CMS Physics Analysis Summary

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Combination of top quark pair production cross section measurements

The CMS Collaboration

Abstract

We present a combination of the measurements of the $pp \to t\bar{t}$ production cross section at $\sqrt{s} = 7$ TeV using data collected by the CMS detector at the Large Hadron Collider. The channels included in the combination are single lepton (e/μ+jets), dilepton (ee, $\mu\mu$, $e\mu$), tau ($\mu\tau$), and fully hadronic decays. The analyses use data corresponding to an integrated luminosity between 0.8 and 1.1 fb^{-1}. A binned maximum likelihood fitter is used for the combination. We find a combined cross section of $\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})$ pb.

1 Introduction

The continued successful operation of the LHC in 2011 has, only halfway through the year, provided a wealth of over 1 fb^{-1} of pp-collision data at $\sqrt{s}$ = 7 TeV which has been used by CMS to both perform direct searches for new physics signatures and test our understanding of Standard Model processes. The quantity of data makes it possible to precisely measure $t\bar{t}$ production and decay properties. CMS has recently undertaken measurements of the $t\bar{t}$ production cross section in four distinct decay channels: single lepton [1], dilepton ee, $\mu\mu$, $e\mu$ combination [2], dilepton $\mu\tau$ [3], and fully hadronic decay [4]. The results are listed in Table 1.

Table 1: Results of recent CMS measurements of the $t\bar{t}$ cross section in four different decay modes.

Measurement	$\sigma_{t\bar{t}}$ [pb]
single lepton	164.4 ± 2.8 (stat.) ± 11.9 (syst.) ± 7.4 (lumi.)
ee, $\mu\mu$, $e\mu$	169.9 ± 3.9 (stat.) ± 16.3 (syst.) ± 7.6 (lumi.)
$\mu\tau$	148.7 ± 23.6 (stat.) ± 26.0 (syst.) ± 8.9 (lumi.)
fully hadronic	136 ± 20 (stat.) ± 40 (syst.) ± 8 (lumi.)

In this document we briefly review the individual measurements and present a combination of these results where a binned maximum likelihood fitter is employed. We also present a cross check of the combination using the BLUE technique [5].

2 Description of Measurements

2.1 Single Lepton

The μ+jets and e+jets combination for 1087 pb^{-1} (muons) and 804 pb^{-1} (electrons) is presented in Ref. [1]. The single lepton sample is composed of events with isolated muons or electrons, at least 1 jet, and missing transverse energy, with the additional requirement that at least one of the jets must be b-tagged. The analysis divides the dataset into subsamples based on lepton flavor, total number of jets (N_{jets}), and number of b-tagged jets (N_{btag}). A binned maximum-likelihood fit to the simple secondary vertex (SSV) mass distributions is performed simultaneously in the subsamples. The salient feature of the analysis is the simultaneous determination of the top-quark pair production cross section and the dominant systematic uncertainties in a combined fit, taking into account the correlations.

2.2 Dilepton $ee, e\mu, \mu\mu$ Combination

The dilepton combination for 1.14 fb^{-1} is presented in Ref. [2]. The dilepton sample is composed of events with at least two energetic leptons (electrons or muons), at least one jet, and missing transverse energy (for the ee and $\mu\mu$ channels only). At least one of the jets must also be tagged as a b-jet. Cross section measurements were performed for each of the dilepton channels (ee, $\mu\mu$, and $e\mu$) using a simple cut-and-count method.

2.3 Dilepton $\mu\tau$

The dilepton $\mu\tau$ measurement for 1.09 fb^{-1} is presented in Ref. [3]. The event sample is composed of events with one energetic muon, a hadronically decaying tau with an electric charge of opposite sign, at least two jets, and missing transverse energy. At least one jet is required to be b-tagged.

2.4 Hadronic

The fully hadronic decay channel measurement for 1.09 fb^{-1} is presented in Ref. [4]. The hadronic sample is composed of events with at least six energetic jets, two of which must be b-tagged.

3 Description of Combination Method

3.1 Binned Maximum Likelihood Combination

The primary combination presented in this note utilizes the binned maximum likelihood fitter from the single lepton analysis, with terms describing the other three measurements added to the existing likelihood. In this way, parameters that are common to all the analyses (the $t\bar{t}$ cross section, for example) can be linked to a single parameter in the likelihood.

3.1.1 Description of Basic Likelihood

The single lepton likelihood is constructed for a simultaneous fit to the SSV mass in subsamples defined by lepton flavor, N_{jets} and N_{btag}. The number of events in a given template X derived from Monte Carlo simulation (MC) and normalized to the integrated luminosity is given by $N_X^{MC}(i,j)$, and $N_{QCD}^{data-pred}$ is the data-driven QCD prediction. These are specific for each jet-tag bin (i,j). The MC prediction for the $t\bar{t}$ component is scaled by a global scale factor $\sigma_{t\bar{t}}$. Note that the $t\bar{t}$ templates are normalized to the integrated luminosity of 1 fb^{-1}, so that $\sigma_{t\bar{t}}$ is then a cross-section expressed in femtobarns.

To include systematic effects in the likelihood, multiplicative corrections that affect the three-dimensional shape (SSV mass, N_{jets} and N_{btag}) are added. The SSV mass shape is already modeled well, so the likelihood is only modified to change the relative normalizations of the jet-tag bins. It is desirable that such multiplicative factors vary as continuous functions of systematic effects, so the fitter can determine the amplitude of the systematic effects. Parametrizing the systematic factors is done with functions $P_N^x(i,j,R_x)$ that depend on the jet-bin j, tag-bin i and the relative shift, R_x, of the factor. We require that $P_N^x(i,j,0) \equiv 1$; that is, with no systematic shift the multiplicative factor is 1.0 and the normalization of the template is therefore unchanged.

The nuisance (systematic) parameters in the fit are the R_x, and they are expressed in terms of the relative shift with respect to the central value of the external measurement, in units of the constraint size. Thus, 0.0 means no shift, $+1.0$ means $+1\sigma$ high, and -1.0 means -1σ low. The shift parameters are all constrained to unit Gaussians in the fit.

The major systematic uncertainties that are included in the maximum likelihood fitter are jet energy scale (JES), b-tagging and light flavor tagging (mistag) efficiency, and the Q^2 of the W+jets MC. The expected number of events in each jet-tag bin can then be written as follows (e.g. for the $t\bar{t}$ and Wbb templates):

$$N_{t\bar{t}}^{pred}(i,j) = \sigma_{t\bar{t}} \cdot N_{t\bar{t}}^{MC}(i,j) \cdot P_N^{btag}(i,j,R_{btag}) \cdot P_N^{Mistag}(i,j,R_{Mistag}) \cdot P_N^{JES}(i,j,R_{JES}) \tag{1}$$

$$N_{Wbb}^{pred}(i,j) = N_{Wbb}^{MC}(i,j) \cdot P_N^{btag}(i,j,R_{btag}) \cdot P_N^{Mistag}(i,j,R_{Mistag}) \cdot P_N^{JES}(i,j,R_{JES}) \cdot P_N^{Q^2}(i,j,R_{Q^2}) \tag{2}$$

The equations for the expected number of events for the Wcx, W+light flavor jets, single top, Z+jets, and QCD background components have forms similar to Eq. 2, but they can be simpler. For example, the Z+jets, single top, and QCD background equations don't depend on R_{Q^2}, as their predictions are unaffected by the Q^2 of the W+jets MC. The fitter minimizes the negative log likelihood

$$-2\ln L = -2\left\{\sum_{i,j}^{tag,jet}\sum_{k}^{bins}\ln P_{oi}\left(N^{data}(i,j)_k, \sum_{c}^{comp.} N_c^{pred}(i,j)_k\right) - \frac{1}{2}\sum_{l}^{constr.}\frac{(z_l-\bar{z}_l)^2}{\sigma_l^2}\right\}, \quad (3)$$

where the sum over k is over SSV mass histogram bins, j over N_{jets}, i over N_{btag}, c over the components of the sample (e.g. $t\bar{t}$, Wbb, QCD), and l over the constraints. P_{oi} is a Poisson probability that the predicted yield given by the templates statistically overlaps with the data. This probability is given by

$$\ln P_{oi}(x,y) = x\ln y - y - \ln\Gamma(x+1), \quad (4)$$

where $\Gamma(x)$ is the Gamma function.

Another category of systematic uncertainties may be treated as affecting only the $t\bar{t}$ acceptance. These uncertainties enter the likelihood using the same technique as the one described above. Each uncertainty becomes a relative shift parameter in the likelihood, and a change in the shift corresponds to a change to template normalization through a multiplicative factor, parametrized as a first degree polynomial. Because acceptance uncertainties affect all jet-tag $t\bar{t}$ templates the same way, the fitter has no ability to choose a non-zero shift. Therefore the inclusion of acceptance uncertainties in the fit does not change the returned $t\bar{t}$ cross section, but it increases its returned uncertainty. The change in returned uncertainty is the same as if the acceptance uncertainty had just been added in quadrature.

3.1.2 Likelihood formulation for counting experiments

As some of the measurements in this combination are counting experiments, one must first reformulate their inputs as likelihood ingredients. For a counting experiment, the count of events observed in data, N, is expressed as a sum of signal S and several backgrounds B_i

$$N = S + \sum_i B_i \quad (5)$$

and thus one obtains the number of $t\bar{t}$ events by subtracting $\sum_i B_i$ from N and propagating the errors accordingly to obtain the error on S.

The same can be achieved by using a profile likelihood approach. One takes the right-hand side of Eq. 5 as the predicted number of events, N_{pred}, and then computes the Poisson likelihood given the observed number of events N and its prediction N_{pred}. In this procedure, the total number of $t\bar{t}$ events, S, can be expressed as a product of a prediction (from Monte Carlo simulation) of the $t\bar{t}$ yield as if the $t\bar{t}$ cross section were 1 fb: $S = s \times N(t\bar{t}|\sigma_{t\bar{t}} = 1\text{ fb})$. Thus the linear coefficient multiplying the $t\bar{t}$ expectation is the scale factor needed to bring 1 fb to the observed $t\bar{t}$ yield, and, after the Poisson likelihood is minimized, it is numerically equal to the $t\bar{t}$ production cross section in femtobarns. Thus $s \equiv \sigma_{t\bar{t}}$.

In order to reuse the fitting infrastructure geared towards template fits, the data and background counts are modeled by histograms with only one bin. Each individual counting experiment analysis already provides a combination of all the backgrounds into $B = \sum_i B_i$. If the total background B is fixed, the fitter returns the $t\bar{t}$ cross section with only the statistical uncertainty. But if the background is allowed to float within its uncertainty, the returned $t\bar{t}$ cross section will also include the corresponding background systematic uncertainty. Following the infrastructure used in the single lepton measurement, the uncertainties are included in the fit model as relative shifts R_x with respect to zero of the multiplicative factor for the signal and background terms. If the shift is zero, the multiplicative scale factor is 1, resulting in the nominal yield. This is accomplished with a multiplicative term $P_N^x(R_x)$ that is linear in R_x. The intercept of the function is one, and the slope is the fractional uncertainty on the template.

3.1.3 Reformulation needed for various inputs

Dilepton $ee, e\mu, \mu\mu$ Combination:

The dilepton measurement itself is already a combination of three counting measurements, as it combines three decays channels (ee, $\mu\mu$, and $e\mu$). For the purpose of this combination, the dilepton measurement is separated into its constituents, and each channel enters the likelihood as a single bin.

Dilepton $\mu\tau$:

As this is a counting experiment, it enters the likelihood as a single bin template.

Hadronic:

The hadronic analysis is based on an unbinned maximum likelihood fit to the reconstructed top-quark mass, so it is not a counting experiment. However, one can parametrize its results so they can be input into the combined likelihood as a single bin. In this case the 14.3% uncertainty returned by the original fitter (a combination of statistical and background uncertainties) is larger than $\sqrt{(S+B)}/S = 13.5\%$ expected with Poisson statistics. This is not unexpected as the original fit to reconstructed top-quark mass automatically included background rate uncertainties. This effect can be replicated in the single bin format by assessing a 3.4% uncertainty on the number of events in the background template for the hadronic channel. This nuisance parameter is the sole background rate uncertainty for this channel, though a background shape uncertainty is assessed separately.

For this combination, including the exact likelihood (and the data points) from the hadronic channel would be impractical. Including a binned form of the hadronic fit would be more reasonable, but such a variation of the original analysis method is unlikely to return the original statistical uncertainty or central value of the hadronic analysis. What is described above ensures that the exact hadronic result enters the likelihood with an appropriate weight and value.

4 Systematic Uncertainties

The combination includes all the systematic uncertainties from the individual channels. The systematic uncertainties can be considered as falling into one of two categories: acceptance uncertainties that affect the normalization of the $t\bar{t}$ template in a channel and background normalization uncertainties. Each uncertainty enters the fit as a nuisance parameter R_x. For uncertainties that are 100% correlated across channels (for example, jet energy scale), a single nuisance parameter is used in the fit and it is tied to the normalization of all the affected templates.

4.1 Background Uncertainties

The various backgrounds and their uncertainties are summarized in Table 2 and discussed briefly below. The backgrounds for the four analyses in the combination are considered separately with no correlation between analyses. For the single top uncertainty it is the case that leaving the channels uncorrelated is the more conservative choice.

For the single lepton analysis, the background normalizations are all parameters in the fit. The QCD background, Z+jets, and single top background are constrained to their expected yields $\pm100\%$, $\pm30\%$, and $\pm30\%$, respectively. The W+jets components' normalizations are allowed to float freely in the fit.

The dilepton (ee, $e\mu$, $\mu\mu$) combination has several background sources: diboson "vector-vector" decays (VV where $V = W$ or Z), single top events, W+jets, QCD, and $Z/\gamma^* \to ee, \mu\mu$ or $\tau\tau$ Drell-Yan (DY) processes. Except for the DY ee and DY $\mu\mu$ uncertainties, the backgrounds are considered correlated across all three channels in the combination. While keeping a 100% correlation for the QCD and W+jets backgrounds, to stay conservative, they have very little influence on the final fit since their contamination is very small and estimated with large uncertainties.

The dilepton $\mu\tau$ analysis considers the following background sources: events where a jet is mis-identified and "fakes" a τ (most commonly from W+jets or $t\bar{t} \to W^+W^-\bar{b} \to \mu\nu qq'\bar{b}$), Drell-Yan $ee/\mu\mu$ (e or μ mis-identified as a τ), Drell-Yan $\tau\tau$, single top, and dibosons. There is also a small Standard-Model $t\bar{t}$ background that is not covered by the fake-τ background.

The dominant background source in the hadronic analysis is QCD multijet events. As the analysis is based on a fit to the reconstructed top-quark mass where the background normalization floats, the QCD rate uncertainty is automatically included in the returned statistical uncertainty. In the reformulation of the mass fit result to a single bin template for this combination, an effective QCD rate uncertainty is assessed so the statistical uncertainty is correctly reproduced.

4.2 $t\bar{t}$ Acceptance Uncertainties

The systematic uncertainties that affect the acceptance of the $t\bar{t}$ events in the analysis were evaluated independently in Ref.[1–4]. For this combination, the sources can be considered 0% or 100% correlated between any two channels. For a source of systematic uncertainty that belongs to a single channel (e.g. uncertainty from the hadronic trigger efficiency affects only the hadronic channel), a single nuisance parameter is added to the fit, and it is tied to the normalization of that channel's $t\bar{t}$ template only. For systematic sources that affect multiple channels, a nuisance parameter will simultaneously modify the normalization of the $t\bar{t}$ templates in those channels.

The list of $t\bar{t}$ acceptance uncertainties is given in Table 3 with the size of the uncertainty in each decay channel. A brief description of each systematic source follows. Note all dilepton combination channels (ee, $e\mu$, and $\mu\mu$) are considered 100% correlated with each other.

Some uncertainties are relevant for all four analyses.

- **JES:** The JES parameter is 100% correlated in all four analyses. The single lepton channel has special treatment, as there are separate second-degree polynomials for each i-jet template of W+jets, $t\bar{t}$, single top, and Z+jets that describe how the normalization of each template changes as a function of the relative shift in JES. The Wcx, Wbx, and Wqq templates share the same W+jets polynomials.
- **b-tagging:** The uncertainties due to the b-tagging scale factors are considered un-

correlated between analyses, as this choice leads to a more conservative combined uncertainty. Therefore they enter the fitter as four independent nuisance parameters. For the single leptons, there are separate polynomials in the fit for the $i-$jet templates of $t\bar{t}$, single top, Wbx, and Wcx that depend on the b-tagging scale factor. The mistag scale factor (an additional parameter) affects the normalization of the Wqq templates only.

- **Pileup:** The sources of this uncertainty are the modeling of pile-up in simulation and the reweighting procedure used to make MC match data. All four $t\bar{t}$ analyses are correlated 100%.
- **$t\bar{t}$ Q^2:** This source accounts for the variation in the number of expected $t\bar{t}$ events due to MC modeling, found by varying the scale used to generate the MC. This effect is combined with the initial and final state radiation (ISR/FSR) modeling systematic uncertainty. This parameter is correlated 100% between channels.
- **Luminosity:** The uncertainty in the integrated luminosity determination is considered 100% correlated between all four analyses, although the size of the effect is not the same in all channels. The $\mu\tau$ and hadronic analyses were completed while the luminosity was known to 6%. The single lepton and dilepton channels benefited from late summer improvements to luminosity calculation methods and have uncertainties of 4.5%.

Other sources are considered in some, but not all, analyses.

- **Lepton efficiency:** This source accounts for the uncertainty in the relative efficiencies in data and simulation for triggering, reconstructing, and identifying leptons. The single lepton, dilepton, and $\mu\tau$ analyses are considered uncorrelated and have separate nuisance parameters.
- **W leptonic branching ratio:** This parameter describes the uncertainty on leptonic branching ratio of the W in the dilepton and $\mu\tau$ analyses. Those channels are 100% correlated.
- **Top-quark mass:** This change in acceptance due to the top-quark mass is correlated 100% in the dilepton, $\mu\tau$, and hadronic channels.
- **Jet and $\not\!\!E_{\mathrm{T}}$model:** This uncertainty is extracted from a comparison of MC generators in the dilepton and $\mu\tau$ analyses. It is 100% correlated in these two channels.
- **Matrix-element to parton-shower matching:** This uncertainty is found from varying the matrix-element to parton-shower (ME-PS) matching. The dilepton, $\mu\tau$, and hadronic channels are correlated 100%.

There were also sources considered by only a single analysis.

- **W+jets Q^2 (single lepton):** The Q^2 of the W+jets MC was considered as a separate source of uncertainty for the single lepton analyses only. Note this is not a $t\bar{t}$ acceptance uncertainty strictly, as this parameter affects the normalization of the W+jets templates. The Wcx, Wbx, Wqq templates share the same W+jets polynomials.
- **PDF (single lepton):** The uncertainty due to the parton distribution functions is assessed in only the single lepton channel.
- **Lepton selection model (dilepton):** This source comes from the uncertainty in the parametrization of lepton efficiency for the dilepton analysis.
- **Decay model (dilepton):** This is the uncertainty due to the τ lepton and hadron decay modeling in the dilepton analysis.

- **τ fake rate ($\mu\tau$):** An 11% uncertainty on the fake τ background rate is translated into this 13% uncertainty on the $t\bar{t}$ acceptance for the $\mu\tau$ channel.
- **τ jet mis-ID ($\mu\tau$):** The uncertainty on the tau jet mis-identification affects only the $\mu\tau$ analysis.
- **Tau and hadron decay model ($\mu\tau$):** This is the theoretical uncertainty on signal acceptance for the $\mu\tau$ analysis.
- **Cross sections of MC background ($\mu\tau$):** This parameter is the sum in quadrature of the uncertainties from all $\mu\tau$ background channels assuming the cross section uncertainties are completely uncorrelated.
- **MC tune (hadronic):** This uncertainty in the underlying event simulation for the hadronic channel is assessed by comparing Z2 and D6T tunes.
- **Trigger (hadronic):** The uncertainty in the hadronic trigger efficiency scale factor affects only the hadronic channel.
- **Background (hadronic):** An uncertainty due to the shape of the background model used in the top-quark mass fit in the hadronic channel is also considered.

5 Combination Results

Before performing the combination of results, it was verfied that the likelihood formulation was capable of reproducing the individual analysis results, their central values as well as their statistical and systematic uncertainties.

The breakdown of the combination's final uncertainty is determined by performing the combination in stages. First only the statistical uncertainties are included in the fit. Then the systematic uncertainty (except the luminosity uncertainty) terms are added to the fit. Finally the statistical, systematic, and luminosity uncertainties are all included in the fit.

For the full combination of the four analyses we find

$$\begin{aligned}
\sigma_{t\bar{t}} &= 167.3 \pm \ \ 2.2 \quad \text{(stat.) pb,} \\
\sigma_{t\bar{t}} &= 165.3 \pm 10.8 \quad \text{(stat.+syst.) pb, and} \\
\sigma_{t\bar{t}} &= 165.8 \pm 13.3 \quad \text{(stat.+syst.+lumi.) pb.}
\end{aligned}$$

Subtracting the uncertainties in quadrature to extract the individual contributions, we find

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb.} \tag{6}$$

In Fig. 1 the value of the combined cross section is shown together with the results of the single measurements and the approximate NNLO predictions of [6, 7], [8] and [9].

The combined cross section in Eq. 6 is cross-checked with the Best Linear Unbiased Estimate method (BLUE [5]). The BLUE method was already used by the CMS collaboration for the combination of the top-quark mass and cross section measurements in the dilepton channels [2, 10] and for the combination of top-quark pair production cross section measurements done with the 2010 datasets [11]. The uncertainties and correlations used for the BLUE combination are identical to those used in the likelihood combination. The BLUE combination gives a cross section of

$$\sigma_{t\bar{t}} = 166.9 \pm 2.7(\text{stat.}) \pm 10.9(\text{syst.}) \pm 7.4(\text{lumi.})\ \text{pb}. \quad (7)$$

Given the different nature of the two methods used, the combined cross sections values are compatible. Use of a likelihood based method allows to improve the total (statistical and systematic) uncertainty by about 3%.

6 Conclusions

The measurements of the $t\bar{t}$ cross section at $\sqrt{s} = 7$ TeV in different channels are combined in this note. The channels included in the combination are single lepton (e/μ+jets), dilepton (ee, $\mu\mu$, $e\mu$), tau ($\mu\tau$), and fully hadronic decays. The binned maximum likelihood fitter is used for the combination and accounts for the correlations of the systematic uncertainties between different channels. The combined cross section of

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb}$$

is obtained. This result is in good agreement with the QCD predictions of 164^{+6}_{-10} pb [6, 7], 163^{+11}_{-10} pb [8], and 149±11 pb [9] that are based on the full NLO matrix elements and the resummation of the leading and next-to-leading soft logarithms. The precision of the combined measurement is 8.0%, which is comparable to the precision of the approximate NNLO theory.

References

[1] CMS Collaboration, "Measurement of the $t\bar{t}$ Pair Production Cross Section at $\sqrt{s} = 7$ TeV using b-quark Jet Identification Techniques in Lepton + Jet Events", *CMS Physics Analysis Summary* **CMS-PAS-TOP-11-003** (2011).

[2] CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV with a luminosity of 1.14 fb^{-1}", *CMS Physics Analysis Summary* **CMS-PAS-TOP-11-005** (2011).

[3] CMS Collaboration, "First measurement of the $t\bar{t}$ production cross section in the dilepton channel with tau leptons in the final state in pp collisions at $\sqrt{s} = 7$ TeV", *CMS Physics Analysis Summary* **CMS-PAS-TOP-11-006** (2011).

[4] CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in the hadronic decay channel in pp collisions at $\sqrt{s} = 7$ TeV", *CMS Physics Analysis Summary* **CMS-PAS-TOP-11-007** (2011).

[5] L. Lyons, D. Gibaut, and P. Clifford, "How to combine correlated estimates of a single physical quantity", *Nucl. Instrum. Meth.* **A270** (1988) 110. doi:10.1016/0168-9002(88)90018-6.

[6] M. Aliev, H. Lacker, U. Langenfeld et al., "HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR", *Comput.Phys.Commun.* **182** (2011) 1034–1046, arXiv:1007.1327. doi:10.1016/j.cpc.2010.12.040.

[7] U. Langenfeld, S. Moch, and P. Uwer, "Measuring the running top-quark mass", *Phys.Rev.* **D80** (2009) 054009, arXiv:0906.5273. doi:10.1103/PhysRevD.80.054009.

[8] N. Kidonakis, “Next-to-next-to-leading soft-gluon corrections for the top quark cross section and transverse momentum distribution”, *Phys.Rev.* **D82** (2010) 114030, arXiv:1009.4935. doi:10.1103/PhysRevD.82.114030.

[9] V. Ahrens, A. Ferroglia, M. Neubert et al., “Renormalization-Group Improved Predictions for Top-Quark Pair Production at Hadron Colliders”, *JHEP* **1009** (2010) 097, arXiv:1003.5827.

[10] CMS Collaboration, “Measurement of the t t-bar production cross section and the top quark mass in the dilepton channel in pp collisions at sqrt(s) =7 TeV”, *JHEP* **1107** (2011) 049, arXiv:1105.5661. doi:10.1007/JHEP07(2011)049.

[11] CMS Collaboration, “Combination of top pair production cross sections in pp collisions at $\sqrt{s}$ = 7 TeV and comparisons with theory”, *CMS Physics Analysis Summary* **CMS-PAS-TOP-11-001** (2010).

Table 2: Percentage rate uncertainties for background components in the combination. Note that the number of significant figures reflects the inputs. For example, the $\mu\tau$ background from DY $ee/\mu\mu$ is 0.7±0.5, making the uncertainty 70%.

channel	background	single lepton	ee	$\mu\mu$	$e\mu$	$\mu\tau$	hadronic
Single lepton	single top	30					
	Z+jets	30					
	QCD	100					
	W+jets	N/A					
Dilepton combination	VV		69	65	49		
	single top		38.2	36.9	33.8		
	W+jets		200	66	41		
	QCD		0.0	100	120		
	DY $\tau\tau$		49	47	37		
	DY ee		51.3				
	DY $\mu\mu$			51.1			
Dilepton $\mu\tau$	fake-τ					6.0	
	DY $ee/\mu\mu$					70	
	DY $\tau\tau$					12	
	single top					5	
	VV					8	
	other $t\bar{t}$					6	
Hadronic	QCD						3.4

Table 3: Effect of 1σ variation in the various $t\bar{t}$ acceptance systematic uncertainties for the channels in the combination. For the single lepton channels, the dependencies are either a flat percentage or are parameterized by a polynomial, one for each (jet,tag) subsample. The entries are given in percentage change to the $t\bar{t}$ acceptance. Note the W+jets Q^2 uncertainty in the single lepton analysis only affects the normalization of the W+jets templates, but we list it in the table for completeness.

systematic source	single lepton	ee	$\mu\mu$	$e\mu$	$\mu\tau$	hadronic
JES	poly	1.9	1.7	1.9	4.4	14.3
b-tag (single)	poly					
b-tag (hadronic)						15.7
b-tag ($\mu\tau$)					5.5	
b-tag (dilepton)		5.0	5.0	5.0		
Pileup	2.6	5.0	5.0	5.0	3.1	0.6
$t\bar{t}$ Q^2	2.8	2.4	2.4	1.8	2.0	10.3
luminosity	4.5	4.5	4.5	4.5	6.0	6.0
Lepton efficiency (single)	3.4					
Lepton efficiency ($\mu\tau$)					2.1	
Lepton efficiency (dilepton)		3.0	1.6	2.3		
W leptonic branching ratio		1.7	1.7	1.7	1.7	
Top quark mass		2.6	2.6	1.5	1.6	5.3
JetMet model		3.2	3.2	0.4	1.0	
ME-PS matching	2.0				1.0	5.2
W+jets Q^2 (single)	poly					
PDF (single)	3.4					
Lepton model (dilepton)		4.0	4.0	4.0		
Decay model (dilepton)		2.0	2.0	2.0		
fake rate ($\mu\tau$)					13.0	
τ jet mis-ID ($\mu\tau$)					7.3	
tau and hadron decay model ($\mu\tau$)					2.0	
MC bkgd ($\mu\tau$)					1.6	
MC tune (hadronic)						8.1
trigger (hadronic)						4.5
bkgd (hadronic)						12.2

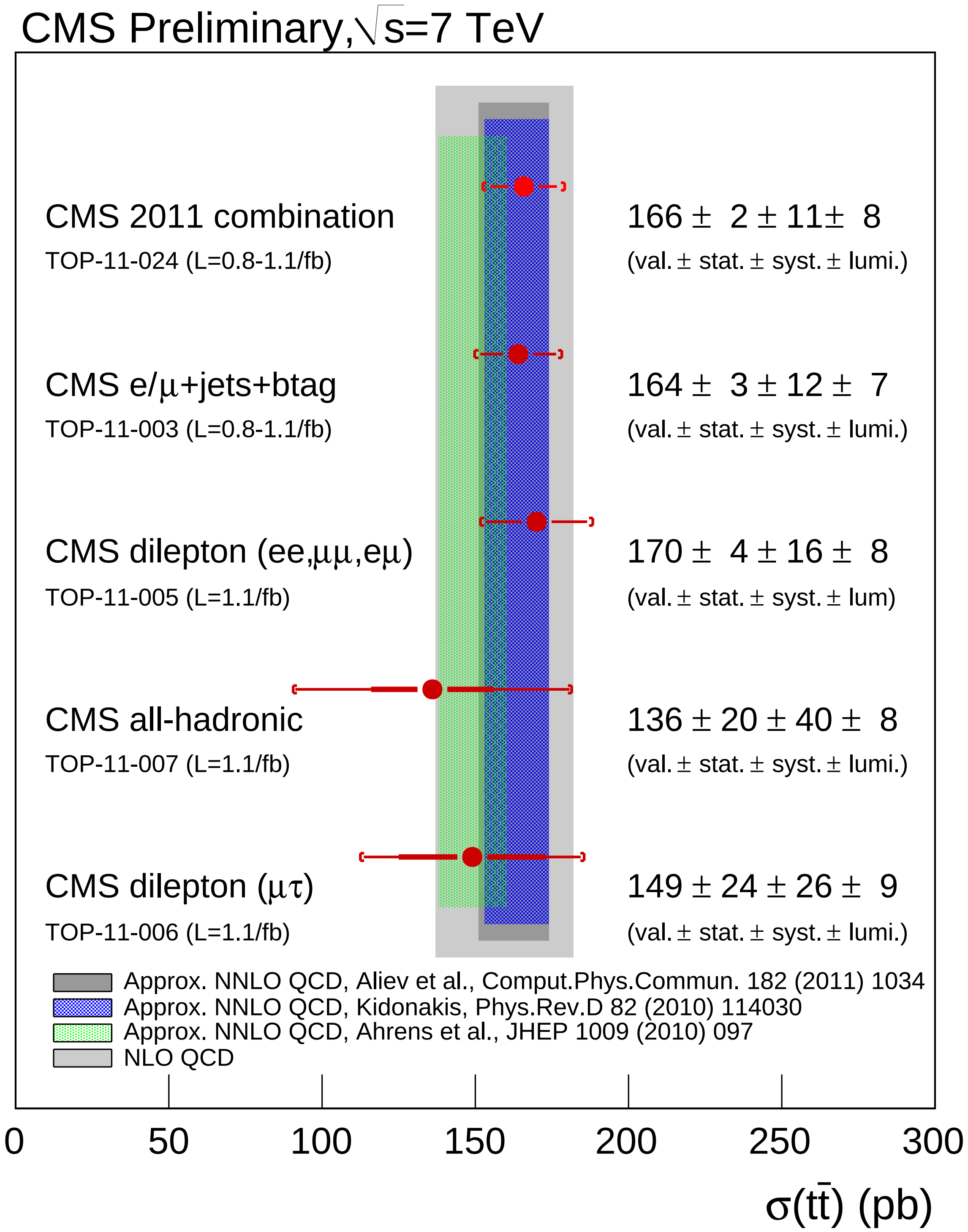

Figure 1: The cross section of the $t\bar{t}$ production obtained by a combination of measurements in different channels at $\sqrt{s} = 7$ TeV. The data are compared to the approximate NNLO calculations [6–9]. The theoretical uncertainties include the variation of the scales as well as the parton distribution functions.