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CMS results on top physics

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We present a review of recent results from the CMS experiment on top quark physics. CMS performed measurements of top quark mass, charge, and decay properties, $\mathrm{t\bar{t}}$ and single top quark production cross sections in several channels, as well as measurements of differential production cross sections and $\mathrm{t\bar{t}}$ production properties: charge asymmetry, spin correlations and top quark polarization. For the first time the cross section ratio $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ and the cross section of $\mathrm{t\bar{t}}$ in association with W and Z bosons have been measured. CMS established evidence of the W-associated single top quark production. Most of the measurements have uncertainties dominated by systematic effects. All of the results are found to be consistent with the standard model predictions.

LHC on the March
20-22 November 2012
Institute for High Energy Physics, Protvino,Moscow region, Russia

[*]Speaker.
[†]I would like to thank the organizers for the interesting and enjoyable conference.

PoS(IHEP-LHC)030

1. Introduction

The top quark is a unique quark in the standard model (SM) due to its large mass above the electroweak symmetry breaking scale, m_t = 173.2 ± 0.9 GeV [1], with a coupling to the Higgs boson near unity. This heavyweight object has a small width $\Gamma = 2.0^{+0.7}_{-0.6}$ GeV [2], much larger than the scale for the perturbative QCD ($\Lambda_{QCD} \approx 200$ MeV). This translates to a top quark lifetime of $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s, and compels the top quark to decay before it can fragment and bound into an hadronic state.

Top quarks are produced abundantly at the Large Hadron Collider (LHC). The LHC provides a high statistics dataset for precision measurements of the top quark mass, top pair and single top production cross sections, and other properties of the top quark. These quantities are being measured with an improved accuracy, and with uncertainties that become dominated by systematic effects. In 2011 a dataset corresponding to an integrated luminosity of 5 fb^{-1} at a centre-of-mass energy $\sqrt{s}$ = 7 TeV was collected, and in 2012 a dataset corresponding to an integrated luminosity of 20 fb^{-1} at $\sqrt{s}$ = 8 TeV was recorded. The CMS detector [3] is one of the two large multi-purpose detectors at the LHC. In this document we present a review of recent measurements performed at the CMS experiment on top quark physics.

2. Top quark pair production cross section

At the LHC top-anti-top pairs are mostly produced through gluon-gluon fusion (90%). Top quarks almost exclusively decay into a W boson and a b quark, $V_{tb} = 0.99915^{+0.00002}_{-0.00005}$ [4]. The measurement of the $t\bar{t}$ cross section has been carried out in all different final states, which are classified based on W boson decays. The $t\bar{t}$ decay channels comprise all-hadronic, lepton+jets and dilepton final states. Events with hadronic decays of τ originating from a W boson are treated as separate categories. The modeling of the $t\bar{t}$ signal at CMS is based on MadGraph [5] with $t\bar{t}$ +up to 3 additional partons at Born level. The generated matrix-element-based events are used as input to PYTHIA [6] for parton showering, simulating proton remnants and decays of unstable particles.

Using the 7 TeV proton-proton collision data the most precise measurement is obtained in the dilepton channel [7]. The event selection requires two isolated opposite sign charged leptons (e or μ) with a transverse momentum $p_T > 20$ GeV, and at least two jets, clustered with the anti-k_T algorithm with a cone $R = 0.5$, and $p_T > 30$ GeV. The contamination from Drell-Yan (DY) events is suppressed by the missing transverse momentum requirement $\not{p}_T > 30$ GeV. The cross section is extracted using a profile likelihood fit in several categories corresponding to different combinations of lepton flavor, jet multiplicities and a number of b-tagged jets. This channel has the highest purity of the $t\bar{t}$ events. The measurement yields $\sigma_{t\bar{t}}$ = 161.9 ± 2.5 (stat.) ± 5.1 (syst.) ± 3.6 (lumi.) pb in good agreement with the available next-to-leading-order calculations [8, 9, 10, 11]. The systematic uncertainty of the measurement is dominated by the theoretical uncertainty on the single top (tW) contribution and experimental uncertainties related to the jet energy scale (JES) and the current knowledge of $\mathscr{B}(W \to \ell\nu)$.

The measurement in the lepton + jets channel [12] is performed using a profile likelihood fit to the multidimensional distribution of the jet multiplicity, the b-tagged jet multiplicity and a reconstructed secondary vertex mass, that allows to discriminate light-flavor quarks and gluon jets

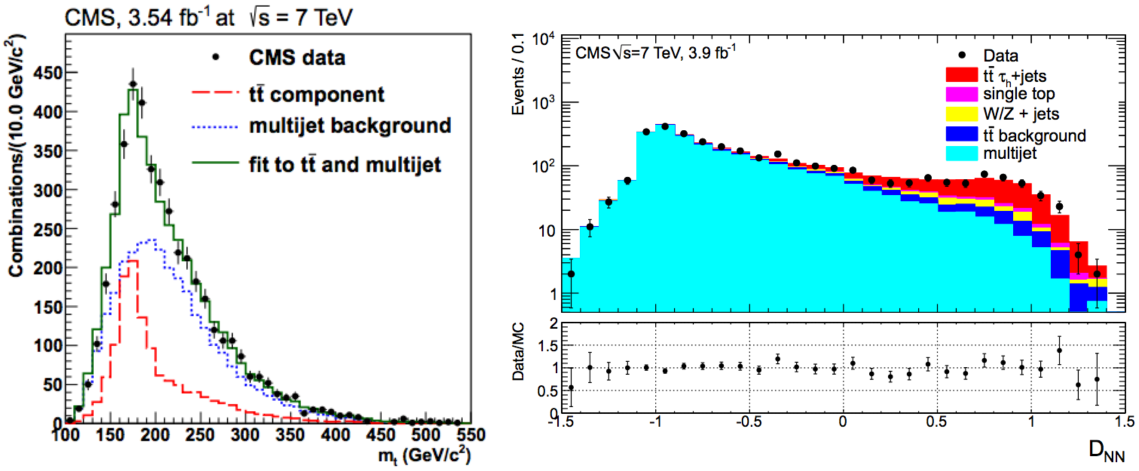


Figure 1: Left: The data fit to the reconstructed mass distribution in the all-hadronic channel. **Right:** The data fit to the neural network output distribution in the measurement of $t\bar{t}$ cross section in the τ + jets channel.

against b-quark jets. In the di-lepton channel containing an hadronic tau lepton ($e\tau_h$ and $\mu\tau_h$) a data driven estimation of τ fake background is employed, and the measurement is performed by fitting a combination of $t\bar{t}$ and background to the top mass distribution [13]. The χ^2-fit to the top quark mass and obtained in this way the reconstructed mass of the top quark (see Fig. 1, left) has been also employed to extract the measurement in the all-hadronic channel [14]. In the hadronic tau + jets channel, that also suffers from a large multi-jet background contamination, the multivariate analysis is performed, and the cross section is extracted from the fit to the neural network output distribution (see Fig. 1, right) [15]. The cross sections measured in these channels are found to be in agreement with the measurement in the dilepton channel and with theoretical predictions but have larger total uncertainty. The $t\bar{t}$ cross section measurements at $\sqrt{s}$ = 7 TeV and 8 TeV are summarized in Fig 2.

The $t\bar{t}$ cross section measurement can be re-interpreted to extract α_s or m_t by establishing the dependency of $\sigma_{t\bar{t}}$ as a function of these quantities. Different PDFs and approximate NLO generators were used to derive the dependency of $\sigma_{t\bar{t}}$ on α_s (see Fig. 3, left). α_s is extracted from a likelihood which convolutes the probability distribution of the experimental measurement in the dilepton channel with the cross section dependency on α_s . Using TOP++ with the NNPDF2.1 PDF set [16] it is determined that $\alpha_s\ (m_Z) = 0.1178^{+0.0046}_{-0.0040}$ [17] in good agreement with the world average. This is the first determination of α_s from top quark events. Alternatively, the dilepton cross section measurement is used to determine the mass of the top quark through its comparison to the NNLO approximations [9, 10, 18] using the pole and the $\overline{\text{MS}}$ quark mass definitions (see Fig.3, right) [19].

3. Top quark mass

The top quark mass is a fundamental parameter of the SM, precise measurement of which provides an important input to the global electroweak fit. At CMS the top quark mass has been measured in the lepton+jets [20], dilepton [21, 22], and all-hadronic [23] channels. The most pre-

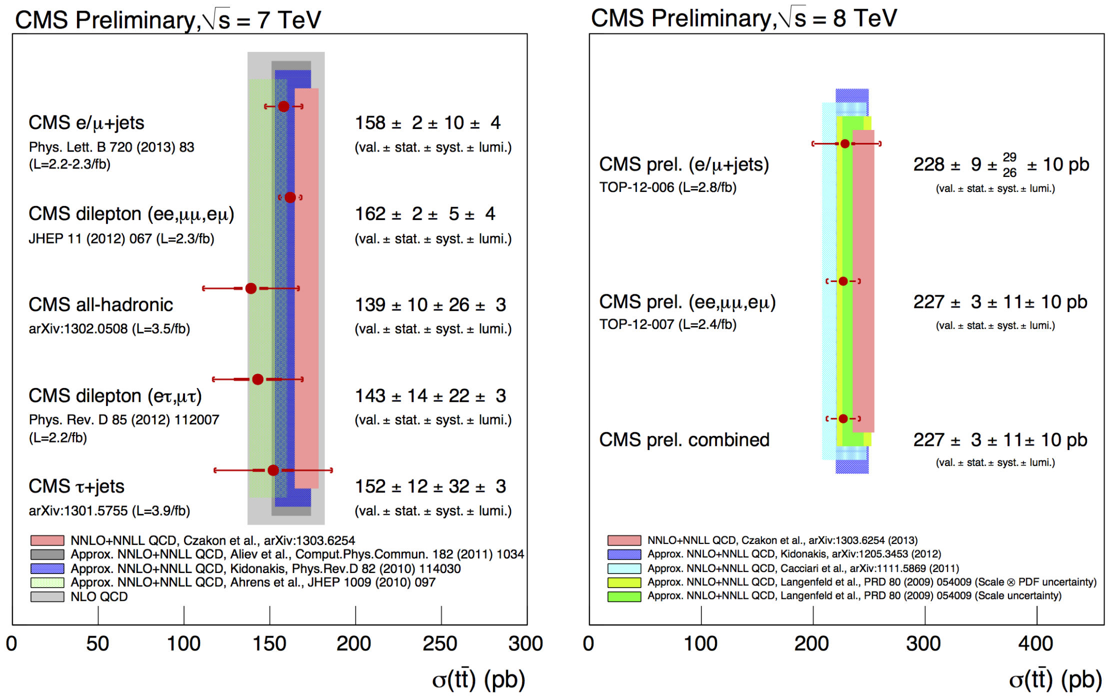


Figure 2: Summary of the $t\bar{t}$ production cross section measurements.

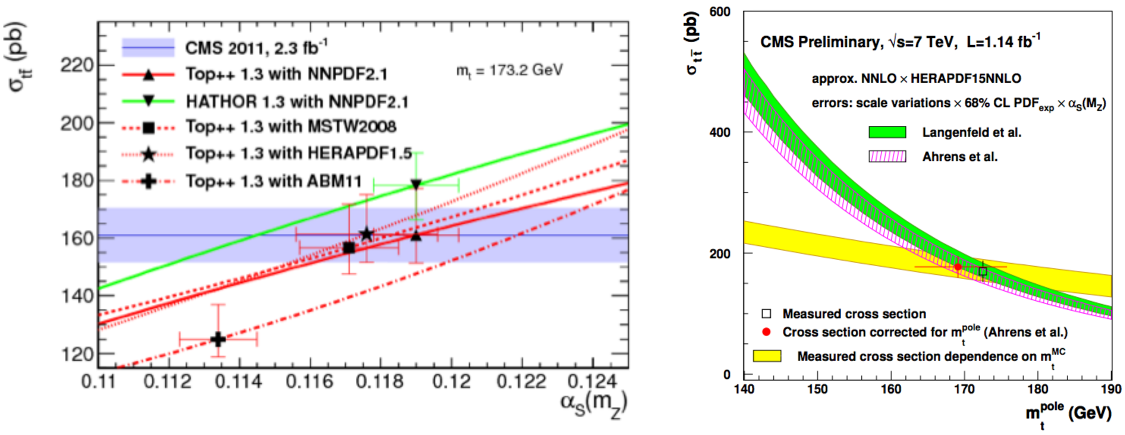


Figure 3: Left: Evolution of the $t\bar{t}$ cross section as a function of α_s for different calculations at approximate NNLO and different PDF sets. **Right:** The measured $t\bar{t}$ cross section (open square) and the measured cross section corrected for the $m_t{}^{pole}$ dependence (closed circle) using theoretical calculations. The dependence of the measured cross section on the m_t in Monte Carlo is shown as a light shaded band. Different approximate NNLO predictions are shown as differently hatched bands.

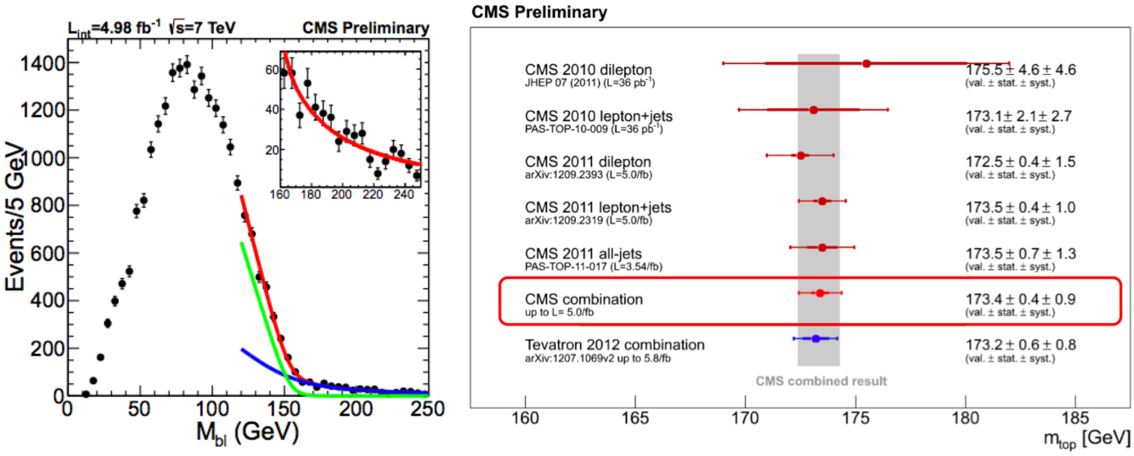


Figure 4: Left: Result of the fit to the lepton-jet invariant mass spectrum and its endpoint using dilepton events. **Right:** Summary of the top quark mass measurements.

cise measurement is performed in the channel of lepton + jets by virtue of the in-situ calibration of the JES using the W $\rightarrow qq'$ reconstructed decay. For the event selection one isolated lepton with $p_T > 30$ GeV, and at least four jets with $p_T > 30$ GeV, with exactly two b-tags are required. A constrained kinematic fit checks the compatibility of each possible permutation with the $\mathrm{t\bar{t}}$ hypothesis. For each permutation probability densities are constructed as a function of m_t and a global JES factor, weighted by the goodness-of-fit probability $\sim \exp\left(-\frac{1}{2}\chi^2\right)$. The most likely values of m_t and JES are extracted by maximizing a weighted product over all event likelihoods. The measured value is m_t = 173.49 ± 0.43 (stat.+JES) ± 0.98 (syst.) GeV. The dominating systematic effects are due to the uncertainties on the b-jet JES and color reconnection.

Measurements in dilepton and all-hadronic channels are in agreement with the measurement in the channel of lepton + jets and the current world average but have larger uncertainty dominated by the uncertainty in the JES. A new CMS measurement in the dilepton channel is performed using a novel model independent technique designed to simultaneously extract all unknown masses in a decay chain [22]. The method is based on the analysis of kinematic endpoints of the invariant mass distributions. Fig. 4, left, shows an example of a fit to the lepton-jet invariant mass spectrum.

The summary of the the top quark mass measurements is presented in Fig. 4, right. These measurements are combined using a Best Linear Unbiased Method technique [24]. The combined CMS measurement is m_t = 173.36 ± 0.38 (stat.) ± 0.91 (syst.).

The measurement of the difference between m_t and $m_{\bar{\mathrm{t}}}$ has also been performed by using ℓ^+ + jets and ℓ^- + jets events, as a test of the CPT symmetry [25]. No evidence for CPT violation is found in the top quark sector with the result being $\Delta\, m_\mathrm{t}$ = -0.44 ± 0.46 (stat.) ± 0.27 (syst.) GeV. It is important to notice that most of the systematic uncertainties cancel out, and this measurement is statistically dominated.

4. Top quark properties

Branching ratio $\mathscr{B}(\mathrm{t} \rightarrow \mathrm{Wb})$. CMS has performed a measurement of the ratio $R = \mathscr{B}(\mathrm{t} \rightarrow \mathrm{Wb})/\mathscr{B}(\mathrm{t} \rightarrow \mathrm{Wq})$ using dilepton events [26]. The event b-tag multiplicity is modeled as a function

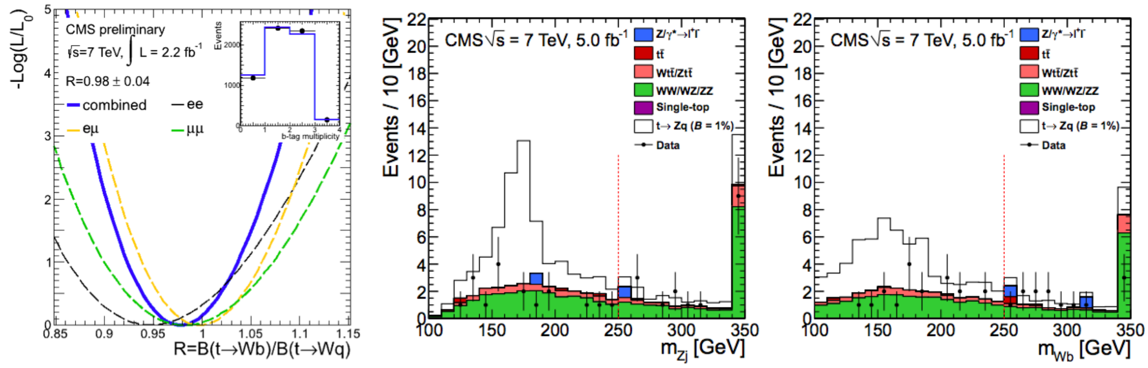


Figure 5: Left: Variation of the profile likelihood used to extract R from data. The inset shows the inclusive b-tag multiplicity distribution and the result of the fit. **Center and Right:** Distributions of m_{Zj} and m_{Wb}. The open histogram shows the expected signal for $B(\mathrm{t} \to \mathrm{Zq}) = 1\%$.

of R for different event categories based on the lepton flavor, and the most likely value is obtained from the maximum likelihood fit. The scan of the likelihood as a function of R is shown in Fig. 4, left. After combination of results from different event categories the value $R_{obs} = 0.98 \pm 0.04$ (stat.+syst.) is measured in agreement with SM predictions. The systematic uncertainty is dominated by the uncertainty in the b-tagging efficiency and the $\mathrm{t\bar{t}}$ modeling due to variations of the renormalization and factorization scale.

Search for Flavor Changing Neutral Current (FCNC) top quark decays. FCNC decays are highly suppressed in the SM by the GIM mechanism, with typical branching ratios of the order of 10^{-14}. However, substantially higher values for FCNC decays are predicted in super-symmetric models with R-parity violation, quark-singlet and topcolor-assisted technicolor models, where the branching ratios for FCNC decay can be as high as of the order of 10^{-4} [27, 28]. CMS performed the search for the FCNC decay $\mathrm{t} \to \mathrm{Zq}$ using the final state with three isolated charged leptons (e or μ) with $p_T > 20$ GeV [29]. At least one opposite-sign same-flavor dilepton pair should be consistent with the Z boson decay. Events are also required to have two jets with $p_T > 30$ GeV, missing transverse momentum $\not{p}_T > 30$ GeV, and the scalar sum of $\not{p}_T$, transverse momenta of jets and leptons (S_T) to be greater than 250 GeV. Events are reconstructed under $\mathrm{t\bar{t}} \to \mathrm{ZqWb}$ hypothesis. The corresponding mass distributions are shown in Fig. 5. No deviation from the SM is observed, and the upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{Zq}) = 0.21\%$ is set at 95% C.L.

W helicity in top decays is fixed by the $V - A$ structure of the tWb vertex and it exhibits itself in the kinematics of the W decay products. The SM predicts the fraction of decays to longitudinally polarized W bosons F_0 to be $\approx 70\%$, the fraction of left-handed W's $F_L \approx 30\%$, while the right-handed fraction F_R is suppressed. CMS measured the helicity fractions in $\mu+$ jets channel by fully reconstructing $\mathrm{t\bar{t}}$ events and the angular dependence of the muon momentum in its parent W boson rest frame with respect to the direction of the W boson momentum in the rest frame of its parent top quark [30]. The results are $F_0 = 0.567 \pm 0.074$ (stat.) ± 0.047 (syst.), $F_L = 0.393 \pm 0.045$ (stat.) ± 0.029 (syst.), $F_R = 0.040 \pm 0.035$ (stat.) ± 0.044 (syst.), which are consistent with the SM. This result allows to set limits on the anomalous coupling constants g_L and g_R shown in Fig. 6, left.

Top quark charge measurement is performed by discriminating between two hypotheses:

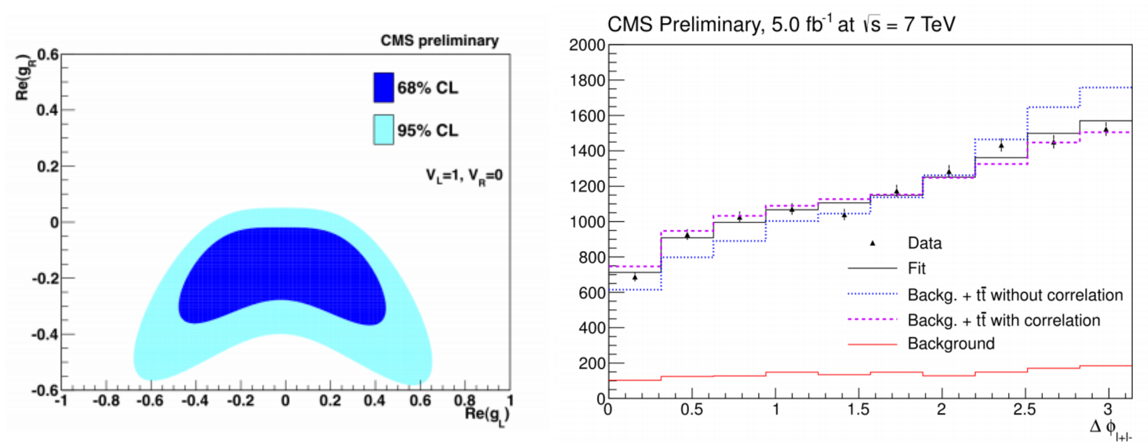


Figure 6: Left: Limits on real components of anomalous couplings g_L and g_R. **Right:** The fit to the combination of hypotheses with and without spin correlations.

the SM prediction of the charge $+2/3e$ against an exotic top quark charge $-4/3e$. The measurement is performed using $\mu+$ jets with two b-tags by exploring charge correlations between muon from W boson decays and soft muons from B-hadron decays in b-jets [31]. The b-jets are assigned to the leptonically or hadronically decaying top quarks using the best approximation to the top quark mass. The numbers of observed events consistent with the SM or the exotic model are converted into an asymmetry A measurement with $A = +1$ being the SM, and $A = -1$ being the exotic model. The measurement yields $A_{meas} = 0.97 \pm 0.12$ (stat.) $\pm$ 0.31 (syst.) in a good agreement with the SM.

Spin correlatons in $t\bar{t}$ production are experimentally accessible, since the top quark decays before hadronization and transfers spin information to its decay products. Measurement is performed in dilepton events using the angular difference in the azimuthal plane between the two leptons $\Delta\phi_{\ell^+\ell^-} = |\phi_{\ell^+} - \phi_{\ell^-}|$ [32]. The data fit is performed to a combination of $t\bar{t}$ templates with and without spin correlations at NLO. Backgrounds events are also accounted for. The combined fit is shown in Fig. 6, right. The spin correlation coefficient in the helicity basis is obtained to be $A_{hel}^{meas} = 0.24 \pm 0.02$ (stat.) $\pm$ 0.08 (syst.), which is in a good agreement from NLO calculations $A_{hel}^{meas} = 0.31$ [33].

Top quark polarization is also measured using dilepton events [34]. It is extracted from the asymmetry

$$P_n = \frac{N(\cos\theta_\ell^+ > 0) - N(\cos\theta_\ell^+ < 0)}{N(\cos\theta_\ell^+ > 0) + N(\cos\theta_\ell^+ < 0)},$$

where θ_ℓ^+ is the production angle of the positively charged lepton in the rest frame of its parent top quark with respect to the direction of the parent top quark in the rest frame of the $t\bar{t}$ system. The background-subtracted data distribution is corrected to parton level using a regularized unfolding procedure. The result is $P_n = -0.009 \pm 0.029$ (stat.) $\pm$ 0.041 (syst.), which is in agreement with the SM.

The charge asymmetry measurement is motivated by the inconsistencies of the Tevatron forward-backward asymmetry measurement in top quark pair events with the SM [35]. The LHC

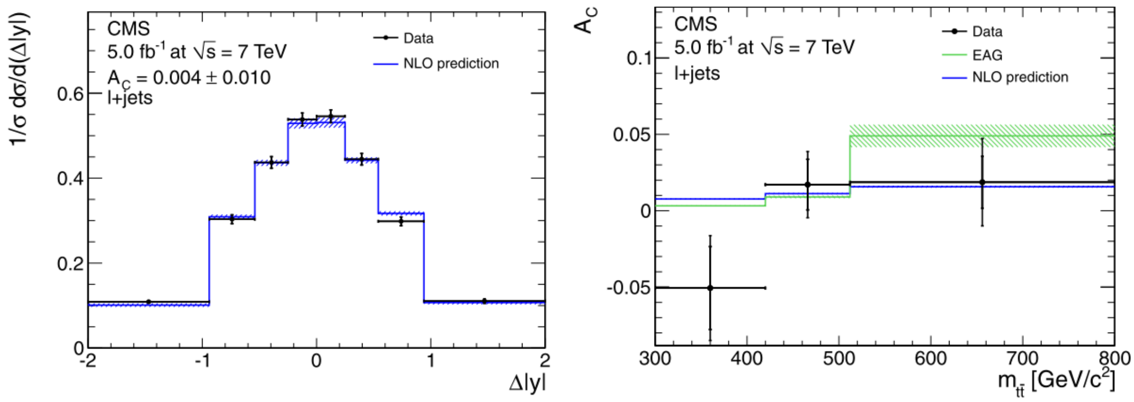


Figure 7: Differential charge asymmetries as a function of $|y_{\rm t}| - |y_{\bar{\rm t}}|$ and $m_{\rm t\bar{t}}$.

cannot probe this effect due to the symmetric initial state of proton-proton collisions. Yet the interference of the born and box diagrams results in a broader absolute rapidity spectrum of the top quark compared to the one of the anti-top quark. The charge asymmetry is defined as

$$A_c = \frac{N^+ - N^-}{N^+ + N^-},$$

where N^+ is the number of events with $|y_{\rm t}| > |y_{\bar{\rm t}}|$, and N^- is the number of events with $|y_{\rm t}| < |y_{\bar{\rm t}}|$. The charge asymmetry is measured using lepton+jets events inclusively, and also as a function of the absolute pseudorapidity and the invariant mass of the $\rm t\bar{t}$ system [36]. The distributions are shown in Fig. 7. The inclusive charge asymmetry is measured to be $A_c = 0.004 \pm 0.010$ (stat.) $\pm$ 0.011 (syst.), which is compatible with the SM expectation of $A_c^{SM} = 0.0115$ [37].

5. Differential and associated top pair production cross sections

The abundance of the $\rm t\bar{t}$ pairs produced at the LHC provides an opportunity for detailed studies of differential distributions. Comparison of observed distributions with theoretical predictions using various Monte Carlo generators provides better understanding of the $\rm t\bar{t}$ production modeling. The differential distributions are also sensitive to possible new physics contributions. In order to facilitate comparisons with theory the measured differential distributions are unfolded to parton level using the regularized unfolding technique. CMS measured the differential distributions using lepton + jets and dilepton events. The normalized distributions of the top quark pair invariant mass $m_{\rm t\bar{t}}$ the top quark transverse momentum and the jet multiplicity are shown in Fig. 8. Distributions of other kinematic quantities can be found in Ref. [38]. The differential distributions are compared with the MADGRAPH, POWHEG and MC@NLO models, and are found in a good agreement. The data exhibit a somewhat softer top quark p_T-dependence compared with the current models, but are better reproduced by an approximate NNLO QCD calculations. A good agreement is observed in modeling of the jet multiplicity spectrum with the MADGRAPH and POWHEG, while MC@NLO shows a steeper spectrum with increasing number of jets [39].

The production of $\rm t\bar{t}$ in association with two extra b-jets constitutes an important background to Higgs boson production in association with $\rm t\bar{t}$ pair, where the Higgs decays into $\rm b\bar{b}$. CMS per-

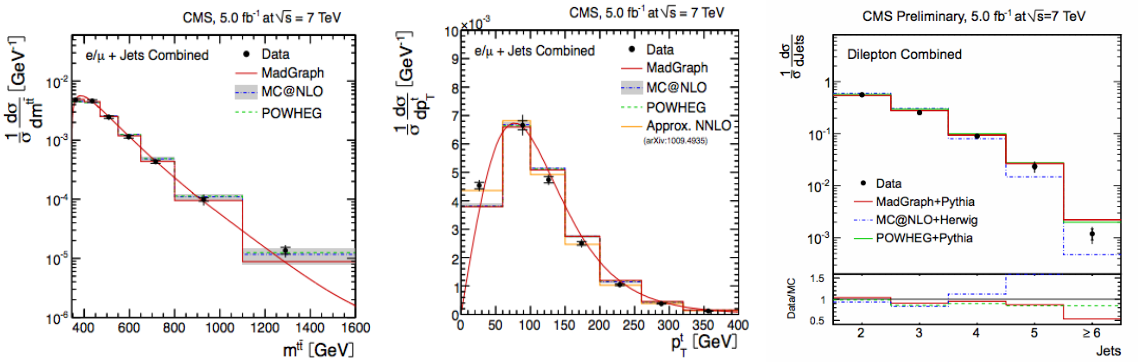


Figure 8: Distributions of the invariant mass of the $t\bar{t}$ system, the top quark transverse momentum and the jet multiplicity in the top quark pair events.

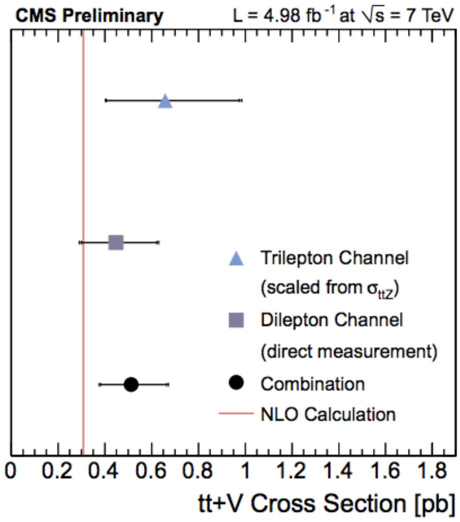
formed the first measurement of the cross sections ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ in the dilepton channel [40]. The measurement is performed by fitting the b-tag multiplicity spectrum with correction to the parton level. The ratio measurement allows to reduce the overall systematic uncertainty with dominant systematic effects due to the b-tag efficiency and the uncertainty on the factorization scale. The result is 3.6 ± 1.1 (stat.) ± 0.9 (syst.) %, which is somewhat higher the predictions from MADGRAPH of 1.2% and POWHEG of 1.3%.

The production of $t\bar{t}$ in association with vector bosons W, Z is important for studying the couplings of the top quark. CMS performed the first measurement of the $t\bar{t}$ +W/Z production cross sections using same-sign dilepton and trilepton events [41]. The results are in agreement with the SM predictions (see Fig. 9, left). Upon combination of the two channels, a 4.7 σ significance for the observation of the $t\bar{t}$ + V production is obtained.

6. Single top production

Besides the dominant production of top quarks in pairs via the strong interaction, top quarks can also be produced singly through the charged-current electroweak interaction. Measurements of the single top quark production cross section provide a direct determination of the magnitude of the $|V_{tb}|$. Within the SM three types of the electroweak single top quark production are possible: t-channel and s-channel processes, and W-associated single top quark production (tW). At the LHC the t-channel process is dominant, while the s-channel production cross section is very small, compared to other channels [42, 43, 44].

CMS performed a measurement of the t-channel single-top-quark production cross section. The cross section is extracted from the fit to pseudo-rapidity of the light quark recoil jet, which goes in the forward/backward direction (see Fig. 9, right). The event selection requires exactly one isolated muon or electron with $p_T >$ 20 and 30 GeV, respectively, and at least two jets with $p_T >$ 30 GeV, at least one of which is b-tagged. Multi-jet background is reduced by cutting on the transverse mass of the W-boson or the missing transverse energy. The mass $m_{b\ell\nu}$ is required to be consistent with the top quark mass. In the 8 TeV analysis these cuts are hardened due to more severe pile-up conditions [45]. The 7 TeV analysis is complemented by two multi-variate techniques based on the artificial neural network and the boosted decision trees that allow to reduce



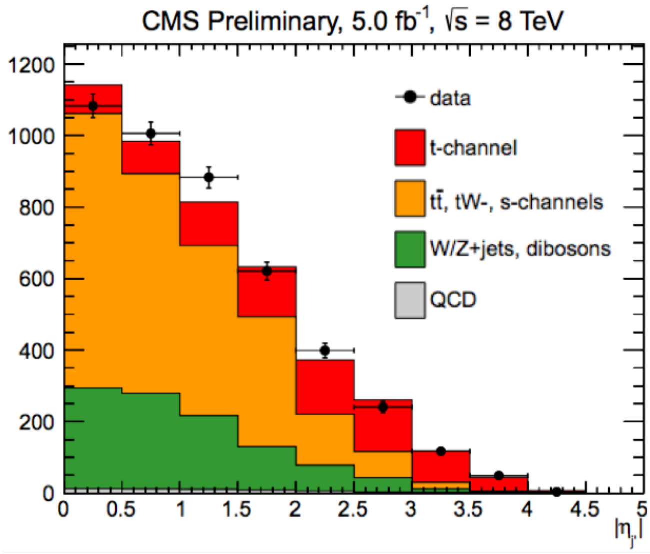


Figure 9: Left: CMS cross section measurements for the production of $t\bar{t}$ + V in the dilepton and trilepton channels as well as their combination, compared with the NLO QCD calculations. **Right:** Distribution of the pseudo-rapidity of the light quark recoil jet after the fit to the data in the t-channel single top production cross section measurement.

statistical and systematic uncertainties. All of the measurements are consistent with each other and the SM predictions [46]. The combination of the 7 TeV analyses using the BLUE technique yields $\sigma_{t-channel}$ = 67.2 ± 3.7 (stat.) ± 3.0 (syst.) ± 3.5 (theor.) ± 1.5 (lumi.), where the dominant uncertainty is due to theoretical uncertainties on background contributions. This measurement allows to extract the $|V_{\text{tb}}|$ CKM matrix element, that is obtained to be $|V_{\text{tb}}|$ = 1.020 ± 0.046 (exp.) ± 0.017 (theor.).

Using 7 TeV data, CMS performed a search for W-associated single top quark production in the dilepton channel [47]. Events are required to have two isolated leptons with $p_T > 20$ GeV, and one or two reconstructed jets with $p_T > 30$ GeV, at least one of which is b-tagged. The *ee* and $\mu\mu$ events with the invariant mass consistent with the Z boson are rejected. Also the top quark pair production contribution is reduced by vetoing extra jets with lower p_T. The cross section is extracted by using the boosted decision tree technique, and complimented by the cut-and-count analysis. The evidence of the W-associated single top production is established with the 4.0 σ significance, and the measured cross section is consistent with the SM.

7. Summary

In this presentation we discussed recent CMS measurements on top quark physics. The measurements include single and pair top quark production cross sections, differential production cross sections, charge asymmetry, spin correlations and top quark polarization in $t\bar{t}$ events, as well as top quark mass, charge, and decay properties. For the first time the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ and the cross section of $t\bar{t}$ in association with W and Z bosons have been measured. The CMS established evidence of the W-associated single top quark production. Most of the measurements have uncertainties dominated by systematic effects. All of the results are found to be consistent with the SM predictions.

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