PROCEEDINGS OF SCIENCE

Measurement of the $\mathrm{t\bar{t}b\bar{b}}$ cross section and the ratio $\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj})$ in the lepton+jets final state at $\sqrt{s}$=8 TeV with the CMS detector

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The production cross sections of a top-quark pair with at least either two additional jets, taken inclusively with respect to the jet flavor ($\mathrm{t\bar{t}jj}$), or two jets originating from b-quarks ($\mathrm{t\bar{t}b\bar{b}}$) are measured in the final state with one lepton and jets. The study is performed for an integrated luminosity of 19.6 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 8$ TeV. To identify the jets originating from the top-quark pair decay a kinematic fit with mass constraints, multivariate classifiers in categories split by the jet multiplicity and b-tag discriminants of the jets are used. The contributions of $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$ with at least two additional b jets or jets of any flavor are measured with a simultaneous template fit using shapes of b-tag discriminants. The measured cross sections $\sigma(\mathrm{t\bar{t}b\bar{b}}) = 271.0 \pm 103.0(\mathrm{stat}) \pm 32.2(\mathrm{syst}) \pm 7.0(\mathrm{lumi})$ fb, $\sigma(\mathrm{t\bar{t}jj}) = 23.1 \pm 2.3(\mathrm{stat}) \pm 2.9(\mathrm{syst}) \pm 0.6(\mathrm{lumi})$ pb and the cross section ratio $\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj}) = 0.0117 \pm 0.0040(\mathrm{stat}) \pm 0.0003(\mathrm{syst})$ correspond to the phase space of additional jets defined at generator-level as: $p_{\mathrm{Taj}} > 40\,\mathrm{GeV/c}$, $|\eta_{\mathrm{aj}}| < 2.5$, $\Delta\mathrm{R_{ajj}} > 0.5$. The parton with leading transverse momentum inside the cone of the jet defines the jet flavor. The obtained results agree with the NLO calculations and with the measurement of CMS in the dilepton channel when the same jet definition is used.

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1. Motivation

The measurements of the associated top-quark pair production with at least two b jets ($\mathrm{t\bar{t}b\bar{b}}$) increases the understanding of the quantum chromodynamics (QCD). The most accurate predictions are next-to-leading order (NLO) calculations [1, 2], which have to be matched with a parton shower (PS). These calculations suffer from large uncertainties. Experimental measurements can constrain these uncertainties. In addition, a good knowledge of the $\mathrm{t\bar{t}b\bar{b}}$ production helps to probe the properties of the Higgs Boson H. To determine its couplings to top and bottom quarks the $\mathrm{t\bar{t}H(b\bar{b})}$ channel plays an important role. Here, the $\mathrm{t\bar{t}b\bar{b}}$ production is an irreducible background component, while the $\mathrm{t\bar{t}qq}$ production with two or more additional jets from light quarks or gluons contributes due to misidentification of these jets as b jets.
The $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$ productions were studied with CMS at $\sqrt{s} = 8$ TeV in the dilepton final state [3]. The measured cross sections $\sigma(\mathrm{t\bar{t}jj})^{\mathrm{dilepton}} = 16.1 \pm 0.7(\mathrm{stat}) \pm 2.1(\mathrm{syst})$ pb, $\sigma(\mathrm{t\bar{t}b\bar{b}})^{\mathrm{dilepton}} = 360 \pm 80(\mathrm{stat}) \pm 100(\mathrm{syst})$ fb and the cross section ratio $\sigma^{\mathrm{dilepton}}_{\mathrm{t\bar{t}b\bar{b}}} / \sigma^{\mathrm{dilepton}}_{\mathrm{t\bar{t}jj}} = 0.022 \pm 0.004(\mathrm{stat})$ ± 0.005 (syst) are marginally consistent with the NLO calculations in the same phase space: $\sigma(\mathrm{t\bar{t}jj})^{\mathrm{NLO}} = 20.1^{+15\%}_{-13\%}$ pb, $\sigma(\mathrm{t\bar{t}b\bar{b}})^{\mathrm{NLO}} = 229^{+18\%}_{-24\%}$ fb and $\sigma^{\mathrm{NLO}}_{\mathrm{t\bar{t}b\bar{b}}}/\sigma^{\mathrm{NLO}}_{\mathrm{t\bar{t}jj}} = 0.011^{+39\%}_{-13\%}$ [2]. The available matrix element (ME) calculations do not include PS contributions which can increase the jet production and can change the flavor of the jets, which influences the $\mathrm{t\bar{t}b\bar{b}}$ and the $\mathrm{t\bar{t}jj}$ cross sections. In this analysis the $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$ cross sections and their ratio $\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj})$ are measured in the lepton+jets final state [4]. To investigate the influence of the PS two different jet flavor definitions are used. For the parton flavor definition the flavor of the additional jets is defined by the flavor of the parton with leading transverse momentum inside the jet cone, while for the particle flavor definition the presence of any heavy flavor (b or c) hadron inside the jet defines the jet flavor.

2. Event selection

The analysis is based on a data sample corresponding to an integrated luminosity of $\mathscr{L}$=19.6 fb^{-1} collected with the CMS experiment at a center-of-mass energy of $\sqrt{s}$=8 TeV. Events with exactly one isolated lepton (muon or electron) and at least four jets with a p_{T} greater than 50 GeV are selected. At least two of these jets have to be identified as b jets, using a combined secondary vertex (CSV) algorithm, which combines information of the secondary vertex with lifetime information of single tracks [5]. A working point with a b-tag efficiency of $\approx 70\%$ and a mistag rate of about 1% and 15% for light and c jets is required. Additional selection criteria on all physics objects are applied. The events are categorized by the jet multiplicity ($4, 5, 6, \geq 7$ jets) after the selection.

3. Reconstruction of the top-quark pair decay

The separation power between the processes $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$ can be increased by the identification of jets in addition to the top-quark pair decay. This is done by a top-quark pair reconstruction separately in each category. In the first step the semileptonic top-quark pair decay is reconstructed with a kinematic fit using energy and momentum conservation and constrains on the top quark and W boson masses. For each 4-jet combination a $\chi^2_{kinefit}$ is calculated. The combination with the smallest value is the most probable one.

To improve the association a gradient boosted decision tree is used. This multivariate classifier combines the most discriminating variables to separate correct and wrong combinations. Information from the kinematic fit and about the event topology like angular relations between jets and leptons or kinematic variables of individual jets are used.
The last step of the top-quark pair reconstruction takes into account the b-tag information of the jets. Combinations where the jets with b quarks coming from the top-quark pair decay are b-tagged are preferred. After all steps the fractions of correctly reconstructed top-quark pair decays estimated from simulations are: 77%, 70%, 66% and 65% for the $4,5,6$ and ≥ 7 jet categories.

4. Template fit

After the association the events can be further categorized by the number of b-tagged jets in addition to the top-quark pair deacy. The separation between $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$ in these categories is based on shapes of the b-tag discriminant CSV. In categories with at least one additional b-tagged jet the CSV sum of all additional jets is used, while in categories without additional b-tagged jets the third highest CSV value of the top-quark pair enables a good separation. A binned maximum likelihood fit is performed in all categories to extract the cross sections. The normalizations of $\mathrm{t\bar{t}b\bar{b}} + \mathrm{t\bar{t}bj}$, $\mathrm{t\bar{t}c\bar{c}} + \mathrm{t\bar{t}qq}$ and other $\mathrm{t\bar{t}}$, which contains the top-quark pair production with less than two additional jets, are used as free parameters while the ratios $\mathrm{t\bar{t}b\bar{b}/t\bar{t}bj}$ and $\mathrm{t\bar{t}c\bar{c}/t\bar{t}qq}$ are treated as nuisance parameters with an uncertainty of 50%. Further nuisance parameters are included representing all other systematic uncertainties, which are dominated by the uncertainties of the jet energy scale and the b-tagging.

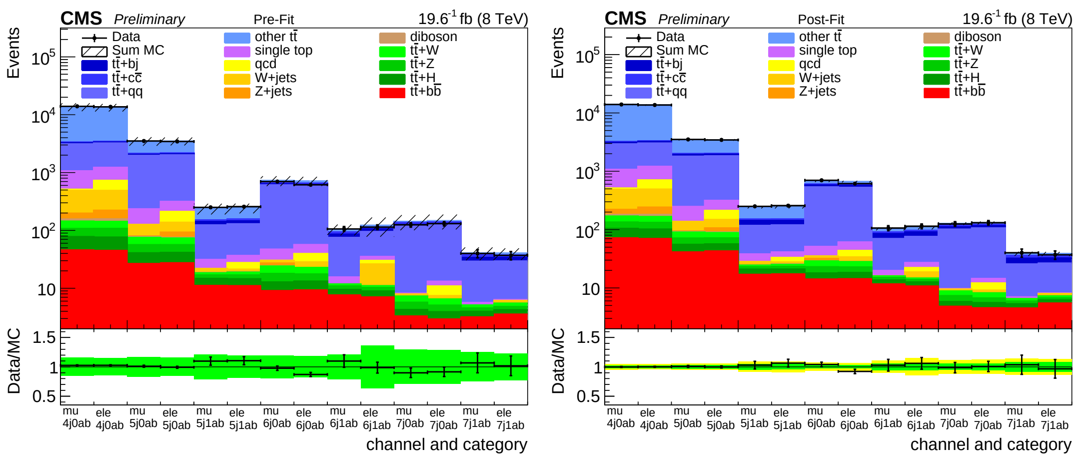

Figure 1: The event yields per category before(left) and after(right) the fit are shown. The green and yellow bands represents the one and two sigma standard deviations of the statistical and systematic uncertainties.

5. Results

Fig. 1 presents the results of the fit, where the event yields of each category is shown before and after the fit. These results can be translated into cross sections $\sigma(\mathrm{t\bar{t}b\bar{b}})$ and $\sigma(\mathrm{t\bar{t}jj})$ taken into account the selection efficiencies and the detector acceptance. The cross sections and their ratio are calculated for the phase space of jets in addition to the top-quark pair with a transverse momentum $p_{\mathrm{Taj}} > 40\,\mathrm{GeV/c}$, $|\eta_{\mathrm{aj}}| < 2.5$ and an angular distance between the additional jets of $\Delta\mathrm{R}_{\mathrm{ajj}} > 0.5$. The results using the parton flavor definition are:

$$\sigma(\mathrm{t\bar{t}jj})^{\mathrm{parton}} = 23.1 \pm 2.3(\mathrm{stat}) \pm 2.9(\mathrm{syst}) \pm 0.6(\mathrm{lumi})\ \mathrm{pb},$$
$$\sigma(\mathrm{t\bar{t}b\bar{b}})^{\mathrm{parton}} = 271.0 \pm 103.0(\mathrm{stat}) \pm 32.2(\mathrm{syst}) \pm 7.0(\mathrm{lumi})\ \mathrm{fb},$$
$$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}^{\mathrm{parton}} = 0.0117 \pm 0.0040(\mathrm{stat}) \pm 0.0003(\mathrm{syst}).$$

The cross sections and the ratio are in good agreement with the NLO calculations obtained in the same phase space. Changing the flavor definition to the particle based one includes a stronger impact of the PS and leads to a softer b-tag discriminant. This corresponds to a larger $\mathrm{t\bar{t}b\bar{b}}$ cross section, while the $\mathrm{t\bar{t}jj}$ cross section is almost not affected:

$$\sigma(\mathrm{t\bar{t}b\bar{b}})^{\mathrm{particle}} = 348.0 \pm 125.3(\mathrm{stat}) \pm 40.7(\mathrm{syst}) \pm 9.0(\mathrm{lumi})\ \mathrm{fb},$$
$$\sigma(\mathrm{t\bar{t}jj})^{\mathrm{particle}} = 23.1 \pm 2.3(\mathrm{stat}) \pm 2.9(\mathrm{syst}) \pm 0.6(\mathrm{lumi})\ \mathrm{pb},$$
$$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}^{\mathrm{particle}} = 0.0151 \pm 0.0049(\mathrm{stat}) \pm 0.0004(\mathrm{syst}).$$

The results agree with the CMS measurements in the dilepton final state, where a similar flavor definition was used. Tab. 1 summarizes the presented results.

	$\sigma_{\mathrm{t\bar{t}b\bar{b}}}$, fb	$\sigma_{\mathrm{t\bar{t}jj}}$, pb	$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$
parton definition:			
this analysis	$271 \pm 40\%$	$23.1 \pm 16\%$	$0.012 \pm 34\%$
NLO calculations	$229\ ^{+18\%}_{-24\%}$	$21.0\ ^{+15\%}_{-13\%}$	$0.011\ ^{+39\%}_{-13\%}$
MADGRAPH+PYTHIA	$174 \pm 28\%$	$24.3 \pm 20\%$	$0.007 \pm 10\%$
particle definition:			
this analysis	$348 \pm 38\%$	$23.1 \pm 16\%$	$0.015 \pm 32\%$
CMS dilepton	$360 \pm 36\%$	$16.1 \pm 14\%$	$0.022 \pm 29\%$
MADGRAPH+PYTHIA	$216 \pm 35\%$	$24.3 \pm 20\%$	$0.009 \pm 14\%$

Table 1: Comparison of the measurement with CMS results in the dilepton channel, theoretical calculations and leading-order MADGRAPH+PYTHIA predictions using the parton or particle jet flavor definition.

References

[1] A.Bredenstein, A.Denner, S.Dittmaier and S.Pozzorini, *NLO QCD corrections to pp→ $t\bar{t}b\bar{b}+X$ at the LHC*, Phys. Rev. Lett. 103 (2009) 012002, arXiv:0905.0110.

[2] 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 1407 (2014) 135, arXiv:1403.2046v3.

[3] CMS Collaboration, *Measurement of the cross section ratio $t\bar{t}b\bar{b}/t\bar{t}jj$ in pp Collisions at 8 TeV*, Phys. Lett. B 746 (2015) 132, arXiv:1411.5621v2.

[4] CMS Collaboration, *Measurement of the $t\bar{t}b\bar{b}$ cross section and the ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ in the lepton+jets final state at $\sqrt{s}$=8 TeV with the CMS detector*, CMS-PAS-TOP-13-016 (2015) https://cds.cern.ch/record/2038631.

[5] CMS Collaboration, *Identification of b-quark jets with the CMS experiment*, J. Instrum. 8 (2013), arXiv:1211.4462.