Measurement of the differential cross sections for top quark pair production as a function of kinematic event variables in pp collisions at $\sqrt{s} = 7$ and 8 TeV

The CMS Collaboration*

Abstract

Measurements are reported of the normalized differential cross sections for top quark pair production with respect to four kinematic event variables: the missing transverse energy; the scalar sum of the jet transverse momentum ($p_T$); the scalar sum of the $p_T$ of all objects in the event; and the $p_T$ of leptonically decaying W bosons from top quark decays. The data sample, collected using the CMS detector at the LHC, consists of 5.0 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV and 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. Top quark pair events containing one electron or muon are selected. The results are presented after correcting for detector effects to allow direct comparison with theoretical predictions. No significant deviations from the predictions of several standard model event simulation generators are observed.

1 Introduction

The CERN LHC produced millions of top quark pairs (t$\bar{t}$) in 2011 and 2012. This allows for a detailed investigation of the kinematic event properties of t$\bar{t}$ production such as the missing transverse energy ($E_{\text{miss}}^T$), the scalar sum of the jet transverse momenta ($H_T$), the scalar sum of the transverse momenta of all objects ($S_T$), and the transverse momentum ($p_W^T$) of leptonically decaying W bosons produced in top quark decays. These measurements can be used to verify current theoretical models, along with their implementation in simulations of t$\bar{t}$ production, and also to measure rare standard model (SM) processes such as t$\bar{t}$ production in association with a W, Z, or Higgs boson. Since top quark pair production is a major background for many searches for physics beyond the SM, it is important that the properties of t$\bar{t}$ events are well understood.

Here, we report measurements carried out using the CMS detector [1] at the LHC at two different proton–proton center-of-mass energies. The data samples used include integrated luminosities of 5.0 fb$^{-1}$ collected in 2011 at $\sqrt{s} = 7$ TeV and 19.7 fb$^{-1}$ from 2012 at $\sqrt{s} = 8$ TeV. The t$\bar{t}$ production cross section is measured as a function of $E_{\text{miss}}^T$, $H_T$, $S_T$, and $p_W^T$, corrected for detector effects, and compared with the predictions from different event generators. Differential t$\bar{t}$ cross sections have previously been measured at the Tevatron [2, 3], and at the LHC [4–9]. These previous measurements study the t$\bar{t}$ production cross section as a function of the top quark kinematics and the kinematics of the t$\bar{t}$ system. The results presented here are complementary, since the t$\bar{t}$ production cross section is measured as a function of variables that do not require the reconstruction of the top quarks from their decay products.

Top quarks decay with close to 100% probability into a W boson and a bottom quark. In this article, we consider the channel in which one of the W bosons decays leptonically into a charged lepton (electron or muon) along with its associated neutrino, while the other W boson decays hadronically. This channel has a branching fraction of around 15% for direct decay to each lepton flavor and a relatively clean experimental signature, including an isolated, high-transverse-momentum lepton, large $E_{\text{miss}}^T$ from the undetected neutrino, and multiple hadronic jets. Two jets are expected to contain $b$ hadrons from the hadronization of the $b$ quarks produced directly in the $t \rightarrow bW$ decay, while other jets (from the hadronic W boson decay or gluon radiation) will typically contain only light and charm quarks.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [1].

3 Simulation

For the Monte Carlo (MC) simulation of the t$\bar{t}$ signal sample the leading-order MadGraph v5.1.5.11 event generator [10] is used with relevant matrix elements for up to three addi-
tional partons implemented. Theoretical production cross section values of $177.3^{+4.6}_{-6.0}$ (scale) ± 9.0 (PDF+$\alpha_S$) pb at $\sqrt{s} = 7$ TeV, and $252.9^{+6.4}_{-8.6}$ (scale) ± 11.7 (PDF+$\alpha_S$) pb at $\sqrt{s} = 8$ TeV, are used for the normalization of these samples. These cross sections are calculated with the Top++2.0 program to next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-logarithm (NNLL) order [11], and assuming a top quark mass $m_t = 172.5$ GeV. The first uncertainty comes from the independent variation of the renormalization ($\mu_R$) and factorization ($\mu_F$) scales, while the second one is associated with variations in the parton distribution function (PDF) and $\alpha_S$, following the PDF4LHC prescription with the MSTW2008 68% CL NNLO, CT10 NNLO, and NNPDF2.3 5f FFN PDF sets [12–16].

The generated events are subsequently processed with PYTHIA v6.426 [17] for parton showering and hadronization. The PYTHIA parton shower is matched to the jets from the hard quantum chromodynamics (QCD) matrix element via the MLM prescription [18] with a transverse momentum ($p_T$) threshold of 20 GeV. The CMS detector response is simulated using GEANT4 [19].

Independent $t\bar{t}$ samples are also generated at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with POWHEG v2 r2819 [20–22]. At 8 TeV, additional samples are generated with both MC@NLO v3.41 [23] and POWHEG v1.0 r1380 [20–22]. All of the POWHEG samples are interfaced with both PYTHIA and HERWIG v6.520 [24], whereas the MC@NLO generator is interfaced with HERWIG for parton showering. These samples, which are all generated to next-to-leading order accuracy, are used for comparison with the final results.

The most significant backgrounds to $t\bar{t}$ production are events in which a W boson is produced in association with additional jets. Other backgrounds include single top quark production, Z boson production in association with multiple jets, and QCD multijet events where hadronic activity is misidentified as a lepton. The simulation of background from W and Z boson production in association with jets is also performed using the combination of MADGRAPH and PYTHIA, with a $p_T$ matching threshold of 10 GeV in this case. These samples are referred to as W+jets and Z+jets, respectively. Single top quark production via $t$- and s-channel W boson exchange [25] and with an associated on-shell W boson [26] are generated using POWHEG. The QCD multijet processes are simulated using PYTHIA. The event yields of the background processes are normalized according to their predicted production cross section values. These are from NNLO calculations for W+jets and Z+jets events [27, 28], next-to-leading order calculations with NNLL corrections for single top quark events [29], and leading-order calculations for QCD multijet events [17].

Samples are generated using the CTEQ6L PDFs [30] for MADGRAPH samples, the CT10 PDFs [31] for POWHEG samples, and the CTEQ6M PDFs [30] for MC@NLO. The PYTHIA Z2 tune is used to describe the underlying event in both the MADGRAPH and POWHEG + PYTHIA samples at $\sqrt{s} = 7$ TeV, whereas the Z2* tune is used for the corresponding samples at $\sqrt{s} = 8$ TeV [32]. The underlying event in the POWHEG + HERWIG samples is described by the AUET2 tune [33], whereas the default tune is used in the MC@NLO + HERWIG sample.

The value of the top quark mass is fixed to $m_t = 172.5$ GeV in all samples. In all cases, PYTHIA is used for simulating the gluon radiation and fragmentation, following the prescriptions of Ref. [34]. Additional simulated hadronic pp interactions (“pileup”), in the same or nearby beam crossings, are overlaid on each simulated event to match the high-luminosity conditions in actual data taking.

Previous measurements of differential $t\bar{t}$ production cross sections at the LHC [4, 5, 8] showed
that several of the \(t\bar{t}\) event generators considered in this analysis predict a harder top quark \(p_T\) spectrum than that observed in data. An additional simulated \(t\bar{t}\) sample is considered here, where the sample produced with the MADGRAPH event generator is reweighted to improve the agreement of the top quark \(p_T\) spectrum with data.

4 Event reconstruction and selection

Parallel selection paths for the two lepton types are implemented, resulting in samples classified as electron+jets and muon+jets. The trigger for the electron+jets channel during the \(\sqrt{s} = 7\) TeV data taking selects events containing an electron candidate with \(p_T > 25\) GeV and at least three reconstructed hadronic jets with \(p_T > 30\) GeV. In the \(\sqrt{s} = 8\) TeV data, at least one electron candidate with \(p_T > 27\) GeV is required, with no additional requirement for jets. In the muon+jets channel, at least one isolated muon candidate with \(p_T > 24\) GeV is required at the trigger level. Each candidate event is required to contain at least one well-measured vertex \([35]\), located within the pp luminous region in the center of CMS.

Events are reconstructed using a particle-flow (PF) technique \([36, 37]\), which combines information from all subdetectors to optimize the reconstruction and identification of individual long-lived particles.

Electron candidates are selected with a multivariate technique using calorimetry and tracking information \([38]\). Inputs to the discriminant include information about the calorimeter shower shape, track quality, track-shower matching, and a possible photon conversion veto. Electron candidates are required to have \(E_T > 30\) GeV and pseudorapidity in the range \(|\eta| < 2.5\). The low-efficiency region \(1.44 < |\eta| < 1.57\) between the barrel and endcap sections of the detector is excluded. Muon candidates are selected with tight requirements on track and vertex quality, and on hit multiplicity in the tracker and muon detectors \([39]\). These requirements suppress cosmic rays, misidentified muons, and nonprompt muons from decay of hadrons in flight. Muon candidates are required to have \(p_T > 26\) GeV and \(|\eta| < 2.1\).

For the lepton isolation requirement, a cone of size \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\) is constructed around the lepton direction, where \(\Delta \eta\) and \(\Delta \phi\) are the differences in pseudorapidity and azimuthal angle (in radians), respectively, between the directions of the lepton and another particle. The \(p_T\) values of charged and neutral particles found in this cone are summed, excluding the lepton itself and correcting for the effects of pileup \([38]\). The relative isolation variable \(I(\Delta R)\) is defined as the ratio of this sum to the lepton \(p_T\). Lepton candidates are selected if they satisfy \(I(0.3) < 0.1\) for electrons, and \(I(0.4) < 0.12\) for muons.

Reconstructed particles are clustered into jets using the anti-\(k_T\) algorithm \([40]\) with a distance parameter of 0.5. The measured \(p_T\) of each jet is corrected \([41]\) for known variations in the jet energy response as a function of the measured jet \(\eta\) and \(p_T\). The jet energy is also corrected for the extra energy deposition from pileup interactions \([42, 43]\). Jets are required to pass loose identification requirements to remove calorimeter noise \([44]\). Any such jet whose direction is less than \(\Delta R = 0.3\) from the identified lepton direction is removed. For the identification of b quark jets (“b tagging”), a “combined secondary vertex” algorithm \([45]\) is used, taking into account the reconstructed secondary vertices and track-based lifetime information. The b tagging threshold is chosen to give an acceptance of 1% for light-quark and gluon jets with a tagging efficiency of 65% for b quark jets.

The final selection requires exactly one high-\(p_T\), isolated electron or muon. Events are vetoed if they contain an additional lepton candidate satisfying either of the following criteria: an
Cross section measurements

We study the normalized $t\bar{t}$ differential production cross section as a function of four kinematic event variables: $E_T^{\text{miss}}, H_T, S_T,$ and $p_T^W$.

The variable $E_T^{\text{miss}}$ is the magnitude of the missing transverse momentum vector $\vec{p}_T^{\text{miss}}$, which is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all PF candidates in the event:

$$E_T^{\text{miss}} = \left[ \left( -\sum_i p_{ix}^i \right)^2 + \left( -\sum_i p_{iy}^i \right)^2 \right]^{\frac{1}{2}},$$

where $p_{ix}^i$ and $p_{iy}^i$ are the $x$ and $y$ momentum components of the $i$th candidate, and the sums extend over all PF candidates. The measured $E_T^{\text{miss}}$ is corrected for pileup and nonuniformities in response as a function of $\phi$ [46].

The variable $H_T$ is defined as the scalar sum of the transverse momenta of all jets in the event,

$$H_T = \sum_{\text{all jets}} p_{T}^{\text{jet}},$$

where the sum extends over all jets having $p_T > 20\text{ GeV}$ and $|\eta| < 2.5$.

The variable $S_T$ is the scalar sum of $H_T, E_T^{\text{miss}}$, and the $p_T$ of the identified lepton,

$$S_T = H_T + E_T^{\text{miss}} + p_T^{\text{lepton}}.$$

Finally, $p_T^W$ is the magnitude of the transverse momentum of the leptonically decaying W boson, which is derived from the momentum of the isolated lepton and $\vec{p}_T^{\text{miss}}$

$$p_T^W = \sqrt{ \left( p_{x}^{\text{lepton}} + p_{x}^{\text{miss}} \right)^2 + \left( p_{y}^{\text{lepton}} + p_{y}^{\text{miss}} \right)^2 },$$

where $p_{x}^{\text{lepton}}$ and $p_{y}^{\text{lepton}}$ are the transverse components of $\vec{p}_T^{\text{lepton}}$, and $p_{x}^{\text{miss}}$ and $p_{y}^{\text{miss}}$ are the transverse components of $\vec{p}_T^{\text{miss}}$.

Figures 1 and 2 show the observed distributions of $E_T^{\text{miss}}, H_T, S_T$, and $p_T^W$, in the $\sqrt{s} = 8\text{ TeV}$ data samples, compared to the sum of the corresponding signal and background distributions from simulation.
Figure 1: The observed distributions of $E_T^{\text{miss}}$ (top) and $H_T$ (bottom) in the $\sqrt{s} = 8$ TeV electron+jets (left) and muon+jets (right) data samples, compared to predictions from simulation. The points are the data histograms, with the vertical bars showing the statistical uncertainty, and the predictions from the simulation are the solid histograms. The shaded region shows the uncertainty in the values from simulation. These include contributions from the statistical uncertainty and the uncertainty in the $t\bar{t}$ cross section. The lower plots show the ratio of the number of events from data and the prediction from the MC simulation.
Figure 2: The observed distributions of $S_T$ (top) and $p_T^W$ (bottom) in the $\sqrt{s} = 8$ TeV electron+jets (left) and muon+jets (right) data samples, compared to predictions from simulation. The points are the data histograms, with the vertical bars showing the statistical uncertainty, and the predictions from the simulation are the solid histograms. The shaded region shows the uncertainty in the values from simulation. These include contributions from the statistical uncertainty and the uncertainty in the $t\bar{t}$ cross section. The lower plots show the ratio of the number of events from data and the prediction from the MC simulation.
For simulated $t\bar{t}$ signal events, these four kinematic variables are also calculated using the momenta of particles in the event, before the simulation of the detector response. We refer to the quantities calculated in this way as the generated variables. The generated value of $E_{\text{miss}}$ is the magnitude of the vector sum of the $p_T$ of all neutrinos in the event. The long-lived particles in the event are clustered into jets in the same way as the reconstructed particles. The generated value of $H_T$ is the sum of the magnitudes of the $p_T$ of these jets with $p_T > 20$ GeV and $|\eta| < 2.5$. The generated values of $S_T$ and $p_{T,W}$ are calculated in the same way as the corresponding reconstructed variables, using the $p_T$ of the charged lepton from the leptonic decay of a W boson coming from $t \rightarrow bW$ decay.

The choice of bin widths for this measurement is optimized separately for each kinematic event variable to minimize the migration between bins. This optimization is based on three criteria: (i) of the simulated signal events for which the value of the generated variable falls in the bin, at least 50% are required to have the reconstructed variable in the same bin (this is sensitive to migration of events out of the bin); (ii) of the simulated signal events for which the value of the reconstructed variable falls in the bin, at least 50% are required to have the generated variable in the same bin (this is sensitive to migration of events into the bin); (iii) the number of reconstructed simulation events in a bin is required to be more than 100. These criteria ensure that bin-to-bin migrations are kept small, while allowing a differential cross section measurement with reasonable granularity.

The number of $t\bar{t}$ events in each bin of each kinematic event variable, and in each channel, is obtained by subtracting the expected contributions of background processes from data. The contributions of single top quark, and W or Z boson plus jet events are estimated from simulation. In the case of the QCD multijet background, the contribution is estimated from data using a control region where the selection criteria are modified to enrich the contribution of QCD multijet events. In the electron+jets channel, the control region is obtained by inverting the photon conversion veto on the electron. In addition to this, the number of b-tagged jets is required to be exactly zero. The small contamination of $t\bar{t}$, single top, W+jets, and Z+jets events in this control region, as estimated from simulation, is subtracted from the data. Then, the ratio of simulated QCD multijet events in the control region and the signal region is used to scale the normalization of the data-driven QCD multijet estimate from the control region to the signal region in the data. The control region in the muon+jets channel is obtained by inverting the isolation criterion on the muon in the selected events, and by requiring exactly zero b-tagged jets. The jet selection criterion is also modified, requiring at least three jets. The same procedure is then followed to estimate the contribution of QCD multijet events in the muon+jets signal region.

The number of $t\bar{t}$ events from data in each bin is then corrected for the small fractions of dileptonic, all-hadronic, and tau $t\bar{t}$ events in the final sample, as determined from simulation, and for experimental effects, such as detector resolution, acceptance, and efficiency. This correction is performed by constructing a response matrix that maps the generated values to the reconstructed values for the four kinematic variables in the simulated $t\bar{t}$ signal events. The response matrix is constructed using the MadGraph $t\bar{t}$ sample. This matrix is then inverted, using regularized singular-value decomposition [47] in the RooUnfold [48] software framework. Since we impose no requirements on the generated events, the procedure corrects to the full signal phase space.

The fully-corrected numbers of $t\bar{t}$ events in the electron+jets and muon+jets channels yield consistent results. These are then added and used to calculate the normalized $t\bar{t}$ differential
production cross section with respect to each kinematic event variable, $X$, using:

$$\frac{1}{\sigma} \frac{d\sigma}{dX} = \frac{1}{N} \frac{x_j}{\Delta X_j},$$

where $x_j$ represents the number of unfolded signal events in bin $j$, $\Delta X_j$ is the width of bin $j$; $\sigma$ is the total $t\bar{t}$ production cross section, and $N = \sum x_i$ is the total number of unfolded signal events.

### 6 Systematic uncertainties

The systematic uncertainties in the experimental and theoretical input quantities are evaluated and propagated to the final results, taking correlations into account. Since the final result is normalized to the total number of events, the effect of uncertainties that are correlated across all bins is negligible. As such, only uncertainties that affect the shape of the measured distributions are significant.

The uncertainty coming from the choice of renormalization and factorization scales in the physics modeling of $t\bar{t}$ events is determined by producing two additional simulated event samples. These samples are generated with both scales simultaneously varied by a factor of two up or down from their default values equal to the $Q$ of the hard process in the event; $Q$ is defined via $Q^2 = m_t^2 + \sum p_T^2$, where the sum is over all additional final-state partons in the matrix element. The effect of varying the renormalization and factorization scales in the $W+jets$ and $Z+jets$ samples is also considered to determine the uncertainty in the shape of this background. The uncertainty arising from the choice of parton shower matching threshold in the event generation is determined in a similar fashion, using additional samples in which the threshold is varied up or down. Uncertainties from the modeling of the hadronization are evaluated by comparing $POWHEG$ v1 simulated samples with two different hadron shower generators ($PYTHIA$ and $HERWIG$). The uncertainty owing to the choice of the PDF is determined by reweighting the simulated events and repeating the analysis using the 44 CTEQ6L PDF error sets [30]. The maximum variation is taken as the uncertainty. Simulated samples with the top quark mass varied by $\pm 1$ GeV, which corresponds to the precision of the measured top quark mass [49], are generated to evaluate the effect of the uncertainty in this parameter. The effect of reweighting the top quark $p_T$ spectrum in simulation, as described in Section 3, is found to have a negligible effect for low values of the kinematic event variables, and increases to 3–7% for the highest values.

Other uncertainties are associated with imperfect understanding of efficiencies, resolutions, and scales describing the detector response. The uncertainty arising from each source is estimated, and the analysis repeated with each corresponding parameter varied within its uncertainty.

The efficiencies and associated uncertainties for triggering and lepton identification are determined from data by a tag-and-probe method [50]. The probabilities for identifying and misidentifying $b$ jets in the simulation are compared to those measured in data, and the resulting correction factors and their uncertainties are determined as a function of jet energy and quark flavor. The uncertainties in the correction factors are typically 2%.

The uncertainty in the jet energy scale (JES) is determined as a function of the jet $p_T$ and $\eta$ [41], and an uncertainty of 10% is included in the jet energy resolution (JER) [41]. The effect of this limited knowledge of the JES and JER is determined by varying the JES and JER in the
simulated samples within their uncertainties. The uncertainty in the JES and JER, as well as uncertainties in the electron, photon, tau, and muon energy scale, are propagated into the calculation of $E_T^{\text{miss}}$. The uncertainty in the electron and photon energy scale is 0.6% in the barrel, and 1.5% in the endcap [38]. The uncertainty in the tau lepton energy scale is estimated to be ±3% [51], while the effect of the uncertainty in the muon momentum measurement is found to be negligible. A 10% uncertainty is assigned to the estimate of the nonclustered energy used in the calculation of $E_T^{\text{miss}}$ [46].

The effect of the uncertainty in the level of pileup is estimated by varying the inelastic pp cross section used in the simulation by ±5% [52].

The uncertainty in the normalization of the background is determined by varying the normalization of the single top, W+jets, and Z+jets processes by ±30%, and the QCD multijet processes by ±100%. The uncertainty in the shape of the QCD multijet distribution in the electron channel is estimated by using an alternative control region in data to determine the contribution of QCD multijet events. This uncertainty is found to have a negligible effect.

The dominant systematic effects are caused by the uncertainties in the modeling of the hadronization and the $t\bar{t}$ signal. For illustrative purposes, typical systematic uncertainties in the $\sqrt{s} = 8\text{ TeV}$ results coming from each of the sources described above are presented in Table 1. The values shown for each kinematic event variable are the median uncertainties over all of the bins for that variable.

Table 1: Typical relative systematic uncertainties in percent (median values) in the normalized $t\bar{t}$ differential cross section measurement as a function of the four kinematic event variables at a center-of-mass energy of 8 TeV (combination of electron and muon channels). Typical values of the total systematic uncertainty are also shown.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$E_T^{\text{miss}}$</th>
<th>$H_T$</th>
<th>$S_T$</th>
<th>$p_T^W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fact./Renorm. scales and matching threshold</td>
<td>7.6</td>
<td>4.0</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Hadronization</td>
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<td>5.0</td>
<td>8.5</td>
<td>3.0</td>
</tr>
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<td>PDF</td>
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<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
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<td>0.7</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Top quark $p_T$ reweighting</td>
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<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Lepton trigger efficiency &amp; selection</td>
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<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>b tagging</td>
<td>0.3</td>
<td>0.1</td>
<td>0.3</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Jet energy scale</td>
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</tr>
<tr>
<td>Jet energy resolution</td>
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<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.2</td>
<td>—</td>
<td>&lt;0.1</td>
<td>0.1</td>
</tr>
<tr>
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<td>0.2</td>
</tr>
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<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>9.9</td>
<td>8.6</td>
<td>9.5</td>
<td>4.4</td>
</tr>
</tbody>
</table>
7 Results

The normalized differential $t\bar{t}$ cross sections as a function of each of the kinematic event variables are shown in Figs. 3 and 4 for the $\sqrt{s} = 7$ TeV data, and in Figs. 5 and 6 for the $\sqrt{s} = 8$ TeV data. The results are also presented in Tables A.1–A.8 of Appendix A.

The data distributions in the figures are compared with the predictions from the event generators in the left-hand plots: MadGraph and POWHEG V2 with two different hadron shower generators, PYTHIA and HERWIG. For the $\sqrt{s} = 8$ TeV results, the predictions from the MC@NLO and POWHEG V1 generators are also shown. The effect on the predicted distributions from varying the modeling parameters (the matching threshold and renormalization scale $Q^2$) up and down by a factor of two for the MadGraph event generator is shown in the right-hand plots for the two MadGraph simulations. The uncertainties shown by the vertical bars on the points in the figures and given in the tables include both the statistical uncertainties and those resulting from the unfolding procedure.

The measurements at $\sqrt{s} = 7$ TeV are well described by all the event generators in the distribution of $E_{T}^{\text{miss}}$. For $S_T$, $p_T^W$, and $H_T$, the event generators predict a somewhat harder spectrum than seen in data. However, the POWHEG V2 + PYTHIA event generator provides a reasonable description of the $H_T$ and $S_T$ differential cross sections.

The results at $\sqrt{s} = 8$ TeV are generally well described by the MC@NLO and the POWHEG V2 + PYTHIA event generators. The POWHEG V2 + HERWIG event generator describes the $E_{T}^{\text{miss}}$ and $p_T^W$ distributions well. However, for $H_T$ and $S_T$ this event generator predicts a harder spectrum than seen in data, at both center-of-mass energies.

The MadGraph event generator generally predicts a harder spectrum than seen in data for all variables. The variations in matching threshold and $Q^2$ in the MadGraph event generator are not sufficient to explain this difference between the prediction and data. However, the MadGraph event generator provides a good description of the data after reweighting the top quark $p_T$ spectrum, as described in Section 3. The prediction obtained from the MadGraph event generator after the reweighting is shown on all the plots.

8 Summary

A measurement of the normalized differential cross section of top quark pair production with respect to the four kinematic event variables $E_{T}^{\text{miss}}$, $H_T$, $S_T$, and $p_T^W$ has been performed in pp collisions at a center-of-mass energy of 7 TeV using 5.0 fb$^{-1}$ and at 8 TeV using 19.7 fb$^{-1}$ of data collected by the CMS experiment.

This study confirms previous CMS findings that the observed top quark $p_T$ spectrum is softer than predicted by the MadGraph, POWHEG, and MC@NLO event generators, but otherwise there is broad consistency between the MC event generators and observation. This result provides confidence in the description of $t\bar{t}$ production in the SM and its implementation in the most frequently used simulation packages.

Acknowledgments

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Figure 3: Normalized $E_T^{\text{miss}}$ (top) and $H_T$ (bottom) differential $t\bar{t}$ cross sections from the combined electron and muon data at $\sqrt{s} = 7$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MADGRAPH + PYTHIA (both the default and after reweighting the top quark $p_T$ spectrum), POWHEG V2 + HERWIG, and POWHEG V2 + PYTHIA. Right: comparison with predictions from the MADGRAPH + PYTHIA event generator found by varying the matching threshold and renormalization scales ($\mu_R, \mu_F$) up and down by a factor of two. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN;
Figure 4: Normalized $S_T$ (top) and $p_T^{W}$ (bottom) differential $t\bar{t}$ cross sections from combined electron and muon data at $\sqrt{s} = 7$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MADGRAPH + PYTHIA (both the default and after reweighting the top quark $p_T$ spectrum), POWHEG V2 + HERWIG, and POWHEG V2 + PYTHIA. Right: comparison with predictions from the MADGRAPH + PYTHIA event generator found by varying the matching threshold and renormalization scales ($\mu_R, \mu_F$) up and down by a factor of two. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GRST (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia);
Figure 5: Normalized $E_T^{\text{miss}}$ (top) and $H_T$ (bottom) differential tt cross sections from combined electron and muon data at $\sqrt{s} = 8$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MadGraph + Pythia (both the default and after reweighting the top quark $p_T$ spectrum), MC@NLO + Herwig, PowHeG V1 + Herwig, PowHeG V2 + Pythia, and PowHeG V2 + Pythia. Right: comparison with predictions from the Pythia event generator found by varying the matching threshold and renormalization scales ($\mu_R$, $\mu_F$) up and down by a factor of two. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and
Figure 6: Normalized $S_T$ (top) and $p_T^{W}$ (bottom) differential $t\bar{t}$ cross sections from combined electron and muon data at $\sqrt{s} = 8$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MADGRAPH + PYTHIA (both the default and after reweighting the top quark $p_T$ spectrum), MC@NLO + HERWIG, POWHEG V1 + HERWIG, POWHEG V2 + PYTHIA, and POWHEG V2 + PYTHIA. Right: comparison with predictions from the MADGRAPH + PYTHIA event generator found by varying the matching threshold and renormalization scales ($\mu_R$, $\mu_F$) up and down by a factor of two. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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References


A Additional tables

The measured values of the $t\bar{t}$ differential cross sections as a function of $E_{T}^{\text{miss}}$, $H_{T}$, $S_{T}$, and $p_{T}^{W}$ for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV are given in the tables below, along with their statistical, systematic, and total uncertainties.

Table A.1: Normalized $t\bar{t}$ differential cross section measurements with respect to the $E_{T}^{\text{miss}}$ variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$E_{T}^{\text{miss}}$ (GeV)</th>
<th>$1/\sigma \ d\sigma/\ dE_{T}^{\text{miss}}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–27</td>
<td>$6.44 \times 10^{-3}$</td>
<td>0.83</td>
<td>4.5</td>
<td>4.6</td>
</tr>
<tr>
<td>27–52</td>
<td>$1.32 \times 10^{-2}$</td>
<td>0.60</td>
<td>2.8</td>
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</tr>
<tr>
<td>52–87</td>
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<td>0.58</td>
<td>1.9</td>
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</tr>
<tr>
<td>87–130</td>
<td>$3.14 \times 10^{-3}$</td>
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</tr>
<tr>
<td>130–172</td>
<td>$8.93 \times 10^{-4}$</td>
<td>1.1</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>172–300</td>
<td>$1.32 \times 10^{-4}$</td>
<td>1.4</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>

Table A.2: Normalized $t\bar{t}$ differential cross section measurements with respect to the $H_{T}$ variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$H_{T}$ (GeV)</th>
<th>$1/\sigma \ d\sigma/\ dH_{T}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120–185</td>
<td>$2.48 \times 10^{-3}$</td>
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<tr>
<td>185–215</td>
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<td>1.4</td>
<td>5.5</td>
<td>5.7</td>
</tr>
<tr>
<td>215–247</td>
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<td>1.3</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>247–283</td>
<td>$4.05 \times 10^{-3}$</td>
<td>1.2</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>283–323</td>
<td>$2.99 \times 10^{-3}$</td>
<td>1.1</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>323–365</td>
<td>$2.06 \times 10^{-3}$</td>
<td>1.1</td>
<td>5.4</td>
<td>5.6</td>
</tr>
<tr>
<td>365–409</td>
<td>$1.37 \times 10^{-3}$</td>
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<td>7.0</td>
<td>7.1</td>
</tr>
<tr>
<td>409–458</td>
<td>$8.93 \times 10^{-4}$</td>
<td>1.1</td>
<td>9.3</td>
<td>9.4</td>
</tr>
<tr>
<td>458–512</td>
<td>$5.49 \times 10^{-4}$</td>
<td>1.2</td>
<td>9.9</td>
<td>10</td>
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<tr>
<td>512–570</td>
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<td>13</td>
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</tr>
<tr>
<td>570–629</td>
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<td>1.8</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>629–691</td>
<td>$1.25 \times 10^{-4}$</td>
<td>2.2</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>691–769</td>
<td>$7.20 \times 10^{-5}$</td>
<td>2.7</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>769–1000</td>
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<td>3.0</td>
<td>17</td>
<td>17</td>
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</tbody>
</table>

Table A.3: Normalized $t\bar{t}$ differential cross section measurements with respect to the $S_T$ variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$S_T$ (GeV)</th>
<th>$1/\sigma , d\sigma/dS_T$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
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<td>8.5</td>
</tr>
<tr>
<td>277–319</td>
<td>$4.12 \times 10^{-3}$</td>
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<td>6.7</td>
<td>6.8</td>
</tr>
<tr>
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<td>1.0</td>
<td>4.2</td>
<td>4.3</td>
</tr>
<tr>
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<td>1.8</td>
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<tr>
<td>408–459</td>
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<td>0.93</td>
<td>4.5</td>
<td>4.6</td>
</tr>
<tr>
<td>459–514</td>
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<td>8.1</td>
<td>8.2</td>
</tr>
<tr>
<td>514–573</td>
<td>$8.96 \times 10^{-4}$</td>
<td>1.1</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
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<td>11</td>
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<tr>
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Table A.4: Normalized $t\bar{t}$ differential cross section measurements with respect to the $p_T^W$ variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
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<tr>
<th>$p_T^W$ (GeV)</th>
<th>$1/\sigma , d\sigma/dp_T^W$ (GeV$^{-1}$)</th>
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<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
</tr>
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<tr>
<td>0–27</td>
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<td>$8.56 \times 10^{-3}$</td>
<td>0.96</td>
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</tr>
<tr>
<td>52–78</td>
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<td>0.81</td>
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<tr>
<td>78–105</td>
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<td>200–237</td>
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<td>2.2</td>
<td>9.9</td>
<td>10</td>
</tr>
<tr>
<td>237–300</td>
<td>$1.63 \times 10^{-4}$</td>
<td>2.9</td>
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<td>13</td>
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</tbody>
</table>
Table A.5: Normalized $t\bar{t}$ differential cross section measurements with respect to the $E_T^{\text{miss}}$ variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>$1/\sigma \frac{d\sigma}{dE_T^{\text{miss}}}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
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<td>27–52</td>
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<td>0.36</td>
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<td>3.9</td>
</tr>
<tr>
<td>52–87</td>
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</tr>
<tr>
<td>87–130</td>
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<td>8.7</td>
</tr>
<tr>
<td>130–172</td>
<td>$8.46 \times 10^{-4}$</td>
<td>0.81</td>
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<td>13</td>
</tr>
<tr>
<td>172–300</td>
<td>$1.18 \times 10^{-4}$</td>
<td>1.3</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>

Table A.6: Normalized $t\bar{t}$ differential cross section measurements with respect to the $H_T$ variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$H_T$ (GeV)</th>
<th>$1/\sigma \frac{d\sigma}{dH_T}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120–185</td>
<td>$2.10 \times 10^{-3}$</td>
<td>0.68</td>
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<td>9.1</td>
</tr>
<tr>
<td>185–215</td>
<td>$4.26 \times 10^{-3}$</td>
<td>0.65</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td>215–247</td>
<td>$4.52 \times 10^{-3}$</td>
<td>0.57</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>247–283</td>
<td>$3.99 \times 10^{-3}$</td>
<td>0.50</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>283–323</td>
<td>$3.12 \times 10^{-3}$</td>
<td>0.46</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>323–365</td>
<td>$2.28 \times 10^{-3}$</td>
<td>0.44</td>
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<td>4.6</td>
</tr>
<tr>
<td>365–409</td>
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<td>0.44</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>409–458</td>
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<td>7.9</td>
</tr>
<tr>
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<td>8.6</td>
</tr>
<tr>
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<td>9.0</td>
</tr>
<tr>
<td>570–629</td>
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<td>9.9</td>
</tr>
<tr>
<td>629–691</td>
<td>$1.64 \times 10^{-4}$</td>
<td>0.82</td>
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<td>9.7</td>
</tr>
<tr>
<td>691–769</td>
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<td>11</td>
</tr>
<tr>
<td>769–1000</td>
<td>$3.78 \times 10^{-5}$</td>
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<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>
Table A.7: Normalized $t\bar{t}$ differential cross section measurements with respect to the $S_T$ variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$S_T$ (GeV)</th>
<th>$1/\sigma \frac{d\sigma}{dS_T}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>146–277</td>
<td>$1.10 \times 10^{-3}$</td>
<td>0.84</td>
<td>6.3</td>
<td>6.3</td>
</tr>
<tr>
<td>277–319</td>
<td>$3.61 \times 10^{-3}$</td>
<td>0.71</td>
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<td>5.9</td>
</tr>
<tr>
<td>319–361</td>
<td>$3.82 \times 10^{-3}$</td>
<td>0.54</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>361–408</td>
<td>$3.24 \times 10^{-3}$</td>
<td>0.46</td>
<td>0.80</td>
<td>0.92</td>
</tr>
<tr>
<td>408–459</td>
<td>$2.41 \times 10^{-3}$</td>
<td>0.48</td>
<td>2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>459–514</td>
<td>$1.66 \times 10^{-3}$</td>
<td>0.57</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>514–573</td>
<td>$1.07 \times 10^{-3}$</td>
<td>0.69</td>
<td>9.0</td>
<td>9.1</td>
</tr>
<tr>
<td>573–637</td>
<td>$6.65 \times 10^{-4}$</td>
<td>0.74</td>
<td>9.6</td>
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<tr>
<td>637–705</td>
<td>$4.03 \times 10^{-4}$</td>
<td>0.71</td>
<td>10</td>
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<tr>
<td>705–774</td>
<td>$2.43 \times 10^{-4}$</td>
<td>0.73</td>
<td>11</td>
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<tr>
<td>774–854</td>
<td>$1.44 \times 10^{-4}$</td>
<td>0.88</td>
<td>9.3</td>
<td>9.4</td>
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<tr>
<td>854–940</td>
<td>$8.21 \times 10^{-5}$</td>
<td>1.2</td>
<td>8.9</td>
<td>9.0</td>
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<tr>
<td>940–1200</td>
<td>$3.15 \times 10^{-5}$</td>
<td>1.5</td>
<td>9.2</td>
<td>9.4</td>
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Table A.8: Normalized $t\bar{t}$ differential cross section measurements with respect to the $p_T^W$ variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

<table>
<thead>
<tr>
<th>$p_T^W$ (GeV)</th>
<th>$1/\sigma \frac{d\sigma}{dp_T^W}$ (GeV$^{-1}$)</th>
<th>± stat. (%)</th>
<th>± syst. (%)</th>
<th>Rel. uncert. (%)</th>
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<tbody>
<tr>
<td>0–27</td>
<td>$3.61 \times 10^{-3}$</td>
<td>0.54</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>27–52</td>
<td>$8.56 \times 10^{-3}$</td>
<td>0.40</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>52–78</td>
<td>$9.23 \times 10^{-3}$</td>
<td>0.34</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>78–105</td>
<td>$7.02 \times 10^{-3}$</td>
<td>0.40</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>105–134</td>
<td>$4.29 \times 10^{-3}$</td>
<td>0.50</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>134–166</td>
<td>$2.22 \times 10^{-3}$</td>
<td>0.55</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>166–200</td>
<td>$1.04 \times 10^{-3}$</td>
<td>0.67</td>
<td>9.6</td>
<td>9.6</td>
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<tr>
<td>200–237</td>
<td>$4.66 \times 10^{-4}$</td>
<td>0.94</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>237–300</td>
<td>$1.69 \times 10^{-4}$</td>
<td>1.2</td>
<td>16</td>
<td>16</td>
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</tbody>
</table>
B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth\textsuperscript{1}, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler\textsuperscript{1}, V. Knünz, A. König, M. Krammer\textsuperscript{1}, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady\textsuperscript{2}, B. Rahbaran, H. Rohringer, J. Schieck\textsuperscript{1}, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz\textsuperscript{1}

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
Universidade Estadual Paulista\textsuperscript{a}, Universidade Federal do ABC\textsuperscript{b}, S\~ao Paulo, Brazil
S. Ahuja\textsuperscript{a}, C.A. Bernardes\textsuperscript{b}, A. De Souza Santos\textsuperscript{b}, S. Dogra\textsuperscript{a}, T.R. Fernandez Perez Tomei\textsuperscript{a}, E.M. Gregores\textsuperscript{b}, P.G. Mercadante\textsuperscript{b}, C.S. Moon\textsuperscript{a,8}, S.F. Novaes\textsuperscript{a}, Sandra S. Padula\textsuperscript{a}, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger\textsuperscript{10}, M. Finger Jr.\textsuperscript{10}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
M. El Sawy\textsuperscript{11,12}, E. El-khateebe\textsuperscript{13}, T. Elkafrawy\textsuperscript{13}, A. Mohamed\textsuperscript{14}, Y. Mohammed\textsuperscript{15}, E. Salama\textsuperscript{13,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva
IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, École Polytechnique, IN2P3-CNRS, Palaiseau, France

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Tbilisi State University, Tbilisi, Georgia
Z. Tamaladze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez
The CMS Collaboration


University of Hamburg, Hamburg, Germany

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath\textsuperscript{20}, F. Sikler, V. Veszpremi, G. Vesztergombi\textsuperscript{21}, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czeleér, J. Karancsi\textsuperscript{22}, J. Molnar, Z. Szillası

University of Debrecen, Debrecen, Hungary
M. Bartók\textsuperscript{23}, A. Makovec, P. Raics, Z.L. Trocsányi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami, A. Fahim, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy

INFN Sezione di Catania, Università di Catania, Catania, Italy
G. Cappello, M. Chiorboli, S. Costa, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbagli, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, S. Gonzi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, A. Tropiano, L. Viliani

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbrì, D. Piccolo, F. Primavera
INFIN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli, F. Ferro, M. Lo Vetere, M.R. Monge, E. Robutti, S. Tosi

INFIN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy

INFIN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy

INFIN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy

INFIN Sezione di Pavia, Università di Pavia, Pavia, Italy
A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

INFIN Sezione di Perugia, Perugia, Italy
L. Alunni Solestizi, M. Biasini, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, G. Mantovani, M. Menichelli, A. Saha, A. Santocchia, A. Spiezia

INFIN Sezione di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy

INFIN Sezione di Roma, Università di Roma, Roma, Italy

INFIN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy

INFIN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, A. Schizzi, A. Zanetti
<table>
<thead>
<tr>
<th>Institution</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kangwon National University, Chunchon, Korea</td>
<td>A. Kropivnitskaya, S.K. Nam</td>
</tr>
<tr>
<td>Kyungpook National University, Daegu, Korea</td>
<td>D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son</td>
</tr>
<tr>
<td>Chonbuk National University, Jeonju, Korea</td>
<td>J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Kim</td>
</tr>
<tr>
<td>Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea</td>
<td>S. Song</td>
</tr>
<tr>
<td>Seoul National University, Seoul, Korea</td>
<td>H.D. Yoo</td>
</tr>
<tr>
<td>Sungkyunkwan University, Suwon, Korea</td>
<td>Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu</td>
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<tr>
<td>Vilnius University, Vilnius, Lithuania</td>
<td>A. Juodagalvis, J. Vaitkus</td>
</tr>
<tr>
<td>Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico</td>
<td>E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez</td>
</tr>
<tr>
<td>Universidad Iberoamericana, Mexico City, Mexico</td>
<td>S. Carrillo Moreno, F. Vazquez Valencia</td>
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<tr>
<td>Benemerita Universidad Autonoma de Puebla, Puebla, Mexico</td>
<td>I. Pedraza, H.A. Salazar Ibarguen</td>
</tr>
<tr>
<td>Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico</td>
<td>A. Morelos Pineda</td>
</tr>
<tr>
<td>University of Auckland, Auckland, New Zealand</td>
<td>D. Krofcheck</td>
</tr>
<tr>
<td>University of Canterbury, Christchurch, New Zealand</td>
<td>P.H. Butler</td>
</tr>
<tr>
<td>National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan</td>
<td>A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib</td>
</tr>
</tbody>
</table>
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vasiliev, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin, L. Dudko, A. Gribushin, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Myagkov, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, M. Ekmedzic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, B. Isildak53, G. Karapinar54, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E.A. Albayrak55, E. G¨ulmez, M. Kaya56, O. Kaya57, T. Yetkin58

Istanbul Technical University, Istanbul, Turkey
K. Cankocak, S. Sen59, F.I. Vardarli

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio
Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli,

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
S. Malik

Purdue University, West Lafayette, USA

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak
Rice University, Houston, USA

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

The Rockefeller University, New York, USA
L. Demortier

Rutgers, The State University of New Jersey, Piscataway, USA

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Beni-Suef University, Bani Sweif, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Zewail City of Science and Technology, Zewail, Egypt
15: Now at Fayoum University, El-Fayoum, Egypt
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Tbilisi State University, Tbilisi, Georgia
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at University of Debrecen, Debrecen, Hungary
23: Also at Wigner Research Centre for Physics, Budapest, Hungary
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, USA
32: Now at Hanyang University, Seoul, Korea
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
42: Also at National Technical University of Athens, Athens, Greece
43: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
46: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
47: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
48: Also at Adiyaman University, Adiyaman, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Cag University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Gaziosmanpasa University, Tokat, Turkey
53: Also at Ozyegin University, Istanbul, Turkey
54: Also at Izmir Institute of Technology, Izmir, Turkey
55: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Yildiz Technical University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Utah Valley University, Orem, USA
64: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
65: Also at Argonne National Laboratory, Argonne, USA
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea