

Contents lists available at [ScienceDirect](http://ScienceDirect.com)

## Physics Letters B

[www.elsevier.com/locate/physletb](http://www.elsevier.com/locate/physletb)

## Search for baryon number violation in top-quark decays



CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

## Article history:

Received 6 October 2013  
 Received in revised form 7 February 2014  
 Accepted 17 February 2014  
 Available online 20 February 2014  
 Editor: M. Doser

## Keywords:

LHC  
 CMS  
 Top quark  
 Baryon number

## ABSTRACT

A search for baryon number violation (BNV) in top-quark decays is performed using pp collisions produced by the LHC at  $\sqrt{s} = 8$  TeV. The top-quark decay considered in this search results in one light lepton (muon or electron), two jets, but no neutrino in the final state. Data used for the analysis were collected by the CMS detector and correspond to an integrated luminosity of  $19.5 \text{ fb}^{-1}$ . The event selection is optimized for top quarks produced in pairs, with one undergoing the BNV decay and the other the standard model hadronic decay to three jets. No significant excess of events over the expected yield from standard model processes is observed. The upper limits at 95% confidence level on the branching fraction of the BNV top-quark decay are calculated to be 0.0016 and 0.0017 for the muon and the electron channels, respectively. Assuming lepton universality, an upper limit of 0.0015 results from the combination of the two channels. These limits are the first that have been obtained on a BNV process involving the top quark.

© 2014 The Authors. Published by Elsevier B.V. Open access under [CC BY license](http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

In the standard model (SM) of particle physics [1–3], baryon number is a conserved quantity as a consequence of an accidental symmetry of the Lagrangian. In fact, it has been proven that extremely small violations can arise from non-perturbative effects [4]. Baryon number violation (BNV) is also predicted in several scenarios of physics beyond the SM such as supersymmetry [5,6], grand unification [7], and models with black holes [8]. Furthermore, BNV is a necessary condition for the observed asymmetry between baryons and antibaryons in the Universe, assuming an evolution from a symmetric initial state [9].

Despite these compelling reasons, no direct evidence of BNV processes has been found to date. Experiments have set stringent limits on BNV in nucleon [10],  $\tau$ -lepton [11–13], c- and b-hadrons [14–16], and Z-boson [17] decays. The possibility that BNV could occur in the decay of the top quark (t) was first considered in Ref. [18], in which a very stringent bound of about  $10^{-27}$  was derived on the branching fraction of the decay  $t \rightarrow \bar{b}\bar{c}\ell^+$ , where  $\ell$  is either an electron or a muon, using the experimental bound on the proton lifetime [10]. However, more recently it has been noted [19] that cancellations between different four-fermion interactions could allow much higher rates of occurrence for the BNV decays  $t \rightarrow \bar{b}\bar{c}\mu^+$  ( $\bar{t} \rightarrow bc\mu^-$ ) and  $t \rightarrow \bar{b}\bar{u}e^+$  ( $\bar{t} \rightarrow bue^-$ ). Other BNV decays of the top quark, involving different flavors for the lep-

ton and quarks, are also discussed in Ref. [19], where in all cases they are described as four-fermion effective interactions, in which both baryon number and lepton number are violated.

In this Letter we search for evidence of such BNV top-quark decays using  $19.52 \pm 0.49 \text{ fb}^{-1}$  of pp collision data at  $\sqrt{s} = 8$  TeV, collected in 2012 with the Compact Muon Solenoid (CMS) detector [20] at the Large Hadron Collider (LHC). These decays are referred to as “BNV decays” in the following, as opposed to the SM decay of the top quark into a W boson and a down-type quark, the latter being a bottom quark in about 99.8% of the cases. Assuming that the BNV decay branching fraction ( $\mathcal{B}$ ) is  $\ll 1$ , the most suitable process for its observation is expected to be pair production of top quarks ( $t\bar{t}$ ), where one top quark undergoes a SM decay into three jets and the other the BNV decay. This process would have the highest cross section among those involving at least one BNV decay and could be effectively separated from background. Two event selections, one for the muon and one for the electron channel, are defined and optimized for such a process. In both cases the final state consists of a lepton, five quarks, and no neutrino.

## 2. The CMS detector

The central feature of the CMS apparatus is a 3.8 T superconducting solenoid of 6 m internal diameter. Inside the coil are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter. Muons are detected by four layers of gas-ionization detectors embedded in the steel flux-return yoke. In addition

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

to the barrel and endcap detectors, CMS has extensive forward calorimetry. A two-stage trigger system selects pp collision events of interest for use in physics analyses. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the  $x$ -axis pointing to the center of the LHC ring, the  $y$ -axis pointing up (perpendicular to the LHC plane), and the  $z$ -axis pointing along the counterclockwise-beam direction. The polar angle  $\theta$  is measured from the positive  $z$ -axis and the azimuthal angle  $\phi$  is measured in the  $x$ - $y$  plane. Muons (electrons) are reconstructed and identified in the pseudorapidity ( $\eta = -\ln[\tan(\theta/2)]$ ) range  $|\eta| < 2.4$  (2.5). The pixel (strip) tracker consists of three (ten) co-axial detection layers in the central region and two (twelve) disk-shaped layers in the forward region. The inner tracker measures charged particle trajectories within the pseudorapidity range  $|\eta| < 2.5$ , and provides an impact parameter resolution of  $\sim 15 \mu\text{m}$ . A detailed description of the CMS detector can be found elsewhere [20].

### 3. Trigger and datasets

The data used for this analysis were collected using isolated-lepton (muon or electron) plus multijet triggers. In the muon (electron) trigger an isolated muon (electron) candidate is required to have a transverse momentum  $p_T$  greater than 20 (25) GeV/ $c$ ,  $|\eta| < 2.1$  (2.5), and be accompanied by at least three jets in  $|\eta| < 2.4$ , with  $p_T > 45, 35, 25$  (50, 40, 30) GeV/ $c$ . The trigger efficiency for signal events passing the offline selection, described in Section 4, is  $83 \pm 2\%$  ( $80 \pm 2\%$ ) for the muon (electron) analysis.

A number of simulated event samples with the most important backgrounds are used to compare observations with SM expectations. The  $t\bar{t}$  + jets,  $W$  + jets, and  $Z$  + jets events are generated with the MADGRAPH v5.1.3.30 event generator [21]. The top-quark mass is set to  $172.5 \text{ GeV}/c^2$  and the branching fraction of top-quark decays to a  $W$  boson and a  $b$  quark is assumed to be one. MADGRAPH is interfaced with PYTHIA v6.426 [22] to simulate parton fragmentation and hadronization. For each production process, data samples corresponding to 0, 1, 2, and 3 extra partons are merged using the “MLM” matching prescription [23] in order to yield a realistic spectrum of accompanying jets. Diboson and QCD multijet events are generated with PYTHIA, whereas single-top-quark samples are generated with POWHEG [24,25]. Samples of  $t\bar{t}W$  and  $t\bar{t}Z$  events with up to one extra parton are generated with MADGRAPH.

A number of signal samples are generated with MADGRAPH v5.1.4.3 [26] interfaced with PYTHIA v8.165 [27]. Two of these samples correspond to events with  $t\bar{t}$ -pair production in which one or both top quarks have a BNV decay. Three other simulated signal samples correspond to the  $tW$ ,  $t$ -channel, and  $s$ -channel processes giving rise to single top-quark production. In each of these cases the top quark has a BNV decay, and samples corresponding to zero and one extra parton are merged. All the fermion-flavor-dependent parameters, which appear in the effective BNV Lagrangian defined in [19], were set to unity. Different choices for these values can in principle lead to variations in the kinematical distributions of the top-quark decay products, but the resulting impact on the final results of the search is negligible.

For all simulated samples, the hard interaction collision is overlaid with a number of simulated minimum-bias collisions. The resulting events are weighted to reproduce the distribution of the number of inelastic collisions per bunch crossing (pileup) measured in data.

A detailed simulation of particle propagation through the CMS apparatus and detector response is performed with the GEANT4 v9.2 [28,29] toolkit.

## 4. Event reconstruction and selection

The signal search is performed by counting events passing a “tight” selection. As explained in Section 5, the sensitivity of the search is substantially improved by also using a “basic” selection that includes the tight one. These two event selections are described below.

### 4.1. Basic selection

Events are reconstructed using a particle-flow (PF) algorithm [30], which consists in reconstructing and identifying each particle with an optimized combination of all subdetector information. Reconstructed particles are categorized into muons, electrons, photons, charged hadrons and neutral hadrons. At least one primary vertex is required to be reconstructed in a cylindrical region defined by the longitudinal distance  $|z| < 24 \text{ cm}$  and radial distance  $r < 2 \text{ cm}$  relative to the center of the CMS detector. The average number of reconstructed primary vertices per event is approximately 15 for the 2012 data-taking period. The reconstructed primary vertex with the largest  $\sum p_T^2$  of all associated tracks is assumed to be produced by the hard-scattering process. All reconstructed muons, electrons and charged hadrons used in this analysis are required to be associated with this primary vertex.

Muons are identified by performing a combined fit to position measurements from both the inner tracker and the muon detectors [31]. They are required to have  $p_T > 25 \text{ GeV}/c$  and  $|\eta| < 2.1$ . Their associated tracks are required to have measurements in at least six of the inner tracker layers, including at least one pixel detector layer, a combined fit  $\chi^2$  per degree of freedom smaller than 10, and to be reconstructed using at least two muon detector layers. In addition, the transverse (longitudinal) impact parameter of the muon track relative to the reconstructed primary vertex is required to be smaller than 0.2 cm (0.5 cm).

Electrons are identified [32] as tracks reconstructed in the inner tracker with measured momenta compatible with their associated energy depositions in the ECAL. Electrons are required to have  $p_T > 30 \text{ GeV}/c$  and  $|\eta| < 2.5$ , with the exclusion of the transition region between barrel and endcaps defined by  $1.444 < |\eta| < 1.566$ . The transverse (longitudinal) impact parameter of the electron track relative to the reconstructed primary vertex is required to be smaller than 0.02 cm (0.1 cm). These requirements are tighter than in the case of muons in order to reject electrons originating from photon conversions, and misidentified hadrons coming from pileup collisions. Additional photon conversion rejection requirements [32] are also applied.

Muon and electron candidates are required to be isolated. Isolation is defined via the variable

$$I_{\text{rel}}^{\ell} = \frac{E_{\text{ch}} + E_{\text{nh}} + E_{\gamma}}{p_T^{\ell} c}, \quad (1)$$

where  $p_T^{\ell}$  is the lepton transverse momentum,  $E_{\text{ch}}$  is the transverse energy deposited by charged hadrons in a cone with aperture  $\Delta R = 0.4$  (0.3) in  $(\eta, \phi)$  around the muon (electron) track, and  $E_{\text{nh}}$  ( $E_{\gamma}$ ) is the transverse energy of neutral hadrons (photons) within this cone. The transverse energies in Eq. (1) are defined as the scalar sum of the transverse momenta of all contributing particles. Muon (electron) candidates are required to have  $I_{\text{rel}}^{\ell} < 0.12$  (0.10).

Events with exactly one lepton candidate satisfying the above criteria are selected for further consideration. Events with one or more additional reconstructed muons (electrons) with  $p_T > 10(15) \text{ GeV}/c$ ,  $|\eta| < 2.5$ ,  $I_{\text{rel}}^{\ell} < 0.2$  are rejected.

All the particles identified by the PF algorithm that are associated with the primary vertex are clustered into jets using

the anti- $k_T$  algorithm [33] with a distance parameter of 0.5. Corrections to the jet energy scale are applied to account for the dependence of the detector response to jets as a function of  $\eta$  and  $p_T$  and the effects of pileup [34]. The energy of reconstructed jets in simulated events is also smeared to account for the 5–10% discrepancy in energy resolution that is observed between data and simulation [34]. At least five jets are required with  $p_T > 70, 55, 40, 30, 30$  GeV/c and  $|\eta| < 2.4$ . The offline jet  $p_T$  thresholds are chosen such that all selected jets are in the trigger efficiency plateau. In addition, at least one of these jets must be identified as originating from a b quark (“b tagging”) by the “combined secondary-vertex” (CSV) algorithm tuned for high efficiency [35]. This algorithm combines information about the impact parameter of tracks and reconstructed secondary vertices within the jet. Its typical efficiency for tagging b-quark jets is about 80%, whereas the mistagging efficiency is about 10% for jets produced by the hadronization of light quarks (u, d, s) or gluons, and about 35% for jets from c quarks [35].

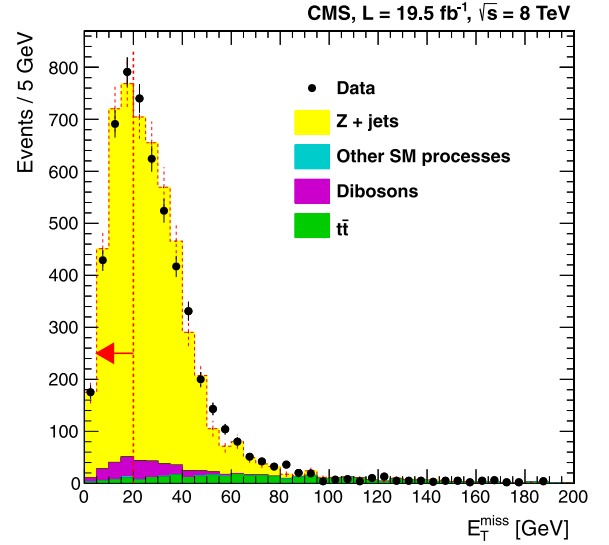
#### 4.2. Tight selection

Two additional requirements define the tight event selection used for the signal search. The first is the presence of small missing transverse energy ( $E_T^{\text{miss}}$ ). In PF reconstruction,  $E_T^{\text{miss}}$  is defined as the modulus of the vector sum of the transverse momenta of all reconstructed particles (charged and neutral) in the event. The jet energy scale corrections are also used to correct the  $E_T^{\text{miss}}$  value [36]. In order to pass the tight selection, events are required to have  $E_T^{\text{miss}} < 20$  GeV. The validity of the simulation for low- $E_T^{\text{miss}}$  events is verified using a data sample enriched in Z + 4 jets  $\rightarrow \mu^+ \mu^- + 4$  jets events. Events in this sample are required to have at least four jets with  $p_T > 30$  GeV/c and  $|\eta| < 2.4$  in addition to two muons with  $p_T > 20$  GeV/c,  $|\eta| < 2.1$ ,  $I_{\text{rel}}^\ell < 0.10$ , and invariant mass in the range 76–104 GeV/ $c^2$ . The  $E_T^{\text{miss}}$  distributions obtained in data and simulation for this event sample are shown in Fig. 1. The simulated distribution is normalized to that observed in data and the two agree within statistical uncertainties. The disagreement in overall yield before normalization is at the level of 7%, which is covered by statistical and theoretical [37] uncertainties. Very similar results are obtained with a di-electron data sample or by requiring five additional jets, instead of four, in either the muon or the electron data samples. With five additional jets, however, the statistical uncertainties are significantly larger.

The second requirement for an event to pass the tight selection is the compatibility of its kinematic properties with the final state produced by  $t\bar{t}$  events where one top quark has a fully hadronic SM decay and the other the BNV decay. This compatibility is tested using the following variable:

$$\chi^2 = \sum_i \frac{(x_i - \bar{x}_i)^2}{\sigma_i^2}, \quad (2)$$

where the  $x_i$  are the reconstructed invariant mass of the W boson from the hadronically decaying top quark, the reconstructed invariant mass of the hadronically decaying top quark, and the reconstructed invariant mass of the top quark with the BNV decay. The values of  $\bar{x}_i$  and  $\sigma_i$  are the expectation values and standard deviations of Gaussian fits to the  $x_i$  distributions obtained from simulated  $t\bar{t}$  events with the two top quarks undergoing the BNV and the fully hadronic SM decay, respectively. Simulation information is used to obtain the correct jet-to-parton association. The number of jet combinations is reduced by not associating jets tagged by the CSV algorithm with the W decay. All other combinations in



**Fig. 1.** Distributions of  $E_T^{\text{miss}}$  in both data and simulation for a sample of events enriched in Z + 4 jets  $\rightarrow \mu^+ \mu^- + 4$  jets events. The simulated distribution is normalized to that observed in data. For both data and simulation the error bars indicate the statistical uncertainty. The vertical dashed line and the arrow indicate the  $E_T^{\text{miss}}$  signal region used in this analysis. The total contribution from other SM processes, such as single-top-quark, W + jets,  $t\bar{t}W$ , and  $t\bar{t}Z$  productions is very small and is hardly visible in the plot.

the event are considered and the one with the smallest  $\chi^2$  is retained. For signal events, the correct jet combination is expected to be chosen in about 60% of the cases. In the tight selection, the smallest  $\chi^2$  is required to be less than 20.

The values of the thresholds on the lepton  $p_T$ ,  $E_T^{\text{miss}}$ ,  $\chi^2$ , as well as the configuration of the b-tagging algorithm were chosen by minimizing the expected upper limit on  $\mathcal{B}$  at 95% confidence level (CL). This procedure also retains high sensitivity for an observation of a BNV decay.

#### 5. Signal search strategy

The search proceeds in the following way: for each assumed value of  $\mathcal{B}$ , the expected contributions from  $t\bar{t}$  ( $N_{t\bar{t}}^{\mathcal{B}}$ ) and  $tW$  ( $N_{tW}^{\mathcal{B}}$ ) production to the yield in the basic selection are scaled such that the total expected yield is normalized to the observed number of events ( $N_{\text{obs}}^{\mathcal{B}}$ ). The sum of the  $t\bar{t}$  and  $tW$  yields in the tight selection ( $N_{\text{top}}^{\mathcal{B}}$ ) is then extracted using the efficiencies,  $\epsilon_{t\bar{t}}^{(\text{T})\mathcal{B}}$  and  $\epsilon_{tW}^{(\text{T})\mathcal{B}}$ , to pass the tight selection for  $t\bar{t}$  and  $tW$  events that satisfy the basic selection criteria. Finally, the comparison between the total expected and observed numbers of events in the tight selection, which is significantly more efficient for the signal than for the background, is used to infer the presence of a signal or set an upper limit on  $\mathcal{B}$ . The impact of a number of systematic uncertainties is significantly reduced as a result of the normalization of simulation to data in the basic selection. Indeed, using this approach, the expected upper limit at 95% CL on  $\mathcal{B}$  is found to improve by a factor of 2.5, while the expected significance of a signal-like deviation from SM expectations increases from about 1.2 standard deviations to 3.6 for a signal with  $\mathcal{B} = 0.005$ . In this procedure we neglect the contributions to a possible BNV signal from events with single-top-quark production via s- and t-channels,  $t\bar{t}W$ , and  $t\bar{t}Z$ , which are treated as non-top background. These contributions are expected to be negligible, as can be inferred from the yields of these processes given in Tables 1 and 2, as estimated from simulation.

Following the approach outlined above, the expression for the expected total yield in the tight selection ( $N_{\text{exp}}^T$ ) is:

$$\begin{aligned} N_{\text{exp}}^T &= N_{\text{top}}^T + N_{\text{bck}}^T \\ &= (N_{\text{obs}}^B - N_{\text{bck}}^B) \left[ \frac{N_{\text{tt}}^B}{N_{\text{tt}}^B + N_{\text{tW}}^B} \cdot \epsilon_{\text{tt}}^{(T|B)} \right. \\ &\quad \left. + \frac{N_{\text{tW}}^B}{N_{\text{tt}}^B + N_{\text{tW}}^B} \cdot \epsilon_{\text{tW}}^{(T|B)} \right] + N_{\text{bck}}^T, \end{aligned} \quad (3)$$

where  $N_{\text{bck}}^B$  ( $N_{\text{bck}}^T$ ) is the yield of the non-top background (including  $s$ - and  $t$ -channel single-top-quark,  $\text{tt}\bar{W}$ , and  $\text{tt}\bar{Z}$  production events, as discussed above) in the basic (tight) selection.

All the quantities in the square brackets of Eq. (3) are functions of  $\mathcal{B}$  and can be expressed in terms of the  $\text{tt}$  and  $\text{tW}$  cross sections ( $\sigma_{\text{tt}}^B$  and  $\sigma_{\text{tW}}^B$ , respectively), integrated luminosity, and efficiencies for passing the basic and tight selections. In terms of these variables, Eq. (3) becomes:

$$\begin{aligned} N_{\text{exp}}^T &= (N_{\text{obs}}^B - N_{\text{bck}}^B) \left[ \frac{1}{1 + \frac{\sigma_{\text{tW}} \epsilon_{\text{tW}}^B(\mathcal{B})}{\sigma_{\text{tt}} \epsilon_{\text{tt}}^B(\mathcal{B})}} \cdot \frac{\epsilon_{\text{tt}}^T(\mathcal{B})}{\epsilon_{\text{tt}}^B(\mathcal{B})} \right. \\ &\quad \left. + \frac{1}{1 + \frac{\sigma_{\text{tt}} \epsilon_{\text{tt}}^B(\mathcal{B})}{\sigma_{\text{tW}} \epsilon_{\text{tW}}^B(\mathcal{B})}} \cdot \frac{\epsilon_{\text{tW}}^T(\mathcal{B})}{\epsilon_{\text{tW}}^B(\mathcal{B})} \right] + N_{\text{bck}}^T. \end{aligned} \quad (4)$$

In Eq. (4),  $\epsilon_{\text{tt}}^B$  ( $\epsilon_{\text{tt}}^T$ ) indicates the efficiency of the basic (tight) selection for  $\text{tt}$  events. Similarly,  $\epsilon_{\text{tW}}^B$  ( $\epsilon_{\text{tW}}^T$ ) indicates the efficiency of the basic (tight) selection for  $\text{tW}$  events. Each of these four efficiency values is a function of  $\mathcal{B}$  and of three (for  $\text{tt}$  events) or two (for  $\text{tW}$  events) efficiency values, which correspond to the different decay modes:

$$\epsilon_{\text{tt}}^X(\mathcal{B}) = 2\mathcal{B}(1 - \mathcal{B})\epsilon_{\text{BNV,SM}}^X + (1 - \mathcal{B})^2\epsilon_{\text{SM,SM}}^X + \mathcal{B}^2\epsilon_{\text{BNV,BNV}}^X, \quad (5)$$

$$\epsilon_{\text{tW}}^X(\mathcal{B}) = (1 - \mathcal{B})\epsilon_{\text{SM}}^X + \mathcal{B}\epsilon_{\text{BNV}}^X, \quad (6)$$

where  $X = B, T$  with B and T denoting the basic and tight selection, respectively, and SM (BNV) indicating the SM (BNV) decay mode of the top quark. With the adopted approach, the search is mostly sensitive to uncertainties in the ratio of  $\epsilon_{\text{SM,SM}}^T$  to  $\epsilon_{\text{SM,SM}}^B$ ,  $N_{\text{bck}}^B$  and  $N_{\text{bck}}^T$ .

## 6. Background evaluation

In order to evaluate the expected yield in the tight selection (Eq. (4)), a number of backgrounds need to be estimated.

### 6.1. Top-quark and electroweak backgrounds

The main background in this analysis is from  $\text{tt}$  events where one of the two top quarks decays to a lepton, a neutrino, and a  $b$  quark while the other one decays to three quarks. As described in Section 5, the estimates of the  $\text{tt}$  and  $\text{tW}$  yields require knowledge of the efficiencies for  $\text{tt}$  and  $\text{tW}$  events, which satisfy the basic selection criteria, to also pass the tight selection. These efficiencies are obtained from simulation. The required  $\text{tt}$  cross section is the prediction at next-to-next-to-leading order (NNLO) that includes soft-gluon resummation at next-to-next-to-leading log (NNLL) [38]. The  $\text{tW}$  cross section is the approximate NNLO prediction from soft-gluon resummation at NNLL [39].

The second-largest background is represented by W and Z production in association with jets. The theoretical predictions for the  $W + \text{jets} \rightarrow \ell\nu + \text{jets}$  and  $Z/\gamma^* + \text{jets} \rightarrow \ell\ell + \text{jets}$  processes,

where  $\ell$  indicates a lepton, are computed by `FEWZ` [40,41] at next-to-next-to-leading order. The efficiencies for events produced by these processes to pass the basic and tight selections are evaluated from simulation and, using the measured value of the integrated luminosity [42], the yields in the basic and tight selections are obtained.

The contributions to the yield in the basic and tight selections from single-top-quark production via  $s$ - and  $t$ -channel processes, and from WW, WZ, ZZ,  $\text{tt}\bar{W}$ , and  $\text{tt}\bar{Z}$  production, are also evaluated from simulation. The cross section value for single-top-quark production via  $s$ -channel is computed using next-to-next-to-leading-logarithm resummation of soft and collinear gluon corrections [43]. The cross section values for  $\text{tt}\bar{W}$  and  $\text{tt}\bar{Z}$  are computed at leading-order (LO) as provided by `MADGRAPH`, including the contributions at LO from processes yielding one extra jet. In all other cases the next-to-leading order (NLO) theoretical predictions, as obtained from `MCFM` [44], are used. The sum of yields predicted by the simulation for all these processes is less than 1% of the total expected yield in both the basic and tight selections.

All cross section values used in the analysis are listed in the second column of Tables 1 and 2. The yields reported in these tables are discussed in Section 8.

### 6.2. QCD multijet background

The QCD multijet background yields are evaluated with two methods, depending on the event selection.

In the first method the isolation requirements for the leptons are inverted (becoming  $0.12 < I_{\text{rel}}^\ell < 0.2$  for muons and  $0.10 < I_{\text{rel}}^\ell < 0.2$  for electrons) in order to enhance the presence of QCD multijet events. These selections are denoted as anti-isolated basic and anti-isolated tight in the following, as opposed to the (isolated) basic and tight selections used in the analysis. The yield of the QCD multijet background in either the tight or basic selection ( $N_{\text{QCD}}$ ) can thus be inferred using the following equation:

$$N_{\text{QCD}} = R \cdot (N_{\text{data}}^{\text{antiiso}} - N_{\text{nonQCD}}^{\text{antiiso}}), \quad (7)$$

where  $R$  is the ratio of the numbers of QCD multijet events in the isolated and anti-isolated selections,  $N_{\text{data}}^{\text{antiiso}}$  is the yield observed in data in the anti-isolated selection, and  $N_{\text{nonQCD}}^{\text{antiiso}}$  is the contribution in the anti-isolated selection from other SM processes. The value of  $N_{\text{nonQCD}}^{\text{antiiso}}$  is estimated from simulation using the cross section values discussed in Section 6.1. The value of  $R$  is estimated from data using the approximation  $R = f/(1 - f)$ , where  $f$  is the so-called ‘‘misidentification rate’’. The misidentification rate is defined as the probability that a genuine jet that has passed all lepton-identification criteria and a looser isolation threshold ( $I_{\text{rel}}^\ell < 0.2$ ) also passes the final analysis isolation threshold. The value of  $f$  is obtained from data in five lepton  $p_T$  bins using a sample of events enriched in  $Z + \text{jets} \rightarrow \mu^+\mu^- + \text{jets}$  events, where a third, loosely isolated lepton, a muon or an electron, is also found. The estimate of the QCD multijet yield is then determined using Eq. (7) in each lepton  $p_T$  bin. The misidentification rate is measured with events whose topology is different from that of events in the final selection. This difference gives rise to the dominant uncertainty in the estimation of the misidentification rate, which is assessed to be 20% from the difference observed in simulation between the true and predicted yields. The systematic uncertainty in  $N_{\text{nonQCD}}^{\text{antiiso}}$  is in the range 20–25% depending on the selection. After also taking into account the statistical uncertainties, this results in a 50. In the case of the muon basic selection the systematic uncertainty in  $N_{\text{nonQCD}}^{\text{antiiso}}$  is larger than the difference  $N_{\text{data}}^{\text{antiiso}} - N_{\text{nonQCD}}^{\text{antiiso}}$  and therefore prevents a sufficiently accurate estimate of the QCD multijet yield. For this reason, a second method, which is described

**Table 1**

Muon channel: assumed cross section values, expected (as discussed in Section 6) and observed yields in the basic and tight selections for an assumed  $B$  value of zero. The “Basic” and “Corrected basic” columns report the yields in the basic selection before and after the normalization procedure described in Section 5. The uncertainties include both statistical and systematic contributions. Many of the reported uncertainties are either correlated or anticorrelated, which explains why the uncertainties in the total expected yields are smaller than those in some of their components. By construction the total expected yield after the normalization procedure is equal to the observed yield.

Process	Cross section (pb)	Basic	Corrected basic	Tight
$t\bar{t}$	246	$38\,800 \pm 7800$	$38\,700 \pm 3600$	$2210 \pm 220$
W + jets	37 500		$6300 \pm 3200$	$230 \pm 120$
Z + jets	3500		$380 \pm 190$	$32 \pm 18$
tW	22.2	$1160 \pm 180$	$1160 \pm 220$	$49 \pm 9$
t-channel	87.1		$250 \pm 130$	$5.7 \pm 3.0$
s-channel	5.55		$31 \pm 16$	$0.84 \pm 0.52$
WW	54.8		$86 \pm 43$	$3.1 \pm 1.7$
WZ	33.2		$41 \pm 21$	$1.43 \pm 0.78$
ZZ	17.7		$5.5 \pm 2.8$	$0.49 \pm 0.28$
$t\bar{t}W$	0.23		$128 \pm 64$	$5.9 \pm 3.0$
$t\bar{t}Z$	0.17		$79 \pm 40$	$4.1 \pm 2.1$
QCD	–		$760 \pm 530$	$112 \pm 56$
Total exp.	–	$48\,000 \pm 8600$	$47\,950 \pm 220$	$2650 \pm 130$
Data	–		47 951	2614

**Table 2**

Electron channel: assumed cross section values, expected (as discussed in Section 6) and observed yields in the basic and tight selections for an assumed  $B$  value of zero. The “Basic” and “Corrected basic” columns report the yields in the basic selection before and after the normalization procedure described in Section 5. The uncertainties include both statistical and systematic contributions. Many of the reported uncertainties are either correlated or anticorrelated, which explains why the uncertainties in the total expected yields are smaller than those in some of their components. By construction the total expected yield after the normalization procedure is equal to the observed yield.

Process	Cross section (pb)	Basic	Corrected basic	Tight
$t\bar{t}$	246	$38\,200 \pm 7700$	$38\,400 \pm 3700$	$2040 \pm 220$
W + jets	37 500		$6500 \pm 3300$	$240 \pm 120$
Z + jets	3500		$760 \pm 380$	$85 \pm 45$
tW	22.2	$1110 \pm 170$	$1120 \pm 210$	$35.6 \pm 6.3$
t-channel	87.1		$230 \pm 120$	$6.6 \pm 3.6$
s-channel	5.55		$27 \pm 14$	$0.70 \pm 0.50$
WW	54.8		$78 \pm 39$	$3.7 \pm 2.0$
WZ	33.2		$45 \pm 23$	$2.1 \pm 1.1$
ZZ	17.7		$11.0 \pm 5.6$	$1.40 \pm 0.70$
$t\bar{t}W$	0.23		$132 \pm 66$	$6.2 \pm 3.1$
$t\bar{t}Z$	0.17		$86 \pm 43$	$4.4 \pm 2.2$
QCD	–		$2800 \pm 1400$	$330 \pm 170$
Total exp.	–	$50\,000 \pm 9300$	$50\,110 \pm 220$	$2750 \pm 160$
Data	–		50 108	2703

**Table 3**

Muon and electron channels: numbers relevant for the estimate of the QCD multijet yield based on the misidentification rate measurement (Eq. (7)). Only the average value of  $f$  is reported, while values computed in bins of  $p_T$  are used in the analysis.

Selection	$N_{\text{data}}^{\text{antiiso}}$	$N_{\text{nonQCD}}^{\text{antiiso}}$	$f$	$N_{\text{QCD}}$
Muon channel				
Tight	412	$268 \pm 55$	$0.44 \pm 0.09$	$112 \pm 56$
Electron channel				
Basic	7162	$4600 \pm 900$	$0.51 \pm 0.10$	$2800 \pm 1400$
Tight	542	$230 \pm 48$	$0.51 \pm 0.10$	$330 \pm 170$

below, is used for this specific selection. In the electron analysis the uncertainties in the QCD multijet background estimates in the basic and tight selections are treated as fully correlated. The numbers relevant for the QCD multijet yield estimation with this first method are given in Table 3.

In the second method the assumption is made that  $E_T^{\text{miss}}$  and  $\chi^2$  are not correlated for QCD multijet events, and the estimated QCD multijet yield in the basic selection ( $N_{\text{QCD}}^{\text{B}}$ ) is obtained from the following equation:

$$N_{\text{QCD}}^{\text{B}} = \frac{N_{\text{QCD}}^{\text{T}}}{\epsilon_{E_T^{\text{miss}}} \epsilon_{\chi^2}}, \quad (8)$$

**Table 4**

Muon channel: numbers relevant for the estimate of the QCD multijet yield based on Eq. (8). As stated in the text, this method is only used for the muon basic selection.

Selection	$\epsilon_{E_T^{\text{miss}}}$	$\epsilon_{\chi^2}$	$N_{\text{QCD}}^{\text{B}}$
Muon channel			
Basic	$0.33 \pm 0.12$	$0.45 \pm 0.16$	$760 \pm 530$

where  $N_{\text{QCD}}^{\text{T}}$  is the QCD multijet yield in the tight selection, as obtained with the first method, and  $\epsilon_{E_T^{\text{miss}}} (\epsilon_{\chi^2})$  is the probability that a QCD multijet event that passes the basic selection has  $E_T^{\text{miss}} < 20$  GeV ( $\chi^2 < 20$ ). The values of  $\epsilon_{E_T^{\text{miss}}}$  and  $\epsilon_{\chi^2}$  are taken from simulation. A total uncertainty of 50% in the product of  $\epsilon_{E_T^{\text{miss}}}$  and  $\epsilon_{\chi^2}$  is assumed, which yields, together with the 50% uncertainty in  $N_{\text{QCD}}^{\text{T}}$ , an overall 70% uncertainty in the estimate of the QCD multijet background in the muon basic selection. The partial correlation with the uncertainty in the QCD multijet background estimate in the muon tight selection is taken into account when determining the final results of the analysis. The numbers relevant for the QCD multijet yield estimation in the muon basic selection with this second method are given in Table 4.

In the electron analysis the contribution of  $\gamma$  + jets processes can potentially give rise to events that pass the basic and the

tight selections. The isolated photon in the event can convert before reaching the calorimeters and be identified as a single isolated electron. From simulation studies it turns out that the central values of the QCD multijet yields estimated with the first method in both the basic and tight selections need to be increased by 2% to account for this contribution.

## 7. Systematic uncertainties

The observable of the likelihood function used in the analysis is the yield in data for the tight selection ( $N_{\text{obs}}^T$ ), while the parameter of interest is  $\mathcal{B}$ . A number of other quantities appear in the likelihood function and affect the estimate of  $N_{\text{exp}}^T$ . They are  $N_{\text{bck}}^B$ ,  $N_{\text{bck}}^T$ , the ratio  $\sigma_{\text{tW}}/\sigma_{\text{t}\bar{\text{t}}}$ , and the ten efficiencies in Eqs. (4)–(6). They are estimated as described in Section 6. Many of these quantities are correlated because of common sources of systematic uncertainties. These correlations are handled using the method presented in Ref. [45], where the  $j$ -th source of systematic uncertainty is associated with a nuisance parameter of true value  $u_j$  constrained by a normal probability density function (PDF)  $\mathcal{G}(u_j)$ . The method results in the parameterization,  $\theta_i(u_j)$ , of the  $i$ -th likelihood quantity  $\theta_i$  in terms of all the  $u_j$  nuisance parameters. Other quantities in the likelihood function are instead either assumed to be independent of any other ( $\sigma_{\text{tW}}$ ,  $\sigma_{\text{t}\bar{\text{t}}}$ , and  $N_{\text{obs}}^B$ ) or correlated with a single other quantity (the QCD multijet contributions to  $N_{\text{bck}}^B$  and  $N_{\text{bck}}^T$ ). In these cases the quantities are simply constrained in the likelihood function by a lognormal PDF  $\rho_k(\tilde{\theta}_k | \theta_k)$ , which describes the probability of measuring a value  $\tilde{\theta}_k$  for the  $k$ -th likelihood quantity should its true value be  $\theta_k$ , and which takes into account possible correlations. With this approach, the likelihood function  $\mathcal{L}$  reads:

$$\mathcal{L}(N_{\text{obs}}^T | \mathcal{B}, \theta_i(u_j), \theta_k) = \mathcal{P}(N_{\text{obs}}^T | N_{\text{exp}}^T(\mathcal{B}, \theta_i(u_j), \theta_k)) \times \prod_j \mathcal{G}(u_j) \cdot \prod_k \rho(\tilde{\theta}_k | \theta_k), \quad (9)$$

where  $\mathcal{P}(N_{\text{obs}}^T | N_{\text{exp}}^T(\mathcal{B}, \theta_i(u_j), \theta_k))$  indicates the Poisson PDF evaluated at  $N_{\text{obs}}^T$  and with expectation value  $N_{\text{exp}}^T(\mathcal{B}, \theta_i(u_j), \theta_k)$  given by Eq. (4).

The sources of systematic uncertainty are discussed below. Unless specified otherwise, each source of systematic uncertainty is varied by  $\pm 1$  standard deviation to infer the relative variation in each of the quantities appearing in the likelihood function.

The uncertainty in the simulated jet energy scale depends on the jet  $p_T$  and  $\eta$ , and is smaller than 3% [34]. This uncertainty is also propagated to the simulated  $E_T^{\text{miss}}$  calculation. It induces uncertainties of the order of 10% in the efficiency values and in the W/Z + jets contributions to  $N_{\text{bck}}^B$  and  $N_{\text{bck}}^T$ , but its impact on the final limits remains very limited because of the highly correlated effects on these quantities.

The jet energy resolution is varied in the simulation within its uncertainty, which is of the order of 10% [34]. This uncertainty is also propagated into the simulated  $E_T^{\text{miss}}$  calculation. Although it induces a relative change in the efficiency values and in the W/Z + jets yield of less than 5%, it is one of the sources of uncertainty with the largest impact on the final limits. In fact assuming no uncertainty in the jet energy resolution causes the expected upper limit at 95% CL on  $\mathcal{B}$  to decrease by about 15%.

The uncertainty in the yield of the QCD multijet background is discussed in Section 6.2. This uncertainty has a significant impact only in the electron analysis, where its effect is comparable to that of the jet energy resolution uncertainty.

The uncertainties in the cross section values of the W + jets and Z + jets backgrounds largely dominate the uncertainty in the values of  $N_{\text{bck}}^B$  and  $N_{\text{bck}}^T$  for the muon analysis, whereas in the electron analysis they are comparable to the uncertainty in the QCD

**Table 5**

Central values and associated overall uncertainties for the quantities appearing in the likelihood function.

Quantity	Muon channel	Electron channel
$\epsilon_{\text{SM,SM}}^B$	$(8.1 \pm 1.5) \times 10^{-3}$	$(8.0 \pm 1.5) \times 10^{-3}$
$\epsilon_{\text{SM,SM}}^T$	$(4.62 \pm 0.93) \times 10^{-4}$	$(4.24 \pm 0.85) \times 10^{-4}$
$\epsilon_{\text{BNV,SM}}^B$	$(7.37 \pm 0.89) \times 10^{-2}$	$(7.33 \pm 0.88) \times 10^{-2}$
$\epsilon_{\text{BNV,SM}}^T$	$(1.86 \pm 0.32) \times 10^{-2}$	$(1.62 \pm 0.27) \times 10^{-2}$
$\epsilon_{\text{BNV,BNV}}^B$	$(1.00 \pm 0.16) \times 10^{-2}$	$(1.55 \pm 0.25) \times 10^{-2}$
$\epsilon_{\text{BNV,BNV}}^T$	$(1.74 \pm 0.32) \times 10^{-3}$	$(2.64 \pm 0.55) \times 10^{-3}$
$\epsilon_{\text{SM}}^B$	$(2.68 \pm 0.32) \times 10^{-3}$	$(2.57 \pm 0.31) \times 10^{-3}$
$\epsilon_{\text{SM}}^T$	$(1.13 \pm 0.14) \times 10^{-4}$	$(8.21 \pm 0.99) \times 10^{-5}$
$\epsilon_{\text{BNV}}^B$	$(2.72 \pm 0.42) \times 10^{-2}$	$(2.80 \pm 0.42) \times 10^{-2}$
$\epsilon_{\text{BNV}}^T$	$(5.38 \pm 0.84) \times 10^{-3}$	$(5.84 \pm 0.82) \times 10^{-3}$
$N_{\text{bck}}^B$	8100 ± 3400	10600 ± 3700
$N_{\text{bck}}^T$	390 ± 140	680 ± 230
$N_{\text{obs}}^B$	47950 ± 220	50110 ± 220
$\sigma_{\text{tW}}$		22.2 ± 1.5 pb
$\sigma_{\text{t}\bar{\text{t}}}$		246 ± 12 pb

**Table 6**

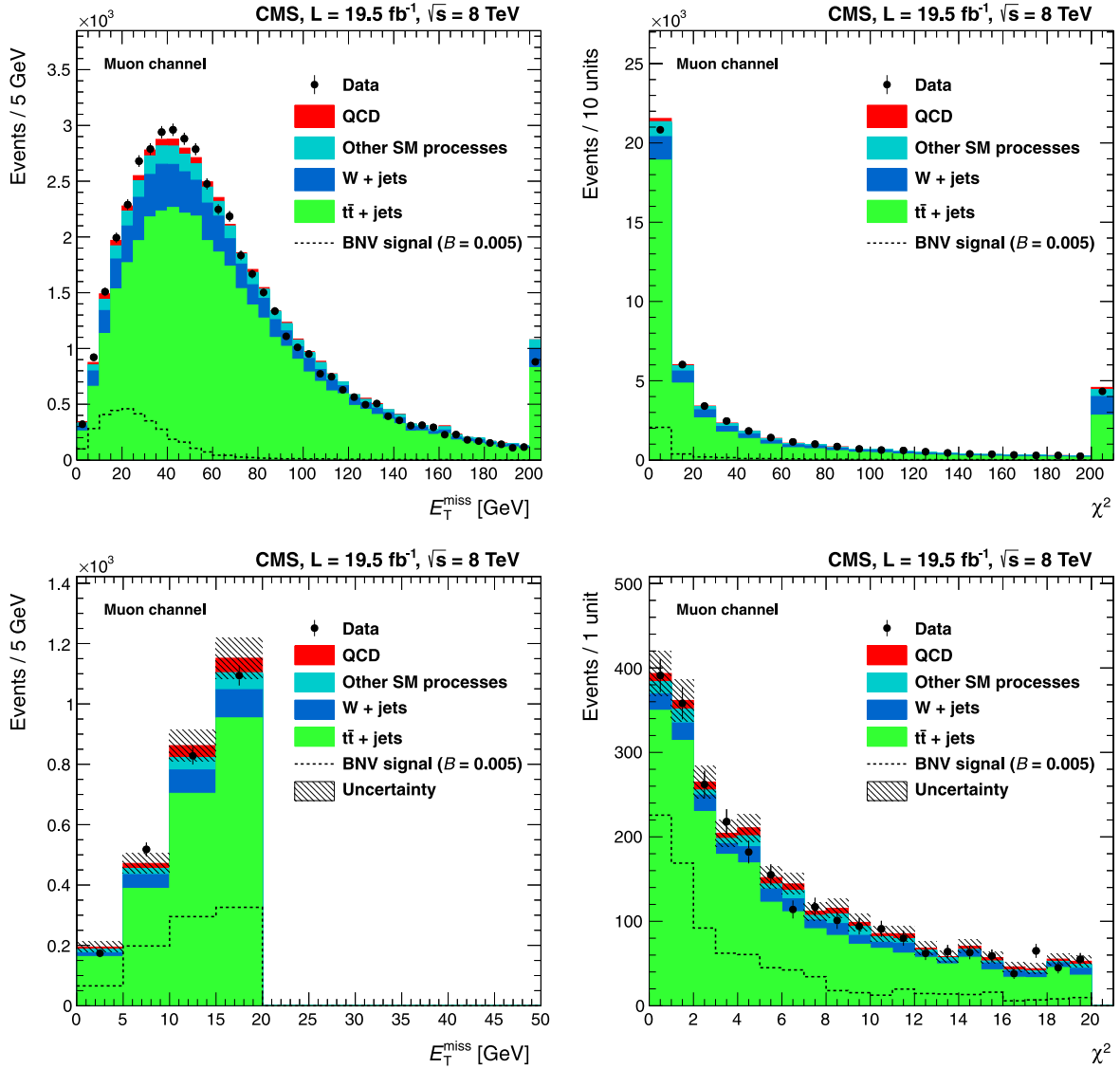
Observed 95% CL upper limit on  $\mathcal{B}$ , expected median 95% CL limit for the  $\mathcal{B} = 0$  hypothesis and ranges that are expected to contain 68% of all observed deviations from the expected median for the muon and electron channels and for their combination.

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0046]
Electron	0.0017	0.0030	[0.0017, 0.0047]
Combined	0.0015	0.0028	[0.0016, 0.0046]

multijet contribution. As described in Section 6, the W + jets and Z + jets cross section values used in this analysis are the theoretical inclusive predictions, which have an uncertainty of about 5% [46]. The CMS measurement [47] of the ratio of the W + 4 jets to the inclusive W cross section (the result for W + 5 jets is not available) is in agreement with the MADGRAPH predictions within the measurement uncertainty, which is at the level of 30%. In addition, the limited number of events in the simulated W + jets and Z + jets samples introduces a statistical uncertainty of about 10% in the yield of these processes in the tight selection. Taking these contributions into account, a conservative uncertainty of 50% in the W + jets and Z + jets cross sections is assumed. This uncertainty is found to have an impact comparable to that of the jet energy resolution on the final limits.

The uncertainties in the final results, related to the factorization and renormalization scales and to the matching thresholds used for interfacing the matrix elements generated with MADGRAPH and the PYTHIA parton showering, are evaluated with dedicated simulated data samples where the nominal values of the thresholds or scales are halved or doubled. The uncertainty in the scales is found to have an impact on the final limits comparable to that of the jet energy resolution uncertainty, while the impact of the uncertainty in the matching thresholds is almost a factor of two smaller than that of the jet energy resolution. The simulated samples are generated using the CTEQ 6.6 parton distribution functions [48]. The impact of the uncertainties in the parton distribution functions is studied following the PDF4LHC prescription [49–53] and is found to be very close to that of the matching thresholds.

A number of other sources of systematic uncertainties are found to have a negligible impact on the final results. They are summarized in the following. The uncertainty in the efficiency of the lepton trigger, identification, and isolation is assessed to be 5% [31, 32] for both muons and electrons. Unclustered reconstructed particles are also used to compute  $E_T^{\text{miss}}$  [36], and thus an uncertainty



**Fig. 2.** Muon channel: observed and SM expected distributions of  $E_T^{\text{miss}}$  (left) and  $\chi^2$  (right). The signal contribution expected for a branching fraction  $\mathcal{B} = 0.005$  for the baryon number violating top-quark decay is also shown. Top: distributions for the basic selection; because of the normalization to data, the integrals of the two distributions are equal; overflowing entries are included in the last bins of the distributions. Bottom: distributions for the tight selection; the shaded band indicating the total uncertainty in the expected yield is estimated assuming that the systematic relative uncertainty has no dependence on  $E_T^{\text{miss}}$  or  $\chi^2$ .

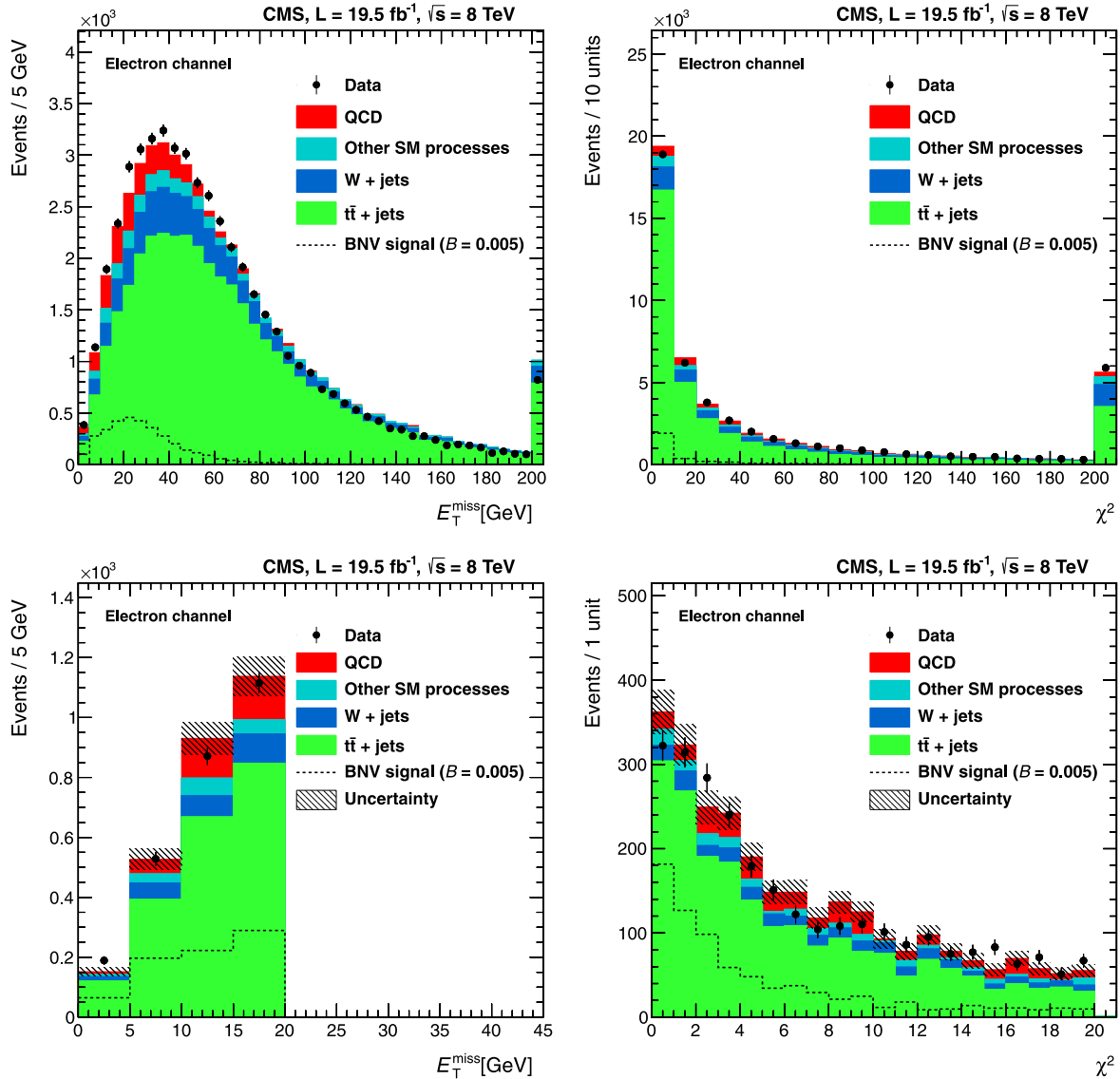
in the model provided by simulation of these particles is reflected in an uncertainty in the final  $E_T^{\text{miss}}$  calculation. The associated systematic uncertainty is estimated by varying the contribution of unclustered particles to  $E_T^{\text{miss}}$  by  $\pm 10\%$ . An uncertainty of 5% in the estimated mean number of pileup collisions is assumed. An uncertainty of 2.6% is assigned to the integrated luminosity [42]. This uncertainty affects only  $N_{\text{bck}}^{\text{B}}$  and  $N_{\text{bck}}^{\text{T}}$ , but is negligible compared with other sources of uncertainty. The uncertainty in the b-tagging efficiency results in an uncertainty in the event selection efficiency in the range 1% to 5% depending on the number, energy,  $\eta$ , and type of the jets in the event [35]. The consequent uncertainty induced in  $N_{\text{exp}}^{\text{T}}$  is about 3% for both the muon and electron channels. The uncertainties in the  $t\bar{t}$  and  $tW$  production cross section values are about 5% [38] and 7% [39] arising from the uncertainties in the factorization and renormalization scales, the parton distribution functions and, in the case of the  $t\bar{t}$  cross section, the top-quark mass. These two uncertainties affect the ratio  $\sigma_{tW}/\sigma_{t\bar{t}}$  in Eq. (4) and are conservatively assumed to be uncorrelated. The uncertainties in the yields from the WW, WZ, and

ZZ processes, as well as from  $s$ - and  $t$ -channel single-top-quark production are neglected since these processes make only small contributions to  $N_{\text{bck}}^{\text{B}}$  and  $N_{\text{bck}}^{\text{T}}$ .

The central values and the overall uncertainties in the quantities used for the calculation of the likelihood function are reported in Table 5 for both the muon and electron analyses.

## 8. Results

Tables 1 and 2 report the yields expected from the different SM processes considered, and the yields observed in data for the muon and electron channels, respectively. In these tables  $\mathcal{B}$  is assumed to be zero. The yields of the  $t\bar{t}$  and  $tW$  processes in the basic selection before and after the normalization procedure described in Section 5 are both reported, the yields before normalization being simply calculated as the products of the theoretical cross sections, the measured values of the integrated luminosity, and the event selection efficiencies obtained from simulation. Because of the normalization procedure many of the uncertainties reported



**Fig. 3.** Electron channel: observed and SM expected distributions of  $E_T^{\text{miss}}$  (left) and  $\chi^2$  (right). The signal contribution expected for a branching fraction  $\mathcal{B} = 0.005$  for the baryon number violating top-quark decay is also shown. Top: distributions for the basic selection; because of the normalization to data, the integrals of the two distributions are equal; overflowing entries are included in the last bins of the distributions. Bottom: distributions for the tight selection; the shaded band indicating the total uncertainty in the expected yield is estimated assuming that the systematic relative uncertainty has no dependence on  $E_T^{\text{miss}}$  or  $\chi^2$ .

in Tables 1 and 2 are correlated or anticorrelated, which explains why the uncertainties in the total expected yields are smaller than those in some of their components. In both the muon and electron channels the observed total yield in the tight selection agrees with the SM expectations.

Fig. 2 (Fig. 3) shows, for the muon (electron) channel, the observed and expected distributions of  $E_T^{\text{miss}}$  and  $\chi^2$  for the basic and tight selections assuming no BNV top-quark decays. The signal distribution expected for  $\mathcal{B} = 0.005$  is also shown. The methods adopted for the QCD multijet background estimates provide no detailed shape information for this contribution. Thus, for the sake of illustration in the plots, the shape of the QCD multijet background contribution in the  $E_T^{\text{miss}}$  distribution is obtained from simulation using events with at least three jets, instead of five, in order to reduce large statistical fluctuations. In the case of the  $\chi^2$  variable, whose calculation requires events with at least five jets, the shape of the QCD multijet background contribution is obtained from data in the anti-isolated regions defined in Section 6.2 after subtraction of the top-quark and electroweak components estimated from

simulation. The discrepancy visible between the observed and expected  $E_T^{\text{miss}}$  distributions in the electron channel basic selection can be accommodated with the 50% uncertainty assumed in the total QCD multijet yield. These distributions are presented for purposes of illustration and are not used in the analysis.

The observed data samples are then used to calculate upper limits on the value of  $\mathcal{B}$ . The upper limit on  $\mathcal{B}$  at 95% CL is obtained with the Feldman–Cousins approach [54]. Pseudoexperiments are generated using the frequentist prescription described in Ref. [55]. The results are summarized in Table 6 for the muon and electron channels, and for their combination. The combined results are obtained by maximizing the product of the two likelihood functions, assuming a common value of  $\mathcal{B}$  for the two channels. Full correlation is assumed for each pair of corresponding nuisance parameters in the two analyses, except for those related to the lepton trigger, identification, and isolation, which are assumed to be independent. The combination of the muon and electron datasets does not significantly improve the upper limit because of the dominant systematic uncertainties related to the modeling of



jets,  $E_T^{\text{miss}}$ , and event kinematic properties, which are fully correlated across the two channels.

## 9. Summary

Data recorded by the CMS detector have been used to search for baryon number violation in top-quark decays. The data correspond to an integrated luminosity of  $19.52 \pm 0.49 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . No significant excess is observed over the SM expectation for events with one isolated lepton (either a muon or an electron), at least five jets of which at least one is b tagged, and low missing transverse energy. These results are used to set an upper limit of 0.0016 (0.0017) at 95% confidence level on the branching fraction of a hypothetical baryon number violating top-quark decay into a muon (electron) and 2 jets. The combination of the two channels under the assumption of lepton universality yields an upper limit of 0.0015. These limits on baryon number violation are the first that have been obtained for a process involving the top quark.

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres 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: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSF (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, 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); NSC (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); the HOMING PLUS programme of Foundation for Polish Science, cofinanced by EU, Regional Development Fund; and the Thalys and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF.

## References

- [1] S.L. Glashow, Partial-symmetries of weak interactions, Nucl. Phys. 22 (1961) 579, [http://dx.doi.org/10.1016/0029-5582\(61\)90469-2](http://dx.doi.org/10.1016/0029-5582(61)90469-2).
- [2] S. Weinberg, A model of leptons, Phys. Rev. Lett. 19 (1967) 1264, <http://dx.doi.org/10.1103/PhysRevLett.19.1264>.

- [3] A. Salam, Weak and electromagnetic interactions, in: N. Svartholm (Ed.), Elementary Particle Physics: Relativistic Groups and Analyticity, Proceedings of the Eighth Nobel Symposium, Almqvist & Wiksell, 1968, p. 367.
- [4] G. 't Hooft, Symmetry breaking through Bell–Jackiw anomalies, Phys. Rev. Lett. 37 (1976) 8, <http://dx.doi.org/10.1103/PhysRevLett.37.8>.
- [5] S.P. Martin, A supersymmetry primer, arXiv:hep-ph/9709356, 1997.
- [6] G.L. Kane (Ed.), Perspectives on Supersymmetry II, Advanced Series on Directions in High Energy Physics, vol. 21, World Scientific, 2010.
- [7] H. Georgi, S.L. Glashow, Unity of all elementary-particle forces, Phys. Rev. Lett. 32 (1974) 438, <http://dx.doi.org/10.1103/PhysRevLett.32.438>.
- [8] J.D. Bekenstein, Nonexistence of baryon number for static black holes, Phys. Rev. D 5 (1972) 1239, <http://dx.doi.org/10.1103/PhysRevD.5.1239>.
- [9] A.D. Sakharov, Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe, Pis'ma Zh. Eksp. Teor. Fiz. 5 (1967) 32, <http://dx.doi.org/10.1070/PU1991v034n05ABEH002497>.
- [10] H. Nishino, et al., Super-Kamiokande Collaboration, Search for proton decay via  $p \rightarrow e^+\pi^0$  and  $p \rightarrow \mu^+\pi^0$  in a large water Cherenkov detector, Phys. Rev. Lett. 102 (2009) 141801, <http://dx.doi.org/10.1103/PhysRevLett.102.141801>, arXiv:0903.0676.
- [11] CLEO Collaboration, R. Godang, et al., Search for baryon and lepton number violating decays of the  $\tau$  lepton, Phys. Rev. D 59 (1999) 091303, <http://dx.doi.org/10.1103/PhysRevD.59.091303>, arXiv:hep-ex/9902005.
- [12] Y. Miyazaki, et al., BELLE Collaboration, Search for lepton and baryon number violating  $\tau^-$  decays into  $\bar{\Lambda}\pi^-$  and  $\Lambda\pi^-$ , Phys. Lett. B 632 (2006) 51, <http://dx.doi.org/10.1016/j.physletb.2005.10.024>, arXiv:hep-ex/0508044.
- [13] LHCb Collaboration, Searches for violation of lepton flavour and baryon number in tau lepton decays at LHCb, Phys. Lett. B 724 (2013) 36, <http://dx.doi.org/10.1016/j.physletb.2013.05.063>, arXiv:1304.4518.
- [14] CLEO Collaboration, P. Rubin, et al., Search for  $D^0 \rightarrow \bar{p}e^+$  and  $D^0 \rightarrow pe^-$ , Phys. Rev. D 79 (2009) 097101, <http://dx.doi.org/10.1103/PhysRevD.79.097101>, arXiv:0904.1619.
- [15] P. del Amo Sanchez, et al., BaBar Collaboration, Searches for the baryon- and lepton-number violating decays  $B^0 \rightarrow \Lambda_c^+\ell^-$ ,  $B^- \rightarrow \Lambda\ell^-$ , and  $B^- \rightarrow \bar{\Lambda}\ell^-$ , Phys. Rev. D 83 (2011) 091101, <http://dx.doi.org/10.1103/PhysRevD.83.091101>, arXiv:1101.3830.
- [16] J.P. Lees, et al., BaBar Collaboration, Searches for rare or forbidden semileptonic charm decays, Phys. Rev. D 84 (2011) 072006, <http://dx.doi.org/10.1103/PhysRevD.84.072006>, arXiv:1107.4465.
- [17] G. Abbiendi, et al., OPAL Collaboration, Search for baryon and lepton number violating  $Z^0$  decays, Phys. Lett. B 447 (1999) 157, [http://dx.doi.org/10.1016/S0370-2693\(98\)01570-6](http://dx.doi.org/10.1016/S0370-2693(98)01570-6), arXiv:hep-ex/9901011.
- [18] W.-S. Hou, M. Nagashima, A. Soddu, Baryon number violation involving higher generations, Phys. Rev. D 72 (2005) 095001, <http://dx.doi.org/10.1103/PhysRevD.72.095001>, arXiv:hep-ph/0509006.
- [19] Z. Dong, G. Durieux, J.-M. Gérard, T. Han, F. Maltoni, Baryon number violation at the LHC: The top option, Phys. Rev. D 85 (2012) 016006, <http://dx.doi.org/10.1103/PhysRevD.85.016006>, arXiv:1107.3805.
- [20] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [21] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn, D.L. Rainwater, T. Stelzer, MadGraph/MadEvent v4: the new web generation, J. High Energy Phys. 0709 (2007) 028, <http://dx.doi.org/10.1088/1126-6708/2007/09/028>, arXiv:0706.2334.
- [22] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 0605 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [23] J. Alwall, S. de Visscher, F. Maltoni, QCD radiation in the production of heavy colored particles at the LHC, J. High Energy Phys. 0902 (2009) 017, <http://dx.doi.org/10.1088/1126-6708/2009/02/017>, arXiv:0810.5350.
- [24] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 0411 (2004) 040, <http://dx.doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [25] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 0711 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [26] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, J. High Energy Phys. 1106 (2011) 128, [http://dx.doi.org/10.1007/JHEP06\(2011\)128](http://dx.doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [27] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, <http://dx.doi.org/10.1016/j.cpc.2008.01.036>, arXiv:0710.3820.
- [28] S. Agostinelli, et al., Geant4 – a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [29] J. Allison, et al., Geant4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, <http://dx.doi.org/10.1109/TNS.2006.869826>.

- [30] CMS Collaboration, Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, <http://cdsweb.cern.ch/record/1279341>, 2010.
- [31] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV, J. Instrum. 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [32] CMS Collaboration, Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at  $\sqrt{s} = 7$  TeV, J. Instrum. 8 (2013) P09009, <http://dx.doi.org/10.1088/1748-0221/8/09/P09009>, arXiv:1306.2016.
- [33] M. Cacciari, G.P. Salam, G. Soyez, The anti- $k_t$  jet clustering algorithm, J. High Energy Phys. 0804 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [34] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, J. Instrum. 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [35] CMS Collaboration, Identification of b-quark jets with the CMS experiment, J. Instrum. 8 (2013) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [36] CMS Collaboration, Missing transverse energy performance of the CMS detector, J. Instrum. 6 (2011) P09001, <http://dx.doi.org/10.1088/1748-0221/6/09/P09001>, arXiv:1106.5048.
- [37] H. Ita, Z. Bern, L.J. Dixon, F. Febres Cordero, D.A. Kosower, D. Maître, Precise predictions for Z-boson +4 jet production at hadron colliders, Phys. Rev. D 85 (2012) 031501, <http://dx.doi.org/10.1103/PhysRevD.85.031501>, arXiv:1108.2229.
- [38] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through  $\mathcal{O}(\alpha_s^4)$ , Phys. Rev. Lett. 110 (2013) 252004, <http://dx.doi.org/10.1103/PhysRevLett.110.252004>, arXiv:1303.6254.
- [39] N. Kidonakis, Differential and total cross sections for top pair and single top production, in: XX International Workshop on Deep-Inelastic Scattering and Related Subjects, Bonn, 2012, p. 831, arXiv:1205.3453.
- [40] K. Melnikov, F. Petriello, The W boson production cross section at the LHC through  $\mathcal{O}(\alpha_s^2)$ , Phys. Rev. Lett. 96 (2006) 231803, <http://dx.doi.org/10.1103/PhysRevLett.96.231803>, arXiv:hep-ph/0603182.
- [41] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order, Comput. Phys. Commun. 182 (2011) 2388, <http://dx.doi.org/10.1016/j.cpc.2011.06.008>, arXiv:1011.3540.
- [42] CMS Collaboration, CMS luminosity based on pixel cluster counting – summer 2013 update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, <http://cdsweb.cern.ch/record/1598864>.
- [43] N. Kidonakis, Next-to-next-to-leading logarithm resummation for s-channel single top quark production, Phys. Rev. D 81 (2010) 054028, <http://dx.doi.org/10.1103/PhysRevD.81.054028>.
- [44] J.M. Campbell, R.K. Ellis, MCFM for the tevatron and the LHC, Nucl. Phys. B, Proc. Suppl. 205–206 (2010) 10, <http://dx.doi.org/10.1016/j.nuclphysbps.2010.08.011>, arXiv:1007.3492.
- [45] J.S. Conway, Nuisance parameters in likelihoods for multisource spectra, in: H.B. Prosper, L. Lyons (Eds.), Proceedings of PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, CERN-2011-006, CERN, 2011, p. 115, <http://arxiv.org/abs/1103.0354v1>.
- [46] CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 1101 (2011) 001, [http://dx.doi.org/10.1007/JHEP01\(2011\)080](http://dx.doi.org/10.1007/JHEP01(2011)080), arXiv:1012.2466.
- [47] CMS Collaboration, Jet production rates in association with W and Z bosons in pp collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 1201 (2012) 010, [http://dx.doi.org/10.1007/JHEP01\(2012\)010](http://dx.doi.org/10.1007/JHEP01(2012)010), arXiv:1110.3226.
- [48] P.M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan, Implications of CTEQ global analysis for collider observables, Phys. Rev. D 78 (2008) 013004, <http://dx.doi.org/10.1103/PhysRevD.78.013004>, arXiv:0809.0944.
- [49] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNulty, T. Sjöstrand, R. Thorne, The PDF4LHC Working Group interim recommendations, arXiv:1101.0538, 2011.
- [50] S. Alekhin, et al., The PDF4LHC Working Group interim report, arXiv:1101.0536, 2011.
- [51] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, C.-P. Yuan, New parton distributions for collider physics, Phys. Rev. D 82 (2010) 074024, <http://dx.doi.org/10.1103/PhysRevD.82.074024>, arXiv:1007.2241.
- [52] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Parton distributions for the LHC, Eur. Phys. J. C 63 (2009) 189, <http://dx.doi.org/10.1140/epjc/s10052-009-1072-5>, arXiv:0901.0002.
- [53] R.D. Ball, et al., NNPDF Collaboration, Impact of heavy quark masses on parton distributions and LHC phenomenology, Nucl. Phys. B 849 (2011) 296, <http://dx.doi.org/10.1016/j.nuclphysb.2011.03.021>, arXiv:1101.1300.
- [54] G.J. Feldman, R.D. Cousins, Unified approach to the classical statistical analysis of small signals, Phys. Rev. D 57 (1998) 3873, <http://dx.doi.org/10.1103/PhysRevD.57.3873>, arXiv:physics/9711021.
- [55] CMS Collaboration, Combined results of searches for a standard model Higgs boson, Phys. Lett. B 710 (2012) 26, <http://dx.doi.org/10.1016/j.physletb.2012.02.064>, arXiv:1202.1488.

## CMS Collaboration

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

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan<sup>1</sup>, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, W. Kiesenhofer, V. Knünz, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, 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, A. Kalogeropoulos, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

*Vrije Universiteit Brussel, Brussel, Belgium*

C. Caillol, B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, L. Perniè, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

*Université Libre de Bruxelles, Bruxelles, Belgium*

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

*Ghent University, Ghent, Belgium*

S. Basegmez, C. Beluffi<sup>3</sup>, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, P. Jez, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, A. Popov<sup>5</sup>, M. Selvaggi, M. Vidal Marono, 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, J. Chinellato<sup>6</sup>, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

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

C.A. Bernardes<sup>b</sup>, F.A. Dias<sup>a,7</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, C. Lagana<sup>a</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

<sup>b</sup> *Universidade Federal do ABC, São Paulo, Brazil*

V. Genchev<sup>2</sup>, P. Iaydjiev<sup>2</sup>, S. Piperov, M. Rodozov, G. Sultanov, 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, X. Wang, Z. Wang

*Institute of High Energy Physics, Beijing, China*

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

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

C. Avila, C.A. Carrillo Montoya, L.F. Chaparro Sierra, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

*Universidad de Los Andes, Bogota, Colombia*

N. Godinovic, D. Lelas, R. Plestina<sup>8</sup>, D. Polic, I. Puljak

*Technical University of Split, Split, Croatia*

Z. Antunovic, M. Kovac

*University of Split, Split, Croatia*

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

*Institute Rudjer Boskovic, Zagreb, Croatia*

A. Attikis, 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*

A.A. Abdelalim<sup>9</sup>, Y. Assran<sup>10</sup>, S. Elgammal<sup>9</sup>, A. Ellithi Kamel<sup>11</sup>, M.A. Mahmoud<sup>12</sup>, A. Radi<sup>13,14</sup>

*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. Murumaa, 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, 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, L. Wendland

*Helsinki Institute of Physics, Helsinki, Finland*

T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, 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, M. Titov

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

S. Baffioni, F. Beaudette, L. Benhabib, M. Bluj<sup>15</sup>, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaue, 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<sup>16</sup>, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>16</sup>, F. Drouhin<sup>16</sup>, J.-C. Fontaine<sup>16</sup>, D. Gelé, U. Goerlach, C. Goetzmann, 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*

S. Gadrat

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

S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze<sup>17</sup>

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

C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

*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, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann<sup>2</sup>, A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

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

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz<sup>18</sup>, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, D. Horton, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann<sup>18</sup>, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, R. Schmidt<sup>18</sup>, T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

M. Aldaya Martin, V. Blobel, H. Enderle, J. Erfle, E. Garutti, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille<sup>19</sup>, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, D. Troendle, E. Usai, L. Vanelderen

*University of Hamburg, Hamburg, Germany*

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff<sup>2</sup>, F. Hartmann<sup>2</sup>, T. Hauth<sup>2</sup>, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov<sup>5</sup>, J.R. Komaragiri, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, D. Martschei, M.U. Mozer, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari, I. Topsis-giotis

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

L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

*University of Athens, Athens, Greece*

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>20</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>21</sup>, A.J. Zsigmond

*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.K. Swain<sup>22</sup>

*National Institute of Science Education and Research, Bhubaneswar, India*

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

*Panjab University, Chandigarh, India*

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

*University of Delhi, Delhi, India*

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh

*Saha Institute of Nuclear Physics, Kolkata, India*

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait<sup>23</sup>, A. Gurtu<sup>24</sup>, G. Kole, S. Kumar, M. Maity<sup>25</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>26</sup>

*Tata Institute of Fundamental Research – EHEP, Mumbai, India*

S. Banerjee, S. Dugad

*Tata Institute of Fundamental Research – HECR, Mumbai, India*

H. Arfaei, H. Bakhshiansohi, S.M. Etesami<sup>27</sup>, A. Fahim<sup>28</sup>, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>29</sup>, M. Zeinali

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

M. Grunewald

*University College Dublin, Dublin, Ireland*

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

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

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

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo <sup>a,b</sup>, G. Cappello <sup>a,b</sup>, M. Chiorboli <sup>a,b</sup>, S. Costa <sup>a,b</sup>, F. Giordano <sup>a,2</sup>, R. Potenza <sup>a,b</sup>, A. Tricomi <sup>a,b</sup>, C. Tuve <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli <sup>a</sup>, V. Ciulli <sup>a,b</sup>, C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, S. Frosali <sup>a,b</sup>, E. Gallo <sup>a</sup>, S. Gonzi <sup>a,b</sup>, V. Gori <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, G. Sguazzoni <sup>a</sup>, A. Tropiano <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbriatore <sup>a</sup>, R. Ferretti <sup>a,b</sup>, F. Ferro <sup>a</sup>, M. Lo Vetere <sup>a,b</sup>, R. Musenich <sup>a</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

A. Benaglia <sup>a</sup>, M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b</sup>, S. Gennai <sup>a</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, M.T. Lucchini <sup>a,b,2</sup>, S. Malvezzi <sup>a</sup>, R.A. Manzoni <sup>a,b,2</sup>, A. Martelli <sup>a,b,2</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</sup>, S. Ragazzi <sup>a,b</sup>, N. Redaelli <sup>a</sup>, T. Tabarelli de Fatis <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, A. De Cosa <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>, A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,2</sup>, M. Merola <sup>a</sup>, P. Paolucci <sup>a,2</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata (Potenza), Napoli, Italy

<sup>d</sup> Università G. Marconi (Roma), Napoli, Italy

P. Azzi <sup>a</sup>, N. Bacchetta <sup>a</sup>, D. Bisello <sup>a,b</sup>, A. Branca <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, P. Checchia <sup>a</sup>, T. Dorigo <sup>a</sup>, F. Fanzago <sup>a</sup>, M. Galanti <sup>a,b,2</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, P. Giubilato <sup>a,b</sup>, F. Gonella <sup>a</sup>, A. Gozzelino <sup>a</sup>, K. Kanishchev <sup>a,c</sup>, S. Lacaprara <sup>a</sup>, I. Lazzizzera <sup>a,c</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, M. Passaseo <sup>a</sup>, J. Pazzini <sup>a,b</sup>, N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Tosi <sup>a,b</sup>, A. Triossi <sup>a</sup>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento (Trento), Padova, Italy

M. Gabusi <sup>a,b</sup>, S.P. Ratti <sup>a,b</sup>, C. Riccardi <sup>a,b</sup>, P. Vitulo <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

M. Biasini <sup>a,b</sup>, G.M. Bilei <sup>a</sup>, L. Fanò <sup>a,b</sup>, P. Lariccia <sup>a,b</sup>, G. Mantovani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, A. Nappi <sup>a,b,†</sup>, F. Romeo <sup>a,b</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>, A. Spiezia <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov <sup>a,30</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, G. Broccolo <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,30</sup>, R.T. D'Agnolo <sup>a,c,2</sup>, R. Dell'Orso <sup>a</sup>, F. Fiori <sup>a,c</sup>, L. Foà <sup>a,c</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,30</sup>, A. Kraan <sup>a</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,30</sup>, A. Messineo <sup>a,b</sup>, C.S. Moon <sup>a,31</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,32</sup>, A.T. Serban <sup>a</sup>, P. Spagnolo <sup>a</sup>, P. Squillacioti <sup>a,30</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>, C. Vernieri <sup>a,c</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, D. Del Re <sup>a,b</sup>, M. Diemoz <sup>a</sup>, M. Grassi <sup>a,b</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, F. Micheli <sup>a,b</sup>, S. Nourbakhsh <sup>a,b</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, L. Soffi <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>, N. Cartiglia <sup>a</sup>, S. Casasso <sup>a,b</sup>, M. Costa <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, M. Musich <sup>a</sup>, M.M. Obertino <sup>a,c</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a,2</sup>, A. Potenza <sup>a,b</sup>, A. Romero <sup>a,b</sup>, M. Ruspa <sup>a,c</sup>, R. Sacchi <sup>a,b</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, U. Tamponi <sup>a</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte <sup>a</sup>, V. Candelise <sup>a,b</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a,2</sup>, G. Della Ricca <sup>a,b</sup>, B. Gobbo <sup>a</sup>, C. La Licata <sup>a,b</sup>, M. Marone <sup>a,b</sup>, D. Montanino <sup>a,b</sup>, A. Penzo <sup>a</sup>, A. Schizzi <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

S. Chang, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Korea

D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, D.C. Son

Kyungpook National University, Daegu, Korea

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

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

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

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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, Korea

I. Grigelionis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz <sup>33</sup>, R. Lopez-Fernandez, 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 Ibarquen

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***P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood***University of Canterbury, Christchurch, New Zealand***M. Ahmad, 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, 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, M. Misiura, W. Wolszczak***Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland***N. Almeida, P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas<sup>2</sup>, J. Varela, P. Vischia***Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal***S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, 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. Vasilov, A. Vorobyev, An. Vorobyev***Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia***Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin***Institute for Nuclear Research, Moscow, Russia***V. Epshteyn, M. Erofeeva, V. Gavrillov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin***Institute for Theoretical and Experimental Physics, 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***A. Belyaev, E. Boos, M. Dubinin<sup>7</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev***Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia***I. Azhgirey, I. Bayshev, S. Bitiukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, 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<sup>34</sup>, M. Djordjevic, M. Ekmedzic, J. Milosevic***University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*

M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas<sup>2</sup>, 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, E. Navarro De Martino, 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, 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. 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. Bendavid, J.F. Benitez, C. Bernet<sup>8</sup>, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi<sup>35</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, A. Hinzmann, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, L. Quertenmont, A. Racz, W. Reece, G. Rolandi<sup>36</sup>, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>37</sup>, D. Spiga, B. Stieger, M. Stoye, A. Tsirou, G.I. Veres<sup>21</sup>, J.R. Vlimant, H.K. Wöhri, S.D. Worm<sup>38</sup>, 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, D. Renker, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, F. Moortgat, C. Nägeli<sup>39</sup>, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, M. Quittnat, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov<sup>40</sup>, M. Takahashi, L. Tauscher<sup>†</sup>, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*

C. Amsler<sup>41</sup>, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, 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, M. Wang

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, N. Suwonjandee

*Chulalongkorn University, Bangkok, Thailand*

A. Adiguzel, M.N. Bakirci<sup>42</sup>, S. Cerci<sup>43</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut<sup>44</sup>, K. Ozdemir, S. Ozturk<sup>42</sup>, A. Polatoz, K. Sogut<sup>45</sup>, D. Sunar Cerci<sup>43</sup>, B. Tali<sup>43</sup>, H. Topakli<sup>42</sup>, M. Vergili

*Cukurova University, Adana, Turkey*

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, G. Karapinar<sup>46</sup>, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E. Gülmez, B. Isildak<sup>47</sup>, M. Kaya<sup>48</sup>, O. Kaya<sup>48</sup>, S. Ozkorucuklu<sup>49</sup>, N. Sonmez<sup>50</sup>

*Bogazici University, Istanbul, Turkey*

H. Bahtiyar<sup>51</sup>, E. Barlas, K. Cankocak, Y.O. Günaydin<sup>52</sup>, F.I. Vardarli, M. Yücel

*Istanbul Technical University, Istanbul, Turkey*

L. Levchuk, P. Sorokin

*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, C. Lucas, Z. Meng, S. Metson, D.M. Newbold<sup>38</sup>, K. Nirunpong, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>53</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Ilic, 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, O. Buchmuller, D. Burton, 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, M. Kenzie, R. Lane, R. Lucas<sup>38</sup>, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko<sup>40</sup>, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi<sup>54</sup>, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle

*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*

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

*Baylor University, Waco, USA*

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, USA*

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

*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, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, J. Pilot, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

*University of California, Davis, Davis, USA*

V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein<sup>†</sup>, E. Takasugi, P. Traczyk, V. Valuev, M. Weber

*University of California, Los Angeles, USA*

J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, 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, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech<sup>55</sup>, F. Würthwein, A. Yagil, J. Yoo

*University of California, San Diego, La Jolla, USA*

D. Barge, C. Campagnari, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, D. Kovalskyi, V. Krutelyov, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Richman, R. Rossin, D. Stuart, W. To, C. West

*University of California, Santa Barbara, Santa Barbara, USA*

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

*California Institute of Technology, Pasadena, USA*

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

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, 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, W. Hopkins, 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, 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, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, S. Kunori, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko<sup>56</sup>, C. Newman-Holmes, V. O'Dell, O. Prokofyev, N. Ratnikova, 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. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic<sup>57</sup>, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

*University of Florida, Gainesville, USA*

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

*Florida International University, Miami, USA*

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

*Florida State University, Tallahassee, USA*

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

*Florida Institute of Technology, Melbourne, USA*

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

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

U. Akgun, E.A. Albayrak<sup>51</sup>, B. Bilki<sup>58</sup>, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya<sup>59</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel, F. Ozok<sup>51</sup>, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin<sup>60</sup>, K. Yi

*The University of Iowa, Iowa City, USA*

B.A. Barnett, B. Blumenfeld, S. Bolognesi, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, C. Martin, 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, J.S. Wood

*The University of Kansas, Lawrence, USA*

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, I. Svintradze

*Kansas State University, Manhattan, USA*

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

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

*University of Maryland, College Park, USA*

A. Apyan, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Kim, M. Klute, Y.S. Lai, A. Levin, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. De Benedetti, A. Gude, J. Haupt, 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*

J.G. Acosta, L.M. Cremaldi, R. Kroeger, S. Oliveros, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

*University of Mississippi, Oxford, USA*

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

*University of Nebraska-Lincoln, Lincoln, USA*

J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

*State University of New York at Buffalo, Buffalo, USA*

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

*Northeastern University, Boston, USA*

A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

*Northwestern University, Evanston, USA*

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*

L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe

*The Ohio State University, Columbus, USA*

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

*Princeton University, Princeton, USA*

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

*University of Puerto Rico, Mayaguez, USA*

E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

*Purdue University, West Lafayette, USA*

**N. Parashar**

*Purdue University Calumet, Hammond, USA*

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

*Rice University, Houston, USA*

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

*University of Rochester, Rochester, USA*

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, 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, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

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

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>61</sup>, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>62</sup>, V. Khotilovich, R. Montalvo, I. Osipenko, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

*Texas A&M University, College Station, USA*

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderov, K. Kovitangoon, S.W. Lee, T. Libeiro, I. Volobouev

*Texas Tech University, Lubbock, USA*

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

*Vanderbilt University, Nashville, USA*

M.W. Arenton, 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*

D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, J. Klukas, A. Lanaro, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, J. Swanson

*University of Wisconsin, Madison, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

- <sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- <sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
- <sup>4</sup> Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
- <sup>5</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- <sup>6</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.
- <sup>7</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>8</sup> Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
- <sup>9</sup> Also at Zewail City of Science and Technology, Zewail, Egypt.
- <sup>10</sup> Also at Suez Canal University, Suez, Egypt.
- <sup>11</sup> Also at Cairo University, Cairo, Egypt.
- <sup>12</sup> Also at Fayoum University, El-Fayoum, Egypt.
- <sup>13</sup> Also at British University in Egypt, Cairo, Egypt.
- <sup>14</sup> Now at Ain Shams University, Cairo, Egypt.
- <sup>15</sup> Also at National Centre for Nuclear Research, Swierk, Poland.
- <sup>16</sup> Also at Université de Haute Alsace, Mulhouse, France.
- <sup>17</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.
- <sup>18</sup> Also at Brandenburg University of Technology, Cottbus, Germany.
- <sup>19</sup> Also at The University of Kansas, Lawrence, USA.
- <sup>20</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- <sup>21</sup> Also at Eötvös Loránd University, Budapest, Hungary.
- <sup>22</sup> Also at Tata Institute of Fundamental Research – EHEP, Mumbai, India.
- <sup>23</sup> Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
- <sup>24</sup> Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- <sup>25</sup> Also at University of Visva-Bharati, Santiniketan, India.
- <sup>26</sup> Also at University of Ruhuna, Matara, Sri Lanka.
- <sup>27</sup> Also at Isfahan University of Technology, Isfahan, Iran.
- <sup>28</sup> Also at Sharif University of Technology, Tehran, Iran.
- <sup>29</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- <sup>30</sup> Also at Università degli Studi di Siena, Siena, Italy.
- <sup>31</sup> Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.
- <sup>32</sup> Also at Purdue University, West Lafayette, USA.
- <sup>33</sup> Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
- <sup>34</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>35</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- <sup>36</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>37</sup> Also at University of Athens, Athens, Greece.
- <sup>38</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>39</sup> Also at Paul Scherrer Institut, Villigen, Switzerland.
- <sup>40</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>41</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>42</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>43</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>44</sup> Also at Cag University, Mersin, Turkey.
- <sup>45</sup> Also at Mersin University, Mersin, Turkey.
- <sup>46</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>47</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>48</sup> Also at Kafkas University, Kars, Turkey.
- <sup>49</sup> Also at Suleyman Demirel University, Isparta, Turkey.
- <sup>50</sup> Also at Ege University, Izmir, Turkey.
- <sup>51</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>52</sup> Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey.
- <sup>53</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>54</sup> Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
- <sup>55</sup> Also at Utah Valley University, Orem, USA.
- <sup>56</sup> Also at Institute for Nuclear Research, Moscow, Russia.
- <sup>57</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>58</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>59</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>60</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>61</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>62</sup> Also at Kyungpook National University, Daegu, Korea.