Measurement of the t[bar over t] Production Cross Section in pp Collisions at √s = 7 TeV with Lepton + jets Final States

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Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV with lepton + jets final states ☆

CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV is presented. The results are based on data corresponding to an integrated luminosity of 2.3 fb^{-1} collected by the CMS detector at the LHC. Selected events are required to have one isolated, high transverse momentum electron or muon, large missing transverse energy, and hadronic jets, at least one of which must be consistent with having originated from a b quark. The measured cross section is $158.1 \pm 2.1\,(stat.) \pm 10.2\,(syst.) \pm 3.5\,(lum.)$ pb, in agreement with standard model predictions.

1. Introduction

Since the discovery of the top quark at the Fermilab Tevatron collider [1,2], considerable advances have been made in understanding its production rates and decay properties in $p\bar{p}$ collisions. The advent of pp collisions at the Large Hadron Collider (LHC) [3] has started a new phase of top quark physics, and the first measurement at the higher center-of-mass energy of 7 TeV was the top quark pair production cross section [4–7]. A precise measurement of the $t\bar{t}$ cross section provides constraints for QCD calculations presently available up to approximate next-to-next-to-leading order (NNLO) [8–11]. It is also important for probing new physics processes that can manifest themselves as an enhancement of the $t\bar{t}$ production rate.

In this Letter, we present a precise measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV utilizing a data set corresponding to an integrated luminosity of 2.3 fb^{-1} recorded by the Compact Muon Solenoid (CMS) experiment at the LHC.

In the standard model (SM), top quarks are produced in pp collisions predominantly via the strong interaction as $t\bar{t}$ pairs, with each top quark decaying almost exclusively into a W boson and a bottom quark. In the analysis presented here, $t\bar{t}$ events are identified in final states in which one of the W bosons decays into a quark pair and the other into a charged lepton (electron or muon) and a neutrino, resulting in events that contain an electron or a muon, a neutrino, and four hadronic jets, two of which result from hadronization of the b and $\bar{b}$ quarks (b-jets). In order to improve the purity of the $t\bar{t}$ candidate event sample, we employ b-tagging algorithms, which are optimized for identification of b-jets. Decays of W bosons into τ leptons are not specifically selected in this analysis, albeit some events enter the event sample due to leptonic decays of the τ.

The technique for measuring the $t\bar{t}$ cross section from the candidate event sample consists of a simultaneous profile likelihood fit to the distribution of invariant masses of particles belonging to identified displaced vertices. These fits are performed as a function of the jet and b-tag multiplicities in the event. The method is similar to the one that was used in a previous CMS measurement [4], though a larger data sample is now studied. Several alternative methods have been employed. In one of these, we perform an inclusive measurement of $t\bar{t}$ production cross section without b-jet identification requirement, while others incorporate different b-tagging algorithms.

2. The CMS detector

The characteristic feature of the CMS detector is a superconducting solenoid of 6 m in diameter, providing an axial magnetic

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* *E-mail address:* cms-publication-committee-chair@cern.ch.

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field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip subdetectors, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan\theta/2]$, with θ being the polar angle of the trajectory of the particle with respect to the counterclockwise-beam direction. Within the field volume, the silicon detectors are surrounded by a crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter that provide high resolution energy measurement of photons, electrons and hadronic jets. Muon detection systems are located outside of the solenoid and embedded in the steel return yoke. They provide muon detection in the range $|\eta| < 2.4$. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A detailed description of the CMS detector can be found in Ref. [12].

3. Event selection

The sample of candidate $\mathrm{t\bar{t}}$ events is collected using dedicated triggers, which require either a muon with transverse momentum (p_T) larger than 30 GeV or a high-p_T electron. The criteria for the electron trigger evolved during the course of data-taking in order to maintain a reasonable trigger rate as the instantaneous luminosity of the LHC increased. For the initial data set, corresponding to an integrated luminosity 0.9 fb^{-1}, the threshold on the p_T of electron candidates varied between 27 and 32 GeV. For the second part of the data set (1.4 fb^{-1}) the trigger required the presence of an electron with $p_\mathrm{T} > 25$ GeV and at least three hadronic jets with $p_\mathrm{T} > 30$ GeV.

The recorded events are reconstructed using the CMS particle-flow algorithm [13], which categorizes observable particles into muons, electrons, photons, charged and neutral hadrons. Energy calibration is performed separately for each particle type. In the offline selection, muons are required to have a good-quality track with $p_\mathrm{T} > 35$ GeV and $|\eta| < 2.1$, and the reconstructed tracks in the silicon tracker are consistent with the track information from the muon systems [14]. Electrons are identified using a combination of the shower shape information in electromagnetic calorimeter and track-cluster matching [15], and are required to have $p_\mathrm{T} > 35$ GeV and $|\eta| < 2.5$. Electron candidates in the transition region between the barrel and forward electromagnetic calorimeters, $1.44 < |\eta| < 1.57$, are not used for the measurement. We also reject electrons coming from photon conversions [15].

Since the lepton from a W decay is expected to be isolated from other activity in the event, we apply isolation requirements. The relative isolation is defined as $I_\mathrm{rel} = (\sum E_\mathrm{T}^\mathrm{charged} + \sum E_\mathrm{T}^\mathrm{photon} + \sum E_\mathrm{T}^\mathrm{neutral})/p_\mathrm{T}$, where p_T is the lepton transverse momentum, and $E_\mathrm{T}^\mathrm{charged}$, $E_\mathrm{T}^\mathrm{photon}$, and $E_\mathrm{T}^\mathrm{neutral}$ are transverse energies of the charged particles, the reconstructed photons, and the neutral particles not identified as photons. The sum of the transverse energies is computed in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the lepton direction, excluding the lepton candidate itself. We require I_rel to be less than 0.125 for muons and 0.10 for electrons.

The signal events are required to have only one electron or muon whose origin is consistent with the reconstructed primary pp interaction vertex [16], defined as the vertex with the largest value for the scalar sum of the p_T of the associated tracks. Events with an additional electron or muon candidate that satisfies less strict lepton identification requirements are vetoed.

Jets are reconstructed using the particle-flow algorithm and are clustered using the anti-k_T jet technique [17] with a distance parameter of 0.5, as implemented in FastJet v2.4.2 [18,19]. In order to account for extra activity within a jet cone from multiple pp interactions per beam crossing, referred to as a pileup, jet energies are corrected for charged hadrons that originate from a vertex other than the primary one, and for the amount of pileup expected in the jet area from neutral jet constituents. Jet energies are also corrected for non-linearities due to different responses in the endcap and barrel calorimeters, and differences between true and simulated calorimeter responses [20]. Each jet is required to have a transverse momentum $p_\mathrm{T} > 35$ GeV and $|\eta| < 2.4$. We select events with at least one jet, or at least three jets for events collected with the electron + jets trigger. To reduce background processes, we require at least one of the jets to be identified as a b-jet by a displaced secondary vertex algorithm known as *Simple Secondary Vertex High Efficiency* [21] with a medium working point. The algorithm has a b-tag efficiency of 55% and a light parton (u, d, s, g) mistag rate of 1.5%.

In addition, events are required to have a significant amount of missing transverse energy ($\not\!\!E_\mathrm{T}$) as evidence of a neutrino from the W boson decay. This is defined as the magnitude of the negative vector sum of the transverse momenta of all of the objects found by the particle-flow algorithm. We require $\not\!\!E_\mathrm{T} > 20$ GeV for both the electron + jets and muon + jets channels.

4. Signal and background modeling

Pair production of top quarks is modeled using the MadGraph v5.1.1 [22] Monte Carlo (MC) event generator, assuming the mass of the top quark $m_\mathrm{t} = 172.5$ GeV. The top quark pairs are generated with up to three additional hard jets using pythia v6.424 with tune Z2 [23] to model parton-showering (PS), and the shower matching is performed using the k_T-MLM prescription [22]. The generated events are further passed through the full CMS detector simulation based on Geant4 [24]. The presence of pileup is incorporated by simulating additional interactions with a multiplicity matching that observed in data.

Leptonically decaying W + jets events constitute by far the largest background. These together with Z + jets events are also generated using MadGraph with up to four jets subject to the matrix-element (ME) description. The W + jets events are generated inclusively with respect to jet flavor. Reconstructed jets are further matched to partons in the simulation, and the W + bottom quark and W + charm quark components are separated from the W + light-flavor (u, d, s, and gluon) component based on the parton flavor.

Other backgrounds include single-top-quark production, simulated with powheg v1.0 [25–27], QCD multijet simulated with pythia, and photon + jet events, which constitute a background for the electron + jets channel, generated by MadGraph. The set of parton distribution functions used by MadGraph is CTEQ6L1 [28], while powheg and pythia use CTEQ6M [28].

The W and Drell–Yan production processes are normalized based on NNLO cross sections, determined using fewz [29]. They correspond to $\sigma_{\mathrm{W}\to\ell\nu} = 31.3 \pm 1.6$ nb and $\sigma_{\mathrm{Z}/\gamma^*\to\ell\ell} = 3048 \pm 132$ pb, where for the Drell–Yan production the invariant mass of two leptons ($\ell = \mathrm{e}$ or μ) is greater than 50 GeV. The single-top-quark t-channel production is normalized to the recent CMS measurement of $\sigma_\mathrm{t} = 67.2 \pm 6.1$ pb [30]. The single-top-quark associated production (tW) is normalized to the approximate NNLO cross section $\sigma_\mathrm{tW} = 15.7 \pm 1.2$ pb [31], and the s-channel is normalized to the next-to-next-to-leading-logarithm prediction of $\sigma_\mathrm{t} = 4.6 \pm 0.2$ pb [32].

The QCD multijet normalization is obtained by fitting SM contributions to the full $\not\!\!E_\mathrm{T}$ distribution in data, though only the yield of QCD multijet events with $\not\!\!E_\mathrm{T} > 20$ GeV enters the normalization. For the electron + jets channel, the QCD multijet background distributions are obtained from MC, and for the muon + jets channel, they are obtained from a background-enriched data sample defined as $I_\mathrm{rel} > 0.125$ and $\not\!\!E_\mathrm{T} < 20$ GeV.

5. Cross section measurement

The $t\bar{t}$ cross section measurement is performed using a maximum profile likelihood fit to the number of reconstructed jets (N_{jet}), the number of b-tagged jets (N_{tag}), and the secondary vertex mass (SVM) distribution in the data. We consider ten event subsamples with N_{jet} values of 1–4 and $\geqslant 5$, and N_{tag} values of 1 and $\geqslant 2$. The SVM is defined as the mass of the sum of four-vectors of the tracks associated to the secondary vertex with an assumption that all particles have the pion mass. For events with two b-tagged jets, SVM corresponds to the highest-p_{T} b-tagged jet. The SVM distribution yields a good discrimination between the contributions from light- and heavy-flavor quark production [4]. The results are obtained by maximizing a binned Poisson likelihood that incorporates contributions from $t\bar{t}$, W + jets, Z + jets, single-top-quark, and QCD multijet production processes. Performing a simultaneous fit across different jet and b-tag multiplicity bins, including regions dominated by background events, constrains the background contributions, resulting in a more precise measurement of the $t\bar{t}$ production cross section.

The W + jets, Z + jets, and single-top-quark background processes are initially normalized to the expected event yields according to their theoretical cross sections. The QCD and photon + jets normalizations are evaluated as described above individually in each N_{jet} and N_{tag} sub-sample, for both channels. These background normalizations are the initial values that enter the profile likelihood fit. The cross section measurement is performed by fitting to the data to obtain corrections to these initial values. The W + jets backgrounds are split into W + b jets, W + c jets, and W + light-flavor (LF) sub-samples, with all three components free in the fit. During the likelihood maximization, the normalizations of each of these components are extracted. The normalizations of the $t\bar{t}$ and W + jets contributions are allowed to float freely. The contributions from small backgrounds, QCD multijet and Z + jets, are conservatively constrained with Gaussian uncertainties of 100% and 30% of their expected event yields, respectively. The single-top-quark contribution is constrained with an uncertainty of 10% [30].

The expected event yield for each background component, per N_{jet} and N_{tag}, is also a function of other parameters, such as the jet energy scale (JES), the b-tagging efficiency and the mistag rate. In addition, the N_{jet} spectrum is affected by the choice of the renormalization and factorization (Q^2) scales. For the W + jets simulation we use a dynamical mass scale of $(m_{\text{W}})^2 + (\sum p_{\text{T}}^{\text{jet}})^2$, where m_{W} is the mass of the W and $\sum p_{\text{T}}^{\text{jet}}$ is the sum of the transverse momenta from the jets in the event. The magnitude of the scale is allowed to vary in the fit by incorporating an effective parameter c_{Q^2} into the likelihood with initial value 1.0, and which is allowed to vary between 0.5 and 2.0. The profile likelihood maximization provides simultaneous measurements of each of these parameters, background contributions and the $t\bar{t}$ cross section.

There are alternative control samples to estimate the JES, the b-tagging efficiency and the mistag rate. The JES uncertainty is measured in control samples to be approximately 3% [20], and this determines a Gaussian constraint on this parameter in the likelihood. To account for differences between simulation and data in the b-tagging efficiencies and the mistag rates, we weight the tagged jets in the simulation up or down by a data-to-simulation scale factor. The b-tagging efficiency and the mistag rate scale factors are constrained to be 1.0 ± 0.1 in the fit, where 10% is the uncertainty in the b-tagging efficiency and the mistag rate [21].

The systematic uncertainties related to JES, Q^2 scale, b-tagging and mistag scale factors are included as nuisance parameters in the profile likelihood fit. Other systematic uncertainties are not directly included in the profile likelihood and taken as additional systematic uncertainties outside of the fit result and are described below.

The efficiencies for triggering, reconstructing, and identifying isolated leptons are determined using $\text{Z} \to \text{ee}$ and $\text{Z} \to \mu\mu$ samples of events, and found to be very similar in the data and simulation. We correct for small differences observed, and account for an additional systematic uncertainty of 3% on these values. The unclustered energy in the detector results in an additional resolution uncertainty of less than 1% on the $\not{E}_{\text{T}}$ scale. The difference in jet energy resolution determined in simulation and data results in an uncertainty of less than 1%.

The theoretical uncertainties in modeling of $t\bar{t}$ production are evaluated from dedicated simulated event samples by varying the theoretical parameters of interest around their nominal values. Such variations are used to construct alternative distributions, from which simulated events can be generated. For each variation, 4000 pseudo-experiments are generated and fitted with the standard configuration. The mean bias of the fitted $t\bar{t}$ cross section is taken as the size of the systematic uncertainty due to the source under study. These include differences in the $t\bar{t}$ signal due to renormalization and factorization scales (4%), the scale for the ME partons to PS matching scheme (2%), pileup modeling in simulation (less than 1%), and the parton distribution function model (less than 1%). The total uncertainty for the $t\bar{t}$ modeling, when adding the above uncertainties in quadrature, is 5.0%.

The systematic uncertainty on the SVM shape is also considered. We have studied several effects, which include pixel resolution and jet-track-association modeling, as well as pileup dependence. These have a negligible effect on the SVM shapes of $t\bar{t}$, single-top-quark, W and Z + jets events. The uncertainty on the SVM shape from QCD multijet background is obtained as follows. For the electron + jets channel we generate pseudo-experiments based on the default and alternative QCD shapes obtained from simulation. To increase the statistical accuracy of the QCD multijet background, the default shape employed in the fit is taken from events with relaxed requirements on the electron isolation and identification, and no $\not{E}_{\text{T}}$ requirement imposed. The alternative shape is obtained from the region corresponding to the event selection used in the $t\bar{t}$ cross section measurement. For the muon + jets channel, the statistical fluctuations in the normalization for the $\not{E}_{\text{T}}$ distributions obtained from muon non-isolated ($I_{\text{rel}} > 0.125$) and isolated ($I_{\text{rel}} < 0.125$) regions are taken as the systematic uncertainty. The integrated luminosity of the event sample is determined with an uncertainty of 2.2% [33].

The list of systematic uncertainties is summarized in Table 1. These include both the uncertainties related to the nuisance parameters in the likelihood fit and the additional uncertainties evaluated from alternative distributions as described above. The individual systematic uncertainties related to the nuisance parameters in the fit are shown for illustrative purposes only. These are obtained as follows. First, the total fit uncertainty is evaluated when the parameter of interest is fixed in the fit. Then this uncertainty is subtracted in quadrature from the total fit uncertainty when all parameters are varied in the fit. Since the treatment of the Q^2 uncertainty in the likelihood fit is dependent on parametrization, we also performed the cross-check with the Q^2 uncertainty treated outside of the fit, and obtained consistent results. The combined systematic uncertainty of the measurement is 6.5%, taking into account the correlations between the nuisance parameters.

The measurement is performed separately for the electron + jets and muon + jets channels, as well as simultaneously for both channels, yielding

Electron + jets

$$\sigma_{t\bar{t}} = 160.6 \pm 3.2\,(\text{stat.}) \pm 11.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \qquad (1)$$

Table 1
List of systematic uncertainties for the electron + jets, muon + jets, and the combined analysis. Due to the correlation between the fit parameters, the combined number is not the root of the quadratic sum of the contributions.

Source	Electron channel	Muon channel	Combined analysis
Quantity	Uncertainty (%)		
Lepton ID/reconstruction/trigger efficiency	3.0	2.0	3.0
$\not\!\!E_T$ resolution due to unclustered energy	0.9	0.3	0.8
Jet energy resolution	0.5	0.5	0.6
$t\bar{t}$ + jets renorm./fact. scales	3.5	4.3	4.3
$t\bar{t}$ + jets ME to PS matching	2.2	1.8	2.2
Pileup	0.5	0.2	0.6
Parton distribution function choice	0.3	0.3	0.3
QCD multijet SVM distribution	1.4	0.4	0.6
Subtotal	5.5	5.1	5.9
Nuisance parameter	Uncertainty (%)		
Jet energy scale	3.9	3.0	2.4
b-tagging efficiency and mistag rate	3.5	2.8	2.1
W + jets renorm./fact. scale	1.6	1.5	1.6
Total systematic uncertainty	7.0	6.2	6.5

Muon + jets

$$\sigma_{t\bar{t}} = 164.2 \pm 2.8\,(\text{stat.}) \pm 10.1\,(\text{syst.}) \pm 3.6\,(\text{lum.})\ \text{pb}, \quad (2)$$

and

Combined

$$\sigma_{t\bar{t}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}. \quad (3)$$

The comparison of the corresponding observed and fitted SVM distributions is shown in Figs. 1 and 2. As a by-product, the fit provides the size of contributions from the SM processes that are backgrounds to $t\bar{t}$ production, as well as in-situ evaluations of other parameters varied in the profile likelihood fit, such as the b-tagging efficiency and the JES correction factor (on top of the standard jet corrections). The results of the combined fit, as well as the results of the fits performed in the electron + jets and muon + jets samples separately, are listed in Table 2, with correlations among parameters shown in Table 3. The $t\bar{t}$ cross section is given in pb, while the contributions from other standard model processes are quoted as scale factors with respect to their theoretical predictions described above. These measured scale factors do not account for a full treatment of the systematic uncertainties and hence are strictly valid only in the context of the fit presented in this Letter. The b-tagging scale factor defined as the ratio of the b-tagging efficiencies in data and simulation is determined to be $96 \pm 1\%$, consistent between the electron + jets and muon + jets channels. The JES correction factor is found to be $100.4 \pm 1.6\%$ and $98.1 \pm 1.2\%$ in the electron + jets and muon + jets channels, respectively, yielding $100.2 \pm 1.0\%$ in the combined fit.

The W + c jets contribution in the data is found to be larger than SM predictions, both in the electron + jets and muon + jets channels. This contribution includes single charm and double charm production, which are both present in the selected events. The W + b jets contribution in the data is also found to be slightly higher than in the simulation. The W + LF jets scale factor in the electron channel is significantly lower than in the muon case. This is because of the presence of a much larger QCD multijet contribution in the electron sample, and its large correlation with the W + LF jets component. The combined W + LF jets/QCD multijet scale factors for muons and electrons are in agreement, being $0.84 \pm 0.09\%$ and $0.71 \pm 0.07\%$, respectively.

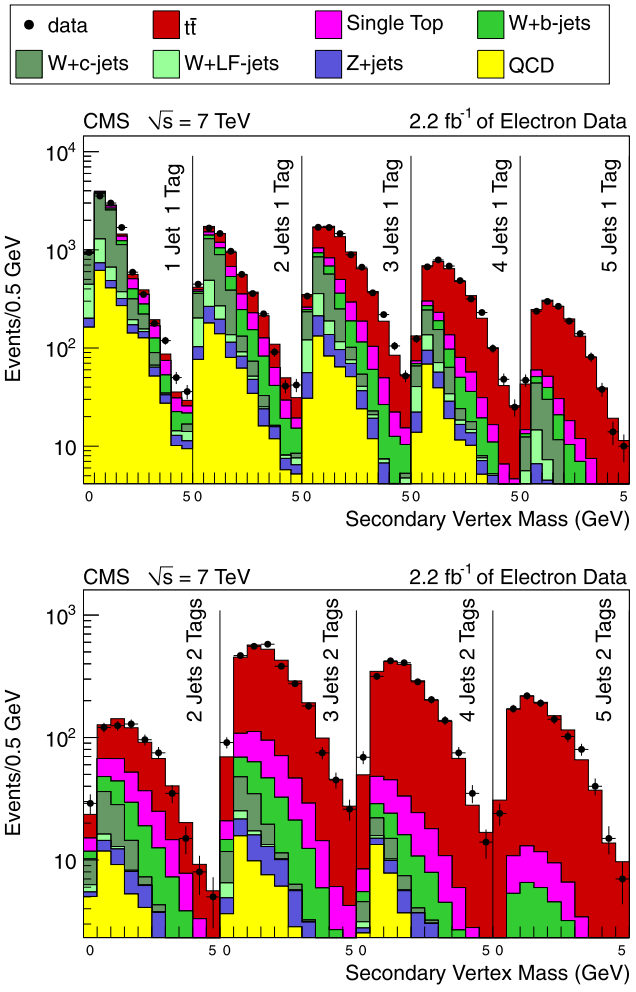

Fig. 1. Results of the combined fit for the electron + jets channel, for single b-tag events (top panel), and for ⩾2b-tag events (bottom panel). The distributions within each panel correspond to events with 1-, 2-, 3-, 4-, and ⩾5-jets, respectively. The error bars indicate statistical uncertainties only.

Table 2
Results of the fit to the combined electron + jets and muon + jets sample, and each channel individually. The contributions from the background processes are quoted as scale factors with respect to their theoretical predictions. The scale factors do not account for a full treatment of the systematic uncertainties and are strictly valid only in the context of the fit. For brevity, the QCD parameters are not shown.

Fit parameters	Electron + jets	Muon + jets	Combined
$\sigma_{t\bar{t}}$ (pb)	160.6 ± 6.6	164.2 ± 5.5	158.1 ± 4.1
Single top	1.05 ± 0.10	1.08 ± 0.10	1.17 ± 0.10
W + b jets	1.19 ± 0.35	0.95 ± 0.18	1.28 ± 0.16
W + c jets	1.54 ± 0.15	1.48 ± 0.05	1.55 ± 0.04
W + LF jets	0.20 ± 0.08	0.57 ± 0.07	0.52 ± 0.06
Z + jets	1.13 ± 0.29	1.08 ± 0.29	1.43 ± 0.29
c_{Q^2}	1.02 ± 0.16	0.94 ± 0.06	1.05 ± 0.05
b-tag	0.95 ± 0.01	0.97 ± 0.01	0.96 ± 0.01
JES	1.00 ± 0.02	0.98 ± 0.01	1.00 ± 0.01
Mistag	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10

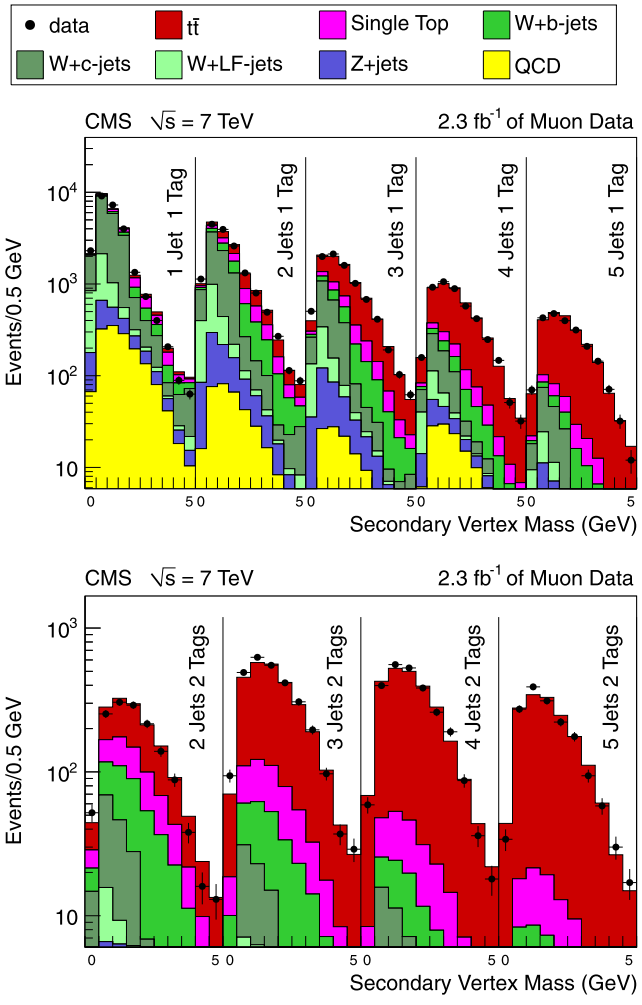

Fig. 2. Results of the combined fit for the muon + jets channel, for single b-tag events (top panel), and for ⩾2b-tag events (bottom panel). The distributions within each panel correspond to events with 1-, 2-, 3-, 4-, and ⩾5-jets, respectively. The error bars indicate statistical uncertainties only.

Because of large correlated uncertainties and due to differences in the correlation matrix for the electron + jets and muon + jets channels, which result from different QCD multi jet contributions in the two channels, the result of the combined fit resides outside of the individual electron + jets and muon + jets measurements. The correlation matrix for the combined fit is given in Table 3. Using 4000 alternative data sets constructed from the simulated events we determine that the combined cross section lies between the individual channel results only in 60% of the cases. For the combined fit we have seven out of ten parameters that are common to both channels, residing outside of the $\pm 1\sigma$ interval between individual electron + jets and muon + jets measurements. Using simulated events we determine this to occur in 10% of the cases.

The $t\bar{t}$ cross section is measured assuming a value of the top quark mass $m_t = 172.5$ GeV. The measured cross section of $t\bar{t}$ production has a dependence on m_t, which is evaluated using dedicated MC samples and can be parameterized in the range of 160–185 GeV as

$$\sigma_{t\bar{t}} = 158.1 \text{ pb} - (m_t - 172.5 \text{ GeV}) \times (1.14 \pm 0.18 \text{ pb/GeV}). \quad (4)$$

6. Alternative analyses

In addition to the main result, we have performed several alternative analyses in the electron + jets and the muon + jets channels using different event selections and different methods to suppress background contributions and measure the $t\bar{t}$ cross section. One analysis does not rely on b-tagging, a second one makes use of the kinematical information from the top quark decays, and a third one relies on a data-based estimate of the dominant background.

The analysis without relying on use of the b-tagging algorithms considers the data set corresponding to 4.6 fb^{-1} (4.9 fb^{-1}) in the electron (muon) + jets channel. The selected events are required to have an electron with $p_T > 35$ GeV or a muon with $p_T > 26$ GeV, and at least 4 jets with $p_T > 30$ GeV. No missing transverse energy requirement is imposed.

The cross section is measured using a binned log-likelihood fit to the mass of the three-jet combination with the highest p_T in the event (M_3). The $t\bar{t}$, W/Z + jets, and QCD multijet components are unconstrained during the fit, with the QCD multijet contributions in the electron + jets and muon + jets channels treated independently. The single-top-quark normalization is constrained to within 30% of its theoretical value.

The $t\bar{t}$, single-top-quark, and W/Z + jets processes are modeled using the simulation, while the QCD multijet contribution is estimated from data using a side-band region with the relative isolation of the lepton greater than 0.25. Signal events, as well as W + jets events, are heavily suppressed by this selection, and subtracted based on simulation. The shape of the subtracted QCD multijet contribution is used for the fit in the signal region, since the M_3 distribution of QCD events does not depend on the relative isolation of the lepton in the event.

Table 3
Correlation matrix of the combined fit to the electron + jets plus muon + jets samples. Only non-QCD parameters are shown.

	$t\bar{t}$	Single t	W + b	W + c	W + LF	Z + jets	c_{Q^2}	b-tag	JES	Mistag
$t\bar{t}$	1.00	−0.13	−0.48	0.33	0.03	0.07	−0.07	−0.70	−0.81	0.00
Single t	−0.13	1.00	−0.52	0.04	0.03	−0.03	0.06	−0.08	0.09	−0.00
W + b	−0.48	−0.52	1.00	0.05	0.13	−0.16	0.27	0.26	0.42	−0.02
W + c	0.33	0.04	0.05	1.00	0.01	0.15	0.71	−0.38	−0.26	−0.02
W + LF	0.03	0.03	0.13	0.01	1.00	−0.19	0.21	−0.03	−0.05	−0.83
Z + jets	0.07	−0.03	−0.16	0.15	−0.19	1.00	0.23	−0.01	−0.10	0.01
c_{Q^2}	−0.07	0.06	0.27	0.71	0.21	0.23	1.00	−0.02	0.15	−0.02
b-tag	−0.70	−0.08	0.26	−0.38	−0.03	−0.01	−0.02	1.00	0.43	−0.02
JES	−0.81	0.09	0.42	−0.26	−0.05	−0.10	0.15	0.43	1.00	0.01
Mistag	0.00	−0.00	−0.02	−0.02	−0.83	0.01	−0.02	−0.02	0.01	1.00

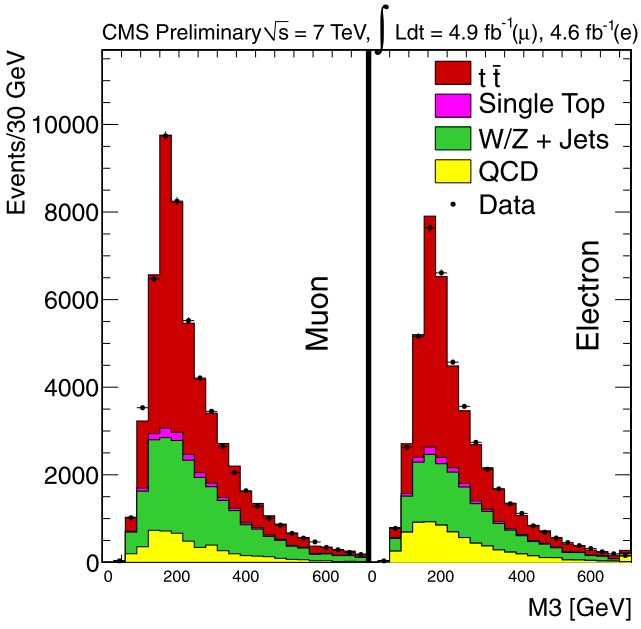

Fig. 3. The mass of the three-jet combination with the highest transverse momenta.

The observed and the fitted M_3 distributions are shown in Fig. 3. The dominant sources of systematic uncertainty are JES, ME to PS matching, and the Q^2 scale uncertainties. In the electron + jets channel the cross section measurement yields

$$\sigma_{t\bar{t}} = 157.1 \pm 3.7\,(\text{stat.})^{+17.2}_{-11.4}\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \quad (5)$$

in the muon + jets channel the cross section is measured as

$$\sigma_{t\bar{t}} = 161.6 \pm 3.5\,(\text{stat.})^{+14.8}_{-22.1}\,(\text{syst.}) \pm 3.6\,(\text{lum.})\ \text{pb}. \quad (6)$$

The combined measurement in the electron + jets and muon + jets channels yields a cross section of

$$\sigma_{t\bar{t}} = 159.7 \pm 2.6\,(\text{stat.})^{+13.1}_{-14.7}\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}. \quad (7)$$

Another measurement uses kinematic information from the leptonic top quark decay $t \to bW \to b\ell\nu_\ell$, namely the mass of the two-particle system consisting of a lepton and a jet associated with a b quark. The jet-to-parton assignment among the four leading jets is performed minimizing a least-squares residual based on the masses of the reconstructed W boson and hadronically decaying top quark in $t \to bW \to bq\bar{q}'$. The baseline event selection is similar to the reference analysis, complemented with the requirement that the jet assigned to the leptonic top quark decay is b-tagged using an algorithm based on measuring the significance of a track impact parameter [21]. The technique is applied to the muon + jets data sample, corresponding to an integrated luminosity 4.9 fb^{-1}. The result of this measurement is $\sigma_{t\bar{t}} = 162.4 \pm 5.4\,(\text{stat.})^{+7.5}_{-11.0}\,(\text{syst.}) \pm 3.6\,(\text{lum.})$ pb, where the dominant systematic uncertainty is due to the JES.

Finally, the third method does not rely on MC simulation for the W + jets background, but exploits the W charge asymmetry [34] in W + jets production at the LHC. The shape of the lepton pseudo-rapidity distribution for the W + jets component is obtained from the data by subtracting the observed distribution for ℓ^- from the one corresponding to ℓ^+. The $t\bar{t}$ cross section is measured by fitting a combination of signal and background components to the observed lepton $|\eta|$ spectrum using a data sample corresponding to an integrated luminosity of 0.9 (1.0) fb^{-1} for electron (muon) + jets. The $t\bar{t}$ cross section is measured with a large expected uncertainty of 42% (23%) in the electron (muon) + jets channel, and agrees with the results of the other analyses.

7. Summary

The $t\bar{t}$ production cross section measurement has been performed at $\sqrt{s} = 7$ TeV using the data collected with the CMS detector and corresponding to an integrated luminosity of 2.3 fb^{-1}.

The $t\bar{t}$ cross section is measured using a profile likelihood fit to the number of reconstructed jets, the number of b-tagged jets, and the secondary vertex mass distribution. The measured cross section for an assumed top quark mass of 172.5 GeV is

$$\sigma_{t\bar{t}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \quad (8)$$

which is in agreement with the QCD predictions of 164^{+10}_{-13} pb [8,9], 163^{+11}_{-10} pb [10] and 149 ± 11 pb [11] that are based on the full next-to-leading-order (NLO) matrix elements and the resummation of the leading and NLO soft logarithms.

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UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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CMS Collaboration

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka [†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

T.S. Anjos [b], C.A. Bernardes [b], F.A. Dias [a,3], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], C. Lagana [a], F. Marinho [a], P.G. Mercadante [b], S.F. Novaes [a], Sandra S. Padula [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

V. Genchev [4], P. Iaydjiev [4], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [5], D. Polic, I. Puljak [4]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran [6], S. Elgammal [7], A. Ellithi Kamel [8], M.A. Mahmoud [9], A. Radi [10,11]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [12], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram [13], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [13], F. Drouhin [13], C. Ferro, J.-C. Fontaine [13], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

F. Fassi, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici [4], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze [14]

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [15]

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann [4], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [16], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [16], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt [16], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille [17], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [4], C. Hackstein, F. Hartmann, T. Hauth [4], M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov [15], J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [18], F. Sikler, V. Veszpremi, G. Vesztergombi [19]

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty [4], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait [20], M. Maity [21], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei [22], H. Bakhshiansohi, S.M. Etesami [23], A. Fahim [22], M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [24], M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b,4], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c,4], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a,b], A. Pompili [a,b], G. Pugliese [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], R. Venditti [a,b], P. Verwilligen [a], G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], A.C. Benvenuti [a], D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], M. Meneghelli [a,b,4], A. Montanari [a], F.L. Navarria [a,b], F. Odorici [a], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], R. Travaglini [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], G. Cappello [a,b], M. Chiorboli [a,b], S. Costa [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], S. Frosali [a,b], E. Gallo [a], S. Gonzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,b]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi [25], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore [a], R. Musenich [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia [a,b], F. De Guio [a,b], L. Di Matteo [a,b,4], S. Fiorendi [a,b], S. Gennai [a,4], A. Ghezzi [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [a,b], A. Massironi [a,b], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], S. Sala [a], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], C.A. Carrillo Montoya [a], N. Cavallo [a,c], A. De Cosa [a,b,4], O. Dogangun [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a], S. Meola [a,d,26], M. Merola [a], P. Paolucci [a,4]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata (Potenza), Napoli, Italy*
[d] *Università G. Marconi (Roma), Napoli, Italy*

P. Azzi [a], N. Bacchetta [a,4], D. Bisello [a,b], A. Branca [a,b,4], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], I. Lazzizzera [a,c], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], S. Vanini [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento (Trento), Padova, Italy*

M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Torre [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], L. Fanò [a,b], P. Lariccia [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Nappi [a,b,†], F. Romeo [a,b], A. Saha [a], A. Santocchia [a,b], A. Spiezia [a,b], S. Taroni [a,b]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

P. Azzurri [a,c], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c,4], R. Dell'Orso [a], F. Fiori [a,b,4], L. Foà [a,c], A. Giassi [a], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,27], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a,28], P. Spagnolo [a], P. Squillacioti [a,4], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], D. Del Re [a,b], M. Diemoz [a], C. Fanelli [a,b], M. Grassi [a,b,4], E. Longo [a,b], P. Meridiani [a,4], F. Micheli [a,b], S. Nourbakhsh [a,b], G. Organtini [a,b], R. Paramatti [a], S. Rahatlou [a,b], M. Sigamani [a], L. Soffi [a,b]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], N. Demaria [a], C. Mariotti [a,4], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a,4], M.M. Obertino [a,c], N. Pastrone [a], M. Pelliccioni [a], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], A. Vilela Pereira [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale (Novara), Torino, Italy*

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], M. Marone [a,b,4], D. Montanino [a,b,4], A. Penzo [a], A. Schizzi [a,b]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

Korea University, Seoul, Republic of Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.H. Ansari, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

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

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin [3], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, A. Popov, L. Sarycheva [†], V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [4], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [29], M. Djordjevic, M. Ekmedzic, D. Krpic [29], J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [30], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC – Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet [5], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi [31], C. Rovelli [32], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [33], D. Spiga, A. Tsirou, G.I. Veres [19], J.R. Vlimant, H.K. Wöhri, S.D. Worm [34], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [35], P. Nef, F. Nessi-Tedaldi,

F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [36], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler [37], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci [38], S. Cerci [39], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar [40], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [41], A. Polatoz, K. Sogut [42], D. Sunar Cerci [39], B. Tali [39], H. Topakli [38], L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [43], M. Kaya [44], O. Kaya [44], S. Ozkorucuklu [45], N. Sonmez [46]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [34], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [47], K.W. Bell, A. Belyaev [47], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias,

R. Nandi, J. Nash, A. Nikitenko [36], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi [48], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp †, A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein †, P. Traczyk, V. Valuev, M. Weber

University of California, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng [49], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech [50], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko [51], C. Newman-Holmes, V. O'Dell, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [52], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

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

U. Akgun, E.A. Albayrak, B. Bilki [53], W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya [54], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok [55], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar [56], P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar

State University of New York at Buffalo, Buffalo, USA

G. Alverson *, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, L. Lusito, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

L. Antonelli, D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

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

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [57], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.
E-mail address: George.Alverson@cern.ch (G. Alverson).
† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[3] Also at California Institute of Technology, Pasadena, USA.
[4] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[5] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
[6] Also at Suez Canal University, Suez, Egypt.
[7] Also at Zewail City of Science and Technology, Zewail, Egypt.
[8] Also at Cairo University, Cairo, Egypt.
[9] Also at Fayoum University, El-Fayoum, Egypt.
[10] Also at British University in Egypt, Cairo, Egypt.
[11] Now at Ain Shams University, Cairo, Egypt.
[12] Also at National Centre for Nuclear Research, Swierk, Poland.
[13] Also at Université de Haute-Alsace, Mulhouse, France.
[14] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[15] Also at Moscow State University, Moscow, Russia.
[16] Also at Brandenburg University of Technology, Cottbus, Germany.
[17] Also at The University of Kansas, Lawrence, USA.
[18] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[19] Also at Eötvös Loránd University, Budapest, Hungary.
[20] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
[21] Also at University of Visva-Bharati, Santiniketan, India.
[22] Also at Sharif University of Technology, Tehran, Iran.
[23] Also at Isfahan University of Technology, Isfahan, Iran.
[24] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[25] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[26] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[27] Also at Università degli Studi di Siena, Siena, Italy.
[28] Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
[29] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[30] Also at University of California, Los Angeles, USA.
[31] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[32] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
[33] Also at University of Athens, Athens, Greece.
[34] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[35] Also at Paul Scherrer Institut, Villigen, Switzerland.
[36] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[37] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[38] Also at Gaziosmanpasa University, Tokat, Turkey.
[39] Also at Adiyaman University, Adiyaman, Turkey.
[40] Also at Izmir Institute of Technology, Izmir, Turkey.
[41] Also at The University of Iowa, Iowa City, USA.
[42] Also at Mersin University, Mersin, Turkey.
[43] Also at Ozyegin University, Istanbul, Turkey.
[44] Also at Kafkas University, Kars, Turkey.
[45] Also at Suleyman Demirel University, Isparta, Turkey.
[46] Also at Ege University, Izmir, Turkey.
[47] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[48] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[49] Also at University of Sydney, Sydney, Australia.
[50] Also at Utah Valley University, Orem, USA.

[51] Also at Institute for Nuclear Research, Moscow, Russia.
[52] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[53] Also at Argonne National Laboratory, Argonne, USA.
[54] Also at Erzincan University, Erzincan, Turkey.
[55] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[56] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[57] Also at Kyungpook National University, Daegu, Republic of Korea.