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Measurement of the mass difference between top and antitop quarks

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Summary. — A measurement of the mass difference between the top quark and the antitop quark ($\Delta m_{\rm t} = m_{\rm t} - m_{\bar{\rm t}}$) is performed using events with a muon and at least four jets in the final state. Data collected in 2011 with the CMS detector at the LHC and corresponding to an integrated luminosity of $1.09\,{\rm fb}^{-1}$ are analyzed. The measured value of $\Delta m_{\rm t} = -1.2 \pm 1.2({\rm stat.}) \pm 0.5({\rm syst.})$ GeV is consistent with the Standard Model.

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1. – Introduction

CPT symmetry is one of the fundamental symmetries in the Standard Model, which is not known to be violated. A direct measurement of a mass difference between particle and anti-particle would indicate a violation of CPT symmetry. The only quark where this measurement can be performed is the top quark, since it decays before the hadronization can take place. This mass difference between the top quark and the antitop quark has been measured before at the Tevatron and no significant deviation from zero was found [1,2]. In this analysis, $\rm t\bar{t}$ events decaying in the μ+jets channel are used. In these events, one of the two top quarks decays hadronically ($\rm t \to bW \to bq\bar{q}'$) and the other top quark decays in the muon channel ($\rm t \to bW \to b\mu\nu_\mu$). Based on the muon charge, the data can be split into two distinct samples consisting of hadronically decaying top or antitop quarks. For each event category, the Ideogram method [3,4] is used to measure the mass of the top quarks and finally both masses are subtracted from each other: $\Delta m_{\rm t} = m_{\rm t}^{\rm hadr,\,Ideogram} - m_{\rm t}^{\rm hadr,\,Ideogram}$.

2. – Event selection and event reconstruction

The measurement is performed on $1.09\,{\rm fb}^{-1}$ of proton-proton collisions at a center-of-mass energy of 7 TeV which were recorded in the first half of 2011 by the CMS detector [5]. These events were first selected by a trigger requiring an isolated muon with $p_{\rm T} > 17\,{\rm GeV}$.

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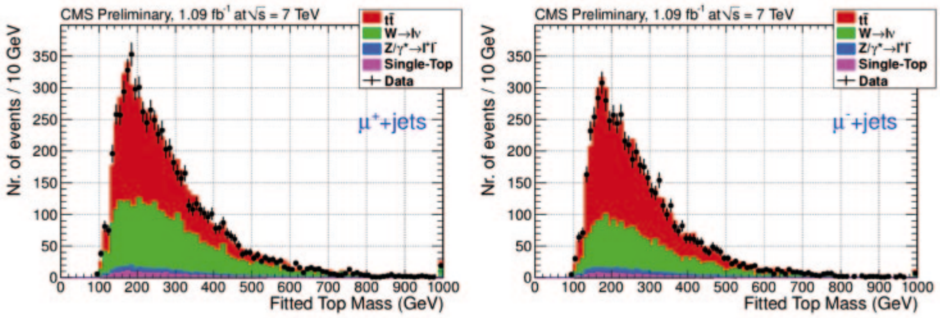

Fig. 1. – Fitted top quark mass for μ^++jets events (left) and μ^-+jets events (right). Only the jet combination with lowest χ^2 from the kinematic fit is shown. The simulation is normalized to the number of observed events in data.

The events are reconstructed with the particle-flow (PF) algorithms [6]. They are selected by requiring exactly one isolated muon with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.1$ and at least four jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$.

A kinematic fit is used to reconstruct the mass of the hadronically decaying top quark. There are 12 possible jet-quark assignments for every event when considering the four leading jets. For each of these, the kinematic fit returns the minimal χ^2 ($\chi^2_{\mathrm{min},i}$), the fitted top quark mass ($m^{\mathrm{Fit}}_{\mathrm{t},i}$) and the uncertainty on the fitted top quark mass ($\sigma_i(m^{\mathrm{Fit}}_{\mathrm{t}})$). Only the jet-quark assignments with $\chi^2_{\mathrm{min},i} < 20$ are considered for further analysis. A comparison between data and simulation of the fitted top quark mass can be found in fig. 1. A good agreement between data and simulated events is observed.

3. – The Ideogram method

The output of the kinematic fit for all the possible jet-quark assignments ($\chi^2_{\mathrm{min},i}$, $m^{\mathrm{Fit}}_{\mathrm{t},i}$ and $\sigma_i(m^{\mathrm{Fit}}_{\mathrm{t}})$) is used in the Ideogram method to measure the top quark mass. For every event a likelihood is calculated

$$\mathcal{L}_{\mathrm{event}}(x; y|m_{\mathrm{t}}, f_{\mathrm{t\bar{t}}}) = f_{\mathrm{t\bar{t}}}\ P_{\mathrm{t\bar{t}}}(x; y|m_{\mathrm{t}}) + (1 - f_{\mathrm{t\bar{t}}})P_{\mathrm{bkg}}(x),$$

x is the number of b-tagged jets $n_{\text{b-tag}}$, the muon charge q^{μ} and the fitted top quark masses $m^{\mathrm{Fit}}_{\mathrm{t},i}$. The quantity y is $\sigma_i(m^{\mathrm{Fit}}_{\mathrm{t}})$ and $\chi^2_{\mathrm{min},i}$. $n_{\text{b-tag}}$ and q^{μ} are factorized out:

$$\begin{aligned} P_{\mathrm{t\bar{t}}}(x; y|m_{\mathrm{t}}) &= P_{\mathrm{t\bar{t}}}(n_{\text{b-tag}}) \cdot P_{\mathrm{t\bar{t}}}(q^{\mu}) \cdot P_{\mathrm{t\bar{t}}}(x_{\mathrm{mass}}; y|m_{\mathrm{t}}), \\ P_{\mathrm{bkg}}(x) &= P_{\mathrm{bkg}}(n_{\text{b-tag}}) \cdot P_{\mathrm{bkg}}(q^{\mu}) \cdot P_{\mathrm{bkg}}(x_{\mathrm{mass}}). \end{aligned}$$

The $\mathrm{t\bar{t}}$ signal probability $P_{\mathrm{t\bar{t}}}(x; y|m_{\mathrm{t}})$ is calculated as a weighted sum over all jet-quark assignments, containing two components: a correct jet combination probability and a wrong jet combination probability:

$$P_{\mathrm{t\bar{t}}}(x_{\mathrm{mass}}; y|m_{\mathrm{t}}) = \sum_{i=1}^{12} w_i \Bigg(f_{\mathrm{gc}} \int \mathrm{d}m' G(m_i|m', \sigma_i) BW(m'|m_{\mathrm{t}}, \Gamma_t) + (1 - f_{\mathrm{gc}}) WP(m_i|m_{\mathrm{t}}) \Bigg).$$

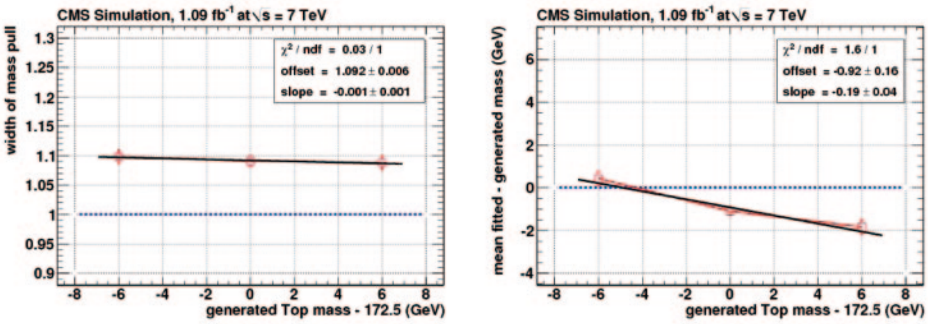

Fig. 2. – Width of the pull distribution (left) and bias on the estimated top quark mass (right) as a function of the generated top quark mass for ℓ+jets events.

The weight w_i is calculated as follows

$$w_i = \exp\left(-\frac{1}{2}\,\chi^2_{\min,i}\right) w_{\text{b-tag}}, \qquad \text{with} \qquad w_{\text{b-tag}} = \prod_j p^j.$$

The probabilities p^j are equal to ε_l, $(1-\varepsilon_l)$, ε_b or $(1-\varepsilon_b)$, depending on the flavor hypothesis for each jet in the jet combination and depending on whether the jet is b-tagged or not. This weight significantly reduces the effect of wrong jet combinations and of background events.

The measured top quark mass is extracted from the combined likelihood of the full sample. This combined likelihood is calculated by combining the individual likelihoods of all the events:

$$\mathcal{L}_{\text{sample}}(x; y|m_{\text{t}}, f_{\text{t}\bar{\text{t}}}) = \prod_j \mathcal{L}_{\text{event,j}}(x; y|m_{\text{t}}, f_{\text{t}\bar{\text{t}}}).$$

Table I. – *Overview of the systematic uncertainties on* Δm_{t}.

Source of systematic effect	Uncertainty on Δm_{t} (GeV)
Jet Energy Scale	0.16
Jet Energy Resolution	0.18
b *vs.* $\bar{b}$ Jet Response	0.10
Signal fraction	0.03
Background composition	0.13
Pileup	0.1
b-tagging efficiency	0.08
b *vs.* $\bar{b}$ tagging efficiency	0.17
Fit calibration statistics	0.3
Parton distribution functions	0.05
Total	0.47

4. – Calibration of the individual mass measurements

The event likelihood is a simplified representation of the underlying probability processes, which means the results need to be calibrated using pseudo-experiments with simulated events. The calibration is performed inclusively for μ+jets events. The bias on the estimated top quark mass as a function of the generated to quark mass is shown in fig. 2. Although the biases are withing 2 GeV, the final results need to be corrected by using the fitted linear calibration curve. The width of the pull distribution is found to be slightly larger than one, so the statistical uncertainties on the final mass measurement are scaled up by about 9%.

5. – Systematic uncertainties

Many of the systematic uncertainties that are important for the measurement of m_{t} are reduced in the context of this measurement, as these systematic effects would alter the measured properties of top and antitop quarks in a similar and correlated manner.

Several sources of systematic uncertainties on the modeling of the physical processes are evaluated, like the modeling of hadronization, underlying event, initial and final-state radiation, factorization scale used, and matching threshold between matrix elements and parton shower. These cross-checks are performed with a precision of 0.6 GeV and no statistically significant impact on the measurement is found. These are not considered further in the context of this analysis. Systematic uncertainties for other effects considered are however included. They are listed in table I. The total systematic uncertainty is taken to be the quadratic sum of the components listed below.

6. – Final results

The final result obtained for $1.09\,\mathrm{fb}^{-1}$ of data taken in 2011 by the CMS experiment is equal to

$$\Delta m_{\mathrm{t}}^{\mathrm{measured}} = -1.20 \pm 1.21\,(\mathrm{stat}) \pm 0.47\,(\mathrm{syst})\ \mathrm{GeV}.$$

The measured value is in agreement with the expectation of the Standard Model. This is the most precise measurement to date of this quantity. More details can be found in [7].

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