PROCEEDINGS OF SCIENCE

Differential measurement of top-quark-pair production with additional jet activity in the dilepton channel at CMS

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A differential measurement of associated $t\bar{t}$ production with additional jets, including b jets, is presented. The measurement is performed in the dilepton decay channels (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) using data corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$ collected in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ with the CMS detector at the LHC. The absolute and normalised differential cross sections for $t\bar{t}$ production are measured as a function of the jet multiplicity for different jet-transverse-momentum thresholds, and as a function of kinematic properties of the leading additional jets. The differential $t\bar{t}b\bar{b}$ cross sections are presented for the first time as a function of kinematic properties of the leading additional b jets. Furthermore, the fraction of events without additional jets above a transverse-momentum threshold is measured. The data are found to be consistent with predictions from several perturbative-QCD event generators and a next-to-leading order calculation.

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1. Introduction

Precise measurements of $t\bar{t}$ production allow to test the expectations of the standard model (SM), and to validate specific calculations in the framework of perturbative quantum chromodynamics (pQCD) at high-energy scales. At the energies of the CERN LHC, about half of the $t\bar{t}$ pairs are accompanied by jets with transverse momentum (p_{T}) greater than 30 GeV that do not originate from the weak decay of the $t\bar{t}$ system (*additional jets*) [1].

These processes also constitute a challenging background to the production of a Higgs boson in association with a $t\bar{t}$ pair ($t\bar{t}H$), where the Higgs boson decays to a bottom-quark pair ($\mathrm{b\bar{b}}$), because of the much larger cross section compared to the $t\bar{t}H$ signal. Such a process has an irreducible nonresonant background from $t\bar{t}$ pair production in association with a $\mathrm{b\bar{b}}$ pair from gluon splitting, as schematically demonstrated in Figure 1.

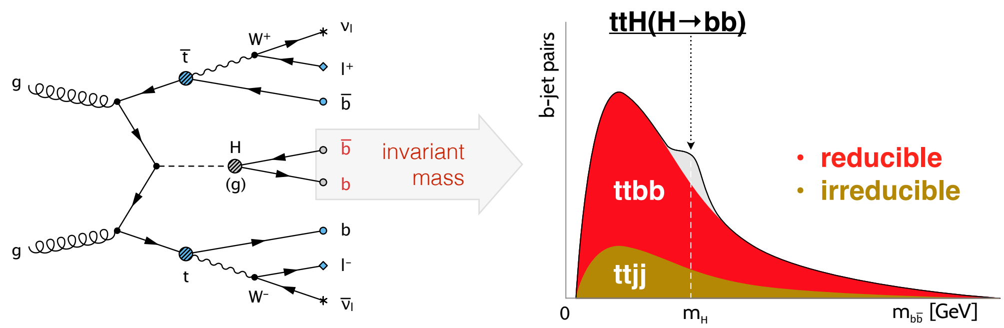

Figure 1: Feynman graph of the $t\bar{t}H(b\bar{b})$ and $t\bar{t}b\bar{b}$ production in the dileptonic final state of the $t\bar{t}$ system (left), and schematic view of the background composition in a $t\bar{t}H$ search (right).

The absolute and normalised differential $t\bar{t}$ cross sections are measured as a function of the jet multiplicity for different jet-p_{T} thresholds, in order to probe the momentum dependence of the hard-gluon emission. The $t\bar{t}+jets$ production cross sections are also measured as a function of kinematic properties of the leading additional jets, extending the previous CMS measurement at $\sqrt{s} = 7\,\mathrm{TeV}$ [1]. And for the first time the $t\bar{t}b\bar{b}$ production cross section is measured differentially as a function of kinematic properties of additional b jets [2].

1.1 Previous inclusive cross-section measurement by CMS

The inclusive $t\bar{t}b\bar{b}$ production cross section in the dilepton channels was already measured by CMS before [3], as well as its ratio to the $t\bar{t}+jets$ cross section with partially canceling systematic uncertainties. The $t\bar{t}+jets$ and $t\bar{t}b\bar{b}$ yields were obtained from a simultaneous template fit of the b-tagging discriminator distributions of the third and fourth jets in the event in decreasing order of the b-tagging discriminator. The fit contained two free parameters, an overall normalisation of the $t\bar{t}$ contribution and the ratio of the $t\bar{t}b\bar{b}$ to $t\bar{t}+jets$ yields. The distributions of the b-tagging discriminator corrected by the fit results are shown in Figure 2. The $t\bar{t}b\bar{b}$ cross section was measured to be 0.029 ± 0.003 (stat) ± 0.008 (syst) pb. The measured $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}+jets}$ ratio is higher than the NLO theoretical prediction, but compatible within 1.6 standard deviations, as shown in Figure 3.

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The differential cross sections described later provide a more stringent test of theoretical QCD predictions, and are especially important for $t\bar{t}H$ searches that are sensitive to kinematic properties of additional b-jets.

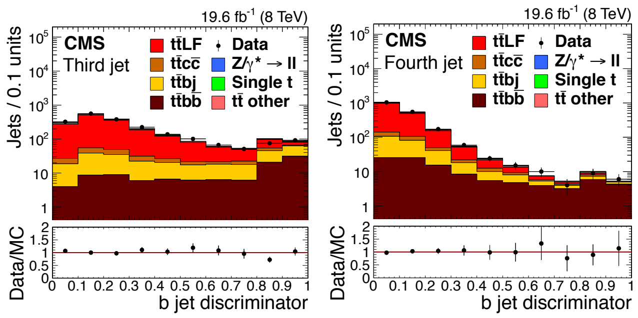

Figure 2: Distributions of b-tagging discriminator for the third and fourth jets in events in decreasing order of b-tagging discriminator value, after the full event selection. Points are from data and stacked histograms from MC simulation corrected for results from the fit to data.

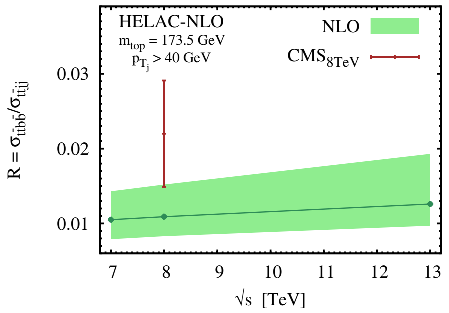

Figure 3: The measured $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}+jets}$ ratio compared to the NLO theoretical prediction as a function of the $\sqrt{s}$ at the LHC. The uncertainty band depicts scale variation [4].

2. Event reconstruction and selection

The event selection is based on the decay topology of the $t\bar{t}$ events, where each top quark decays into a W boson and a b quark. Since dileptonic channel is considered in this analysis, the presence of at least two isolated oppositely-charged leptons ($p_T > 20$ GeV, $|\eta| < 2.4$) is required, as well as missing transverse momentum ($\not{E}_T > 40$ GeV) owing to the neutrinos from leptonic W-boson decays, and highly-energetic jets ($p_T > 20$ GeV, $|\eta| < 2.4$). The heavy-quark content of the jets is identified through b-tagging techniques, which have been optimised independently for the $t\bar{t}+jets$ and $t\bar{t}b\bar{b}$ cases.

For $t\bar{t}+jets$ selection, a minimum of two jets is required, of which at least one must be tagged as a b jet with the probability of mistagging jets originating from light quarks (u, d, or s) or gluons of around 10 %. For $t\bar{t}b\bar{b}$ selection, due to a larger amount of b jets in the final state, at least three b-tagged jets are required with the lower mistagging probability of around 1 %. The detailed description of the event reconstruction and selection is documented in [2].

3. Identification of additional jets in the event

To study additional jet activity in the data, it is crucial to identify jets arising from the decay of the $t\bar{t}$ system. In particular, when measuring properties of additional jets, the two b jets from the top-quark decays have to be identified in events with more than two b jets. This is achieved by following two independent but complementary approaches individually optimised for $t\bar{t}+jets$ and $t\bar{t}b\bar{b}$ final states.

For $t\bar{t}+jets$ case the full kinematic reconstruction of the $t\bar{t}$ system is performed based on $\not{E}_T$ and the information on identified jets and leptons, taking into account detector-resolution effects on the input parameters of the reconstruction [5]. This method is used because it provides optimal performance in the case where b jets originate primarily from the $t\bar{t}$ decay. Efficiency of correct identification of the two jets originating from the $t\bar{t}$ decay in $t\bar{t}+jets$ events is about 70 %.

For $t\bar{t}b\bar{b}$ case a multivariate approach is used, which is based on a boosted decision tree (BDT), and is optimised for events with additional b jets. This method identifies the two jets that most likely originate from the top-quark decays, without the full reconstruction of the $t\bar{t}$ system. The remaining highest-p_{T} b-tagged jets are treated as additional. The BDT is trained on $t\bar{t}H(b\bar{b})$ simulations with different assumptions of the Higgs-boson mass in the range 110-140 GeV. A total of twelve variables are included in the BDT, which are expected to be Lorentz invariant, minimising potential $m_{b\bar{b}} \to m_H$ bias for additional b jets[2]. Efficiency of correct assignment for the pair of additional b jets in $t\bar{t}b\bar{b}$ events is around 40 %.

4. Differential $t\bar{t}$ cross sections

The absolute differential $t\bar{t}$ cross section as a function of variable x_i is defined as:

$$\frac{d\sigma_{t\bar{t}}}{dx_i} = \frac{\sum_j A_{ij}^{-1} \cdot (N_{\mathrm{data}}^j - N_{\mathrm{bkg}}^j)}{\Delta_x^i \cdot \mathscr{L}}, \tag{4.1}$$

where j represents the bin index, i is the index of the corresponding generator-level bin, N_{data}^j and N_{bkg}^j are the numbers of data and estimated background events respectively in bin j, $\mathscr{L}$ is the integrated luminosity, and Δ_x^i is the bin width. Effects from detector efficiency and resolution, leading to migration of events from any bin i to the measured bin j, are corrected by the use of a regularised inversion of the response matrix, denoted by A_{ij}^{-1}.

The presented cross sections are defined at the particle level, and are reported for the visible phase space of the $t\bar{t}$ system, which requires the leptons ($p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$) and b jets ($p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.4$) from the $t\bar{t}$ decay as well as additional jets and b jets ($p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$) to be within the detector acceptance. The cross sections are also measured for the full phase space of the $t\bar{t}$ system, requiring only additional jets and b jets to be within the above-mentioned kinematic range, without additional requirements on the decay products of the $t\bar{t}$ system, and including the correction for the corresponding dileptonic branching fraction [2].

4.1 Cross sections as a function of jet multiplicity

In Figure 4, the absolute differential $t\bar{t}$ cross sections are shown for three different jet-p_{T} thresholds: $p_{\mathrm{T}} > 30$, 60, and 100 GeV. The measured cross sections are compared to a range of MC predictions, using different versions of matrix-element and parton-shower generators.

In general, no large deviations between data and the different MC prediction are observed. Variations in the renormalisation and factorisation scales lead to a slightly worse description of the data up to high jet multiplicities. Simulations interfaced with PYTHIA8 parton-shower generator predict larger jet multiplicities than measured in the data for all the considered p_{T} thresholds

4.2 Cross sections as a function of the kinematic properties of the additional jets

In Figure 5 the absolute differential cross sections are shown as functions of kinematic properties of additional jets. The uncertainties in the measured cross sections are dominated by systematic

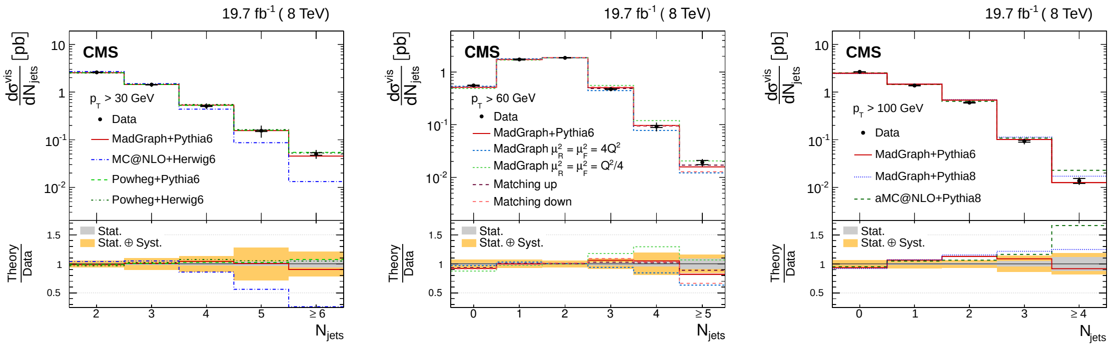

Figure 4: Absolute differential $t\bar{t}$ cross sections in the visible phase space of the $t\bar{t}$ system as a function of jet multiplicity for jets with $p_T > 30$ GeV (left), 60 GeV (middle), and 100 GeV (right).

effects, primarily from jet energy scale, scale uncertainties and shower modelling. The results are compared to predictions from four different generators: POWHEG interfaced with PYTHIA6 and HERWIG6 parton showers, MC@NLO+HERWIG6, and MADGRAPH+PYTHIA6 with varied renormalisation, factorization, and jet-parton matching scales. For the better shape comparison, all predictions are normalised to the measured cross section. In general, all simulations provide a reasonable description of the distributions for all the variables.

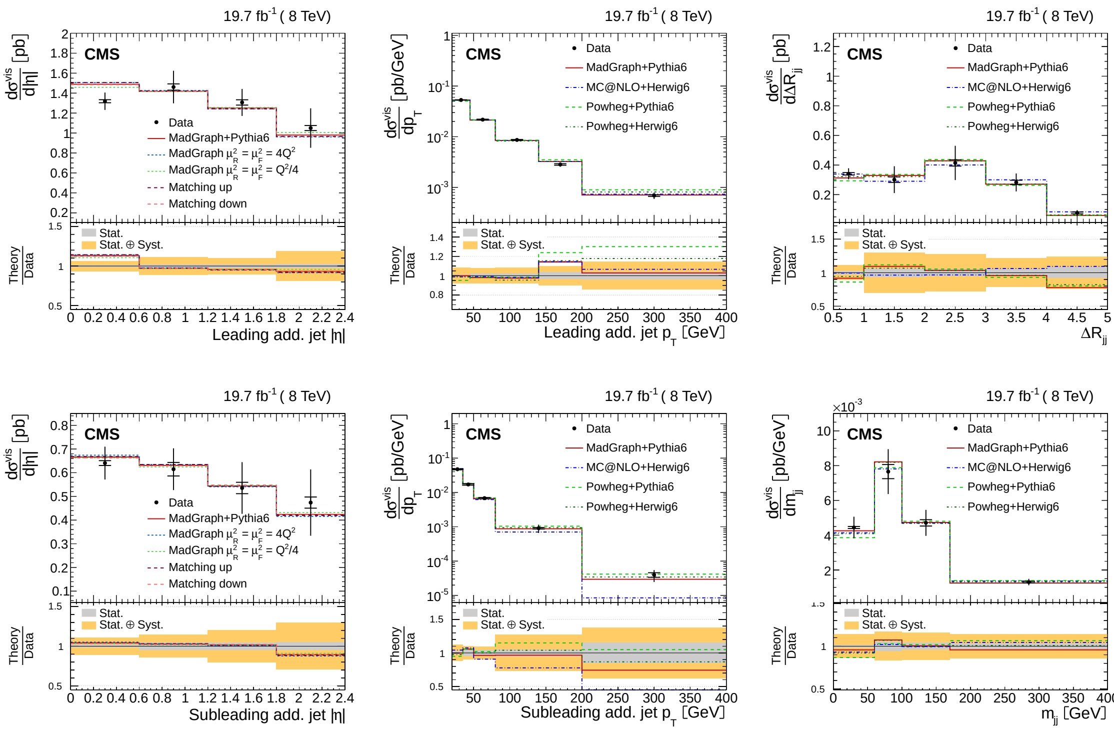

Figure 5: Absolute differential $t\bar{t} + jets$ cross sections in the visible phase space of the $t\bar{t}$ system as a function of kinematic properties of additional jets. Theory predictions are normalised to Data.

4.3 Cross sections as a function of the kinematic properties of the additional b jets

Figure 6 shows the absolute differential cross sections as functions of kinematic properties of additional b jets. Doe to the high b jets multiplicity, precision of the measured $t\bar{t}b\bar{b}$ cross sections is limited by statistical uncertainties. The dominant systematic uncertainties are the b tagging efficiency and jet energy scale. The measured cross sections are compared to the same four MC predictions as in $t\bar{t}+jets$ case, which are normalised to Data. The $t\bar{t}b\bar{b}$ cross sections are also compared to the dedicated NLO calculation by POWHEL+PYTHIA6 [6], which has lower dependence on the renormalisation and factorisation scales, and therefore is not normalised to the measured cross section. The current statistical precision does not allow to discriminate between different theoretical predictions, which describe all the measured cross sections. The integral of the differential $t\bar{t}b\bar{b}$ cross section was ensured to be consistent with the previous inclusive measurement by CMS after implementing a nearly identical cross-section definition [7].

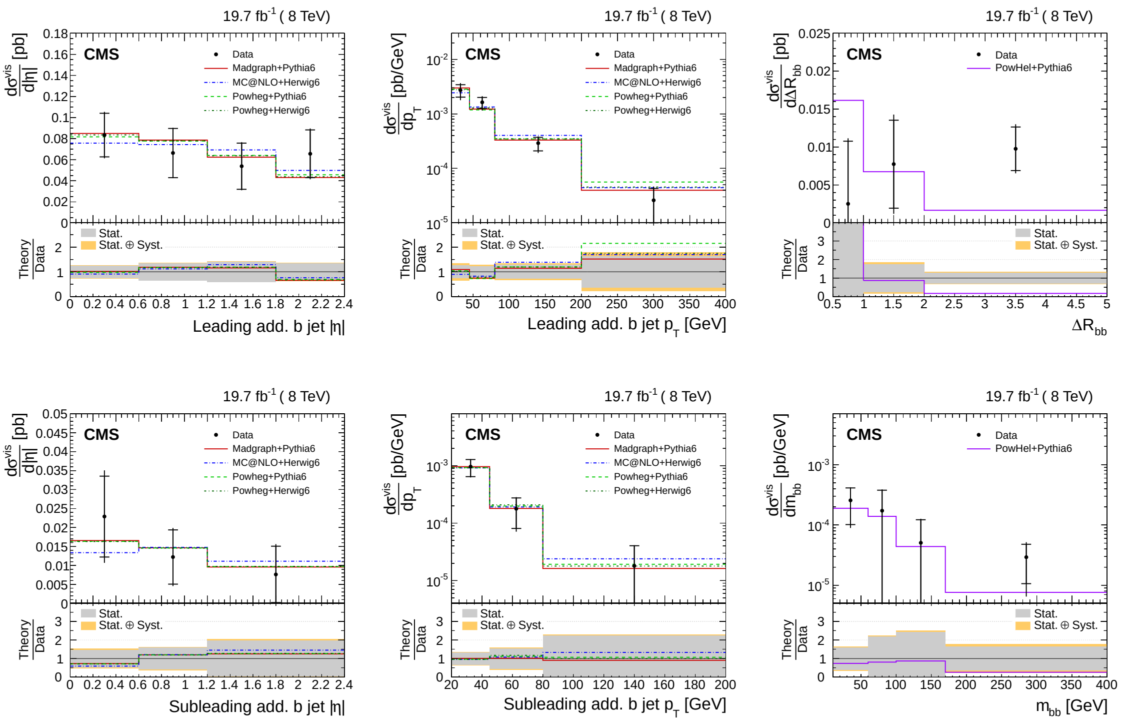

Figure 6: Absolute differential $t\bar{t}b\bar{b}$ cross sections in the visible phase space of the $t\bar{t}$ system as a function of kinematic properties of additional b jets. Theory predictions are normalised to Data in the left and middle columns.

5. Summary

Measurements of the absolute and normalised differential $t\bar{t}$-production cross sections have been presented using pp collisions at a $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$. The cross sections were measured in the dilepton decay channel of the $t\bar{t}$ system as a function of the number of jets in the event, for three different jet-p_T thresholds, and as a function of the kinematic variables of the leading and subleading additional jets and b jets. In general, the different measurements are in agreement with the SM predictions from various event generators, within their uncertainties. An extensive documentation of the measurement can be found in [2].

The correct description of $t\bar{t} + jets$ production is important as a test of QCD and in searches for new supersymmetrric particles or $t\bar{t}H(b\bar{b})$ production. The $t\bar{t}b\bar{b}$ differential cross sections, measured here for the first time, provide crucial information about the main irreducible background in the search for $t\bar{t}H(b\bar{b})$ production.

References

[1] CMS Collaboration, *Measurement of jet multiplicity distributions in* $\mathrm{t\bar{t}}$ *production in* pp *collisions at* $\sqrt{s}$ = *7 TeV*, *Eur. Phys. J. C* **74** (2014) 3014, [1404.3171].

[2] CMS collaboration, C. Collaboration, *Measurement of* $\mathrm{t\bar{t}}$ *production with additional jet activity, including b quark jets, in the dilepton decay channel using pp collisions at* $\sqrt{s} = 8$ *TeV*, 1510.03072.

[3] CMS collaboration, C. Collaboration, *Measurement of the cross section ratio* $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ *in* pp *collisions at* $\sqrt{s} = 8$ *TeV*, *Phys. Lett. B* **746** (2015) 132, [1411.5621].

[4] G. Bevilacqua and M. Worek, *On the ratio of* $t\bar{t}b\bar{b}$ *and* $t\bar{t}jj$ *cross sections at the CERN Large Hadron Collider*, *JHEP* **07** (2014) 135, [1403.2046].

[5] CMS collaboration, C. Collaboration, *Measurement of the differential cross section for top quark pair production in pp collisions at* $\sqrt{s} = 8\,$*TeV*, *Eur. Phys. J.* **C75** (2015) 542, [1505.04480].

[6] M. V. Garzelli, A. Kardos and Z. Trócsányi, *Hadroproduction of* $t\bar{t}b\bar{b}$ *final states at LHC: predictions at NLO accuracy matched with parton shower*, *JHEP* **03** (2015) 083, [1408.0266].

[7] N. Bartosik, *Associated top-quark-pair and b-jet production in the dilepton channel at* $\sqrt{s} = 8$ *TeV as test of QCD and background tt+Higgs production*. PhD thesis, U. Hamburg, Dept. Phys., Hamburg, 2015.