross section with respect to the invariant

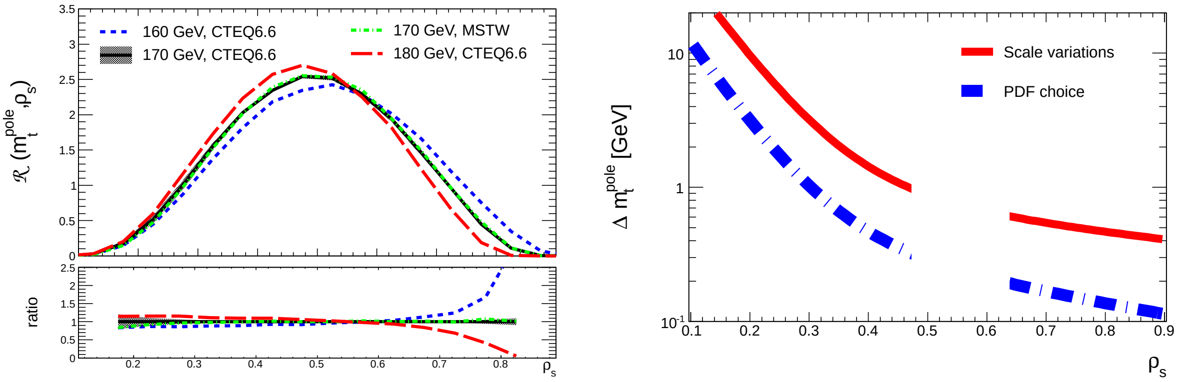


**Figure 1.** Left: $\mathcal{R}(m_t^{\text{pole}}, \rho_s)$ calculated at NLO accuracy for different masses $m_t^{\text{pole}} = 160$, 170 and 180 GeV. For $m_t^{\text{pole}} = 170$ GeV the scale and PDF uncertainties evaluated as discussed in the text are shown. The ratio with respect to the result for $m_t^{\text{pole}} = 170$ GeV is shown in the lower plot.
Right: Expected impact of scale (magenta line) and PDF (blue dashed line) uncertainties on the measured top-quark mass value. The region where $\mathcal{R}$ is essentially insensitive to the top-quark mass is not shown.

mass squared $s_{t\bar{t}j}$ of the final state. More precisely we study the dimensionless distribution

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \tag{1}$$

where $\rho_s$ is defined as $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$ with a fixed value for $m_0 = 170$ GeV.

In this study, the pole mass scheme has been chosen. The study of the convergence of the theoretical uncertainties coming from the PDFs or from the truncation of the perturbative series have been performed following the same criteria of the previous section. To investigate the sensitivity of the distribution $\mathcal{R}$ to the top-quark mass we have calculated $\mathcal{R}$ for different $m_t^{\text{pole}}$. The result is shown in Figure 1 (left). The three curves need to cross since the area under each curve is normalized to one. The crossing happens at $\rho_s \approx 0.55$. At this point the distribution is essentially insensitive to the top-quark mass. For $\rho_s$ close to one we expect that the production of heavier quark masses is suppressed compared to lighter masses. For large energies we observe that the mass dependence is small as one would naively expect. From Figure 1 we conclude that a significant mass dependence can be observed for $0.3 < \rho_s < 0.5$ and $0.6 < \rho_s$.

The impact ofthe scale variations or the PDF choice on the extraction of $m_t^{\text{pole}}$ using these distributions has been evaluated. This is summarized in Figure 1 (right). In both cases we see that $\Delta m_t^{pole} < 1$ GeV. The main source of uncertainty come from the scale variation while the impact of the PDF uncertainties is much smaller.

To investigate further the impact of higher order corrections and the effect of the parton shower we have compared the predictions for $\mathcal{R}(m_t^{\text{pole}}, \rho_s)$ using different approximations: LO, $t\bar{t}$@NLO + POWHEG [18], $t\bar{t} + 1$-jet @NLO + POWHEG [17]. These comparisons show that the $\mathcal{R}$ distribution exhibit a high theoretical stability as far as different approaches give compatible results for the $\mathcal{R}$ distribution.

We are thus lead to the conclusion that from the theoretical perspective $\mathcal{R}$ provides an interesting alternative to existing methods for top-quark mass measurements.

## 4. Experimental viability study

We study now the stable final state particles originated from typical $t\bar{t} + 1\text{-jet} + X$ events as produced in proton-proton interactions at 7 TeV center-of-mass energy. The results presented here illustrates qualitatively the viability and the potential of the method for *à la LHC* environment. In any case, a real experimental determination will necessarily need a more detailed and careful detector analysis.

This study only considers the so called semi-leptonic decay channel which assumes that one of the two $W$ boson decays leptonically (just consider electron or muon channels) whereas the remaining $W$ boson decays hadronically.

Here and in the Table 2 we briefly summarize effects that have been studied: the event generator and fragmentation model: POWHEG with Pythia's parton shower versus MC@NLO [19] with Herwig's parton shower [20, 21];backgrounds, mainly QCD and $W$+jets; the impact of a wrongly reconstructed jet energy; the unfolding procedure to correct the $\mathcal{R}$ distribution to the perturbative partonic level; different modelling of color reconnection; and the statistical error depending on the collected luminosity.

**Table 2.** Summary of the experimental uncertainties studied

| Source of uncertainty | Result |
|---|---|
| Event Gen. & fragm. model | $\Delta m_t^{\text{pole}} \sim 0.2 \pm 0.2$ GeV $(\rho_s > 0.6)$ |
| Backgrounds | $\sim 5\%$ of the events |
| Jet reconstruction | $\Delta m_t^{\text{pole}} \sim 0.8$ GeV $(\rho_s > 0.6)$ assuming a 3% for the jet energy scale uncertainty |
| Unfolding | $\Delta m_t^{\text{pole}} \sim 0.3$ GeV $(\rho_s > 0.6)$ |
| Color Reconnection | $\Delta m_t^{\text{pole}} < 0.25$ GeV at 95%$CL$ $(\rho_s > 0.6)$ |
| Statistics | $\Delta m_t^{\text{pole}} \sim 1.4$ GeV per 5 $fb^{-1}$ $(\rho_s > 0.6)$ |

It is important to say that a real analysis using data and detector specific tools is needed to understand the exact value of the uncertainties affecting the determination of $m_t^{\text{pole}}$ but we can estimate that a total error around of 1 GeV is achievable.

## 5. Conclusions

A new method to measure the top-quark mass at hadron colliders (specifically at LHC) has been presented here. This method is based on a differential distribution of the $t\bar{t}+1$-jet cross section with respect $\sim 1/s_{t\bar{t}j}$. In this analysis the renormalization scheme of the top-quark mass is uniquely defined. Also, this method, presents a well mass sensitivity and low uncertainties coming form uncalculated higher order corrections and from the parton distribution functions. This uncertainties are estimated to be below 1 GeV. Finally, the preliminary study of the experimental viability shows that precisions of $\sim 1$ GeV are achievable. This study has not been addressed to any particular experiment, so a real analysis using data and detector specific framework is needed.

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