Measurement of $t\bar{t}$-production cross section at 7 TeV and study of the W asymmetry in pp-collision

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Abstract

The goal of this project is to measure the production cross section of top quark pairs starting from data collected by the CMS experiment at LHC in 2011. In particular, the production cross section is measured in muon and jet final states in a pp-collision at $\sqrt{s} = 7$ TeV. A data sample of corresponding integrated luminosity of 50 pb^{-1} is used. A selection based on cuts and event selection variables is applied in order to reject background contamination.
Moreover, by using the same sample of data, an analysis on the W asymmetry is performed.

1 $t\bar{t}$-production cross section

1.1 Introduction

Top quark pairs are produced at a very high rate at the LHC, due to the strong force that acts when protons collide. This large available statistics allows for detailed studies of the $t\bar{t}$-production process as a function of several kinematics variables. These precision measurements can then be compared with theoretical predictions in order to extract SM parameters but also to test the validity of the SM theory and to look for hints of new physics. The large amount of top quarks decays rapidly via the weak process $t \to Wb$. According to the SM, the branching ratio of this channel is predicted to be almost 100%. The top quark is also the heaviest fundamental particle that has been produced so far at colliders, and its large mass implies that it decays before hadronizing, giving us the unique opportunity to study a quark not in a bound state but as a bare particle.

In our analysis, the lepton+jets channel is considered:

$$t\bar{t} \to W^-\bar{b}W^+b \to q\bar{q}'\bar{b}l^+\nu_l b \quad \text{or} \quad l^-\bar{\nu}_l\bar{b}q''\bar{q}'''b.$$

Specifically, the signature of our process consist in a muon, its corresponding neutrino and four jets, where two of them come form the hadronisation of the bottom quark. The energy of muons is obtained from the corresponding track momentum using the combined information of the silicon tracker and the muon system.

1.2 Events selection strategy

In order to remove background contamination of the signal, section 4 of [2] has been followed. In the following, all the applied cuts and requirements are explained.
Neutrinos are detected through the missing energy. The missing transverse energy of the neutrinos produced by the W boson is used to remove larger multijet background in muon channel. In particular, the following cut is required:

$$E_T^{\text{miss}} > 30 \text{ GeV}. \tag{1}$$

Then, events with at least one isolated muon are selected by imposing:

$$p_T^{\text{muon}} > 25 \text{ GeV} \quad \text{and} \quad |\eta^{\text{muon}}| < 2.1 \; ; \tag{2}$$

where p_T^{muon} and η^{muon} represent the transverse momentum and the rapidity of the isolated muon. Moreover, an upper limit on the relative isolation is demanded:

$$I_{\text{rel}} < 0.12 \quad . \tag{3}$$

These cuts on the muon are introduced, since the muon emitted from the W boson is expected to be isolated from other product of the event.

Finally, at least four jets are required with:

$$p_T^{\text{jet}} > 40 \text{ GeV} \quad \text{and} \quad |\eta^{\text{jet}}| < 2.5 \quad . \tag{4}$$

Since we are interested to have at least one jet coming from the bottom quark (called b-jet), the discriminating variable b-tag is used in order to individuate these jets. Indeed, if this variable is larger than 2, the jet has an higher probability to come from a b quark.

After these considerations, contamination from the background process are minimized.

1.3 Measurement of the cross section

The total (inclusive) cross section for a given process is:

$$\sigma_{\text{tot.}} = \frac{N_{\text{events}}}{A \; \varepsilon \int \mathcal{L} dt}, \tag{5}$$

where N_{events} is the number of measured signal events, A is the acceptance of the process, ε is experimental efficiency and $\mathcal{L}$ is the instantaneous luminosity.

The choice of the observable used to compute the cross section is dictated by the highest value of the ratio

$$\frac{S}{\sqrt{S+B}}, \tag{6}$$

where S and B are the number of simulated signal and background, meaning that the contamination of the background is minimal. The values S and B are simulated with the trigger and are determined through IntegralAndError method from TH1F class of ROOT. This is the case of "Number of jets" observable (figure 1).

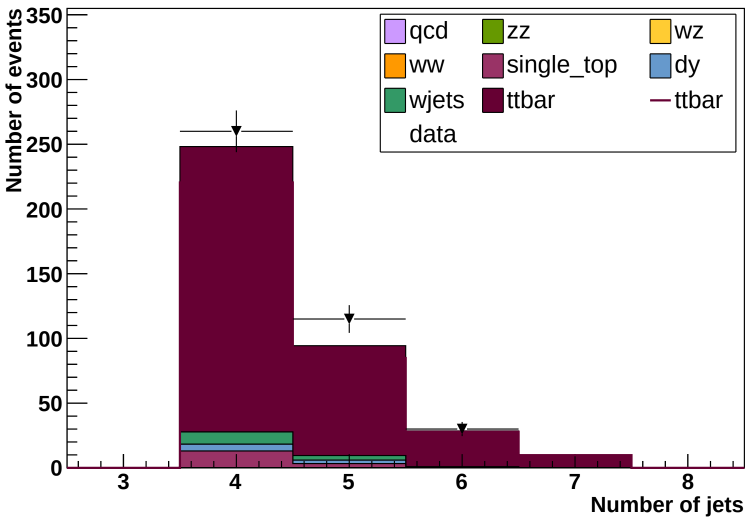

Figure 1: Number of jets

The number of observed events N_{events} can be found by subtracting a Monte Carlo prevision of the number of background events B to the number of measured data D (which includes background events surviving our selection and is determined similar to S and B). Therefore:

$$N_{\text{events}} = D - B. \tag{7}$$

The acceptance factor A takes into account all the selection cuts that has been applied and the fact that only semileptonic decay of the top quark pair in the muon channel is considered. To compute it, the number of simulated $t\bar{t}$ events before ($N_{t\bar{t}}^{\text{tot}}$) and after ($S$) the cuts are used:

$$A = \frac{S}{N_{t\bar{t}}^{\text{tot}}}. \tag{8}$$

The last important parameter that allows us to define the quality of the selection procedure is the the trigger efficiency ε of the process. It is defined as

$$\varepsilon = \frac{S}{S_{\text{no trigg}}}, \tag{9}$$

where $S_{\text{no trigg}}$ are the number of simulated signal without the trigger.

1.4 Results

The $t\bar{t}$ pair production cross section at 7 TeV measured in the muon+jet channel is:

$$\sigma_{t\bar{t}}^{\text{exp}} = 203.09 \pm 15.12(\text{stat.}) \pm 10.20(\text{syst.}) \;\; \text{pb} \tag{10}$$

$$\sigma_{t\bar{t}}^{\text{exp}} = 203.09 \pm 25.32(\text{tot.}) \;\; \text{pb} \tag{11}$$

The errors are computed using error propagation formula and assuming uncorrelated variables. The integrated luminosity is $L = 50$ pb^{-1}, with an assumed systematic uncertainty of 10%. In the following, all the used quantities with their statistical uncertainties are listed.

$D \pm \Delta D = 405.0 \pm 20.12$
$B \pm \Delta B = 37.96 \pm 5.46$
$S \pm \Delta S = 343.03 \pm 9.53$
$N_{t\bar{t}}^{\text{tot}} \pm \Delta N_{t\bar{t}}^{\text{tot}} = 7928.61 \pm 89.04$
$S_{\text{no trigg}} \pm \Delta S_{\text{no trigg}} = 410.60 \pm 10.41$
$N_{\text{events}} \pm \Delta N_{\text{events}} = 367.04 \pm 20.85$
$A \pm \Delta A = 0.043 \pm 0.001$
$\varepsilon \pm \Delta\varepsilon = 0.835 \pm 0.031$

1.5 Discussion

The predicted value of the cross section at $\sqrt{s} = 7$ TeV computed at NNLO is:

$$\sigma_{t\bar{t}}^{\text{theory}} = 173.60^{+11.24}_{-11.78} \text{ pb} \;\; . \tag{12}$$

Our measured cross section is in agreement with the theoretical prediction. Indeed, the χ^2 value computed through

$$\chi^2 = \frac{1}{2}\frac{(\sigma_{t\bar{t}}^{\text{exp}} - \sigma_{t\bar{t}}^{\text{theory}})^2}{(\Delta\sigma_{t\bar{t}}^{\text{exp}})^2 + (\Delta\sigma_{t\bar{t}}^{\text{theory}})^2} \tag{13}$$

is $\chi^2 = 0.57$.

2 W asymmetry

2.1 Introduction

In the LHC, two dominant process are responsible of the W production: $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$. In a pp-collision, the probability of interaction between an anti-up and a down quark is lower than in a $p\bar{p}$-collision, due to the valence quarks of the proton (uud) and implies a larger presence of W^+ rather than W^-. The asymmetry between W^+ and W^- is closely related to the presence of these quarks, and therefore can be used to better define and measure the parton distribution functions (PDFs).

The W boson decays in a muon and a neutrino, meaning that the W asymmetry can be studied through the muon charge asymmetry, defined as:

$$\mathcal{A}_\mu(\eta) = \frac{\left(\frac{d\sigma_{W\mu^+}}{d\eta_\mu}\right) - \left(\frac{d\sigma_{W\mu^-}}{d\eta_\mu}\right)}{\left(\frac{d\sigma_{W\mu^+}}{d\eta_\mu}\right) + \left(\frac{d\sigma_{W\mu^-}}{d\eta_\mu}\right)} \tag{14}$$

The signature of this decay consists in a high transverse momentum of the muon accompanied by missing transverse momentum of the escaping neutrino. Therefore, only two conditions are imposed to the transverse momentum and the pseudorapidity of the muons:

$$p_T > 30 \text{ GeV} \qquad \text{and} \qquad |\eta| < 0.4 \ . \tag{15}$$

2.2 Results

In order to compute the asymmetry $\mathcal{A}_\mu$, the following formula is used:

$$\mathcal{A}_\mu = \frac{N^+ - N^-}{N^+ + N^-}, \tag{16}$$

where $N^\pm$ are the number of signal events of a single muon $\mu^\pm$, or equivalently, of $W^\pm$. These numbers can be extrapolated in two different ways, via the invariant mass distribution and the missing transverse energy distribution, which will be explained in the following sections.

2.2.1 First option: invariant mass distribution

The idea is to measure $N^\pm$ as the area under the function that fits the invariant transverse mass of the W boson, which for massless daughters, is defined as:

$$M_{T,W}^2 = 2p_T^{\text{muon}} E_T(1 - \cos\Delta\varphi) \tag{17}$$

with

$$\vec{p}_T^{\ \text{muon}} = (p_x, p_y) \tag{18}$$

$$\vec{p}_T^{\ \text{neutrino}} = (E_{T,x}, E_{T,y}) \qquad \text{so that} \qquad E_T^2 = E_{T,x}^2 + E_{T,y}^2 \tag{19}$$

and $\Delta\varphi$ is the angle between the momenta.
The fitting function consists in a double Gaussian for the signal and an error function for background (figure 2):

$$f(x)_{\text{fit}} = a_0[\text{erf}(x, a_1, a_2) + 1] + a_3 G(x, a_4, a_5) + a_6 G(x, a_7, a_8), \tag{20}$$

where the Gaussian is defined as:

$$G(x, \lambda_1, \lambda_2) = \exp\left\{ -\frac{1}{2}\left(\frac{x-\lambda_1}{\lambda_2}\right)^2 \right\}, \tag{21}$$

and the error function:

$$\mathrm{erf}(x, \lambda_1, \lambda_2) = \frac{2}{\sqrt{\pi}} \int_0^{\frac{x-\lambda_1}{\lambda_2}} e^{-t^2} dt \ . \tag{22}$$

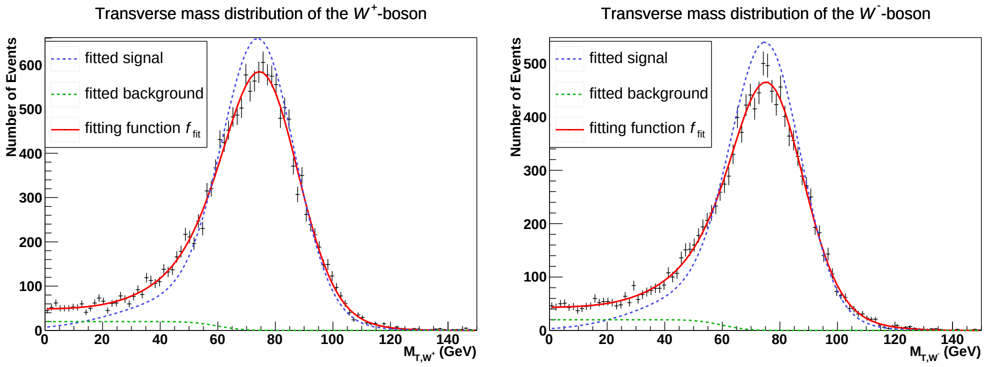

Figure 2: The panels shown the behaviour of the fitting functions.

The integrals under the fitting curves and their errors are computed through Integral and IntegralError method from TF1 class of ROOT. Their values corresponds to $N^{\pm}$ and are:

$$N^+ \pm \Delta N^+ = 24330.22 \pm 187.28 \qquad N^- \pm \Delta N^- = 19309.81 \pm 170.20 \ .$$

Through equation 16, the result of the asymmetry $\mathcal{A}_\mu^{(1)}$ is found:

$$\mathcal{A}_\mu^{(1)} \pm \Delta\mathcal{A}_\mu^{(1)} = 0.115 \pm 0.0058 \ . \tag{23}$$

2.2.2 Second option: MET distribution

This method is similar as the one used in the first section, but in this case histograms of the MET distribution are considered (figure 3). Indeed, $N^{\pm}$ are computed by subtracting the number of simulated background events (B) to the data (D). B and D are computed as before. Their values are:

$$N^+ \pm \Delta N^+ = 15680.22 \pm 135.22 \qquad N^- \pm \Delta N^- = 12069.38 \pm 309.48 \ ,$$

leading to an asymmetry $\mathcal{A}_\mu^{(2)}$ of:

$$\mathcal{A}_\mu^{(2)} \pm \Delta\mathcal{A}_\mu^{(2)} = 0.130 \pm 0.013 \ . \tag{24}$$

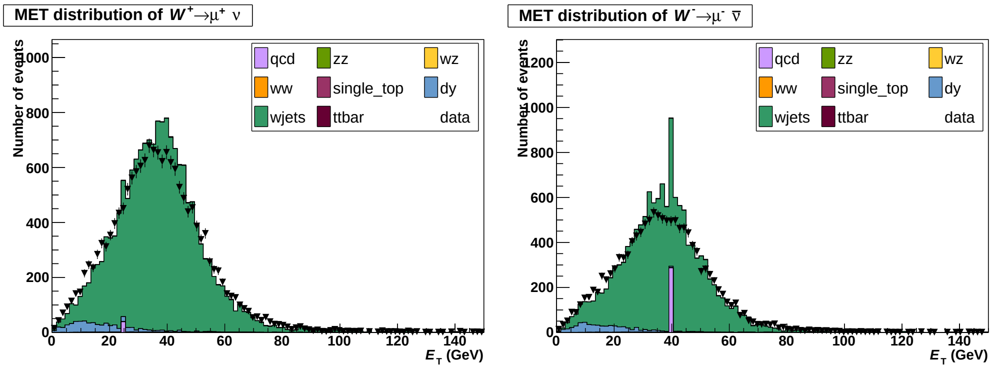

Figure 3: The histogram on the left shows the distribution of the missing transverse energy corresponding to the $W^+ \to \mu^+ + \nu$ process, while the right histogram for $W^- \to \mu^- + \bar{\nu}$.

2.3 Discussion

Through different methods we obtain consistent results. In particular, they lead to an averaged asymmetry of:

$$\overline{\mathcal{A}_\mu} = 0.117 \pm 0.0053 \quad . \tag{25}$$

References

[1] CMS collaboration (2016), *Measurement of the $t\bar{t}$ production cross section in the $e^{-}\mu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV*, arXiv:1603.02303v2

[2] CMS collaboration (2017), *Measurements of the $t\bar{t}$ production cross section in lepton+jets final states in pp collisions at 8 TeV and ratio of 8 to 7 TeV cross sections*

[3] Cesare Bini (2013), *Data analysis in Particle Physics*

[4] CMS collaboration (2014), *Measurement of the muon charge asymmetry in inclusive $pp \rightarrow W + X$ production at $\sqrt{s} = 7$ TeV and an improved determination of light parton distribution functions*

[5] Particle Data Group (2019), *top quark*