

Measurement of the W boson helicity fractions in the decays of top quark pairs to lepton + jets final states produced in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

CERN, Switzerland



ARTICLE INFO

Article history:

Received 29 May 2016

Received in revised form 1 October 2016

Accepted 4 October 2016

Available online 11 October 2016

Editor: M. Doser

Keywords:

CMS

Physics

Top

Anomalous couplings

Helicity

ABSTRACT

The W boson helicity fractions from top quark decays in $t\bar{t}$ events are measured using data from proton–proton collisions at a centre-of-mass energy of 8 TeV. The data were collected in 2012 with the CMS detector at the LHC, corresponding to an integrated luminosity of 19.8 fb^{-1} . Events are reconstructed with either one muon or one electron, along with four jets in the final state, with two of the jets being identified as originating from b quarks. The measured helicity fractions from both channels are combined, yielding $F_0 = 0.681 \pm 0.012(\text{stat}) \pm 0.023(\text{syst})$, $F_L = 0.323 \pm 0.008(\text{stat}) \pm 0.014(\text{syst})$, and $F_R = -0.004 \pm 0.005(\text{stat}) \pm 0.014(\text{syst})$ for the longitudinal, left-, and right-handed components of the helicity, respectively. These measurements of the W boson helicity fractions are the most accurate to date and they agree with the predictions from the standard model.

© 2016 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The data from proton–proton (pp) collisions produced at the CERN LHC provide an excellent environment to investigate properties of the top quark, in the context of its production and decay, with unprecedented precision. Such measurements enable rigorous tests of the standard model (SM), and deviations from the SM predictions would indicate signs of possible new physics [1–4].

In particular, the W boson helicity fractions in top quark decays are very sensitive to the Wtb vertex structure. The W boson helicity fractions are defined as the partial decay rate for a given helicity state divided by the total decay rate: $F_{L,R,0} \equiv \Gamma_{L,R,0}/\Gamma$, where F_L , F_R , and F_0 are the left-handed, right-handed, and longitudinal helicity fractions, respectively. The helicity fractions are expected to be $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$, and $F_R = 0.0017 \pm 0.0001$ at next-to-next-to-leading order (NNLO) in the SM, including electroweak effects, for a top quark mass $m_t = 172.8 \pm 1.3$ GeV [5]. Anomalous Wtb couplings, i.e. those that do not arise in the SM, would alter these values.

Experimentally, the W boson helicity can be measured through the study of angular distributions of the top quark decay products. The helicity angle θ^* is defined as the angle between the direction

of either the down-type quark or the charged lepton arising from the W boson decay and the reversed direction of the top quark, both in the rest frame of the W boson. The distribution for the cosine of the helicity angle depends on the helicity fractions in the following way,

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8} (1 - \cos\theta^*)^2 F_L + \frac{3}{4} (\sin\theta^*)^2 F_0 + \frac{3}{8} (1 + \cos\theta^*)^2 F_R. \quad (1)$$

This dependence is shown in Fig. 1 for each contribution separately, normalised to unity, and for the SM expectation. Charged leptons (or down-type quarks) from left-handed W bosons are preferentially emitted in the opposite direction of the W boson, and thus tend to have lower momentum and be closer to the b jet from the top quark decay, as compared to charged leptons (or down-type quarks) from longitudinal or right-handed W bosons.

The measurement of the W boson helicity is sensitive to the presence of non-SM couplings between the W boson, the top quark, and the bottom quark. A general parametrisation of the Wtb vertex can be expressed as [1,6]

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

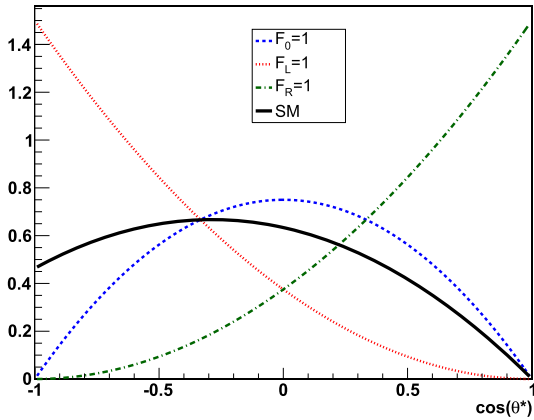


Fig. 1. Predicted $\cos\theta^*$ distributions for the different helicity fractions. The distributions for the fractions F_0 , F_L , and F_R are shown as dashed, dotted, and dash-dotted lines, respectively, and the sum of the three contributions according to the SM predictions is displayed as a solid line.

$$\begin{aligned} \mathcal{L}_{Wtb} = & -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- \\ & -\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}, \end{aligned} \quad (2)$$

where V_L , V_R , g_L , g_R are vector and tensor couplings (complex constants), $q = p_t - p_b$, and p_t (p_b) is the four-momentum of the top quark (b quark), P_L (P_R) is the left (right) projection operator, and h.c. denotes the Hermitian conjugate. Hermiticity conditions on the possible dimension-six Lagrangian terms also impose $\text{Im}(V_L) = 0$ [7]. In the SM and at tree level, $V_L = V_{tb}$, where $V_{tb} \approx 1$ is the Cabibbo–Kobayashi–Maskawa matrix element connecting the top and the bottom quarks and $V_R = g_L = g_R = 0$. The relationships between the W boson helicity fractions and the anomalous couplings including dependences on the b quark mass are given in Ref. [8].

The helicity fractions of W bosons in top quark decays were first measured at the Tevatron Collider [9–11]. They have been also measured at the LHC, using samples containing $t\bar{t}$ events obtained in pp collisions at 7 TeV, and having either one [12,13] or two [12] charged leptons in the final state. The CMS Collaboration also reported measurements using event topologies that contain one single reconstructed top quark [14], in pp collisions at 8 TeV. Limits on anomalous couplings have also been reported, derived from W boson helicity measurements [12–14], and from single top quark differential cross section production measurements [15].

This Letter describes a measurement of the W boson helicity fractions in $t\bar{t}$ events involving one lepton and multiple jets, $t\bar{t} \rightarrow (W^+b)(W^-b) \rightarrow (\ell^+ \nu_\ell b)(q\bar{q}b)$, and its charge conjugate, where ℓ is an electron or a muon, including those from leptonic decays of a tau lepton. Final states corresponding to such processes are referred to as lepton + jets. The measurement relies on the analysis strategy described in Ref. [13]. The measurement is performed using pp collisions at centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1} , collected during 2012 by the CMS detector.

2. The CMS detector

The CMS detector is a multipurpose apparatus of cylindrical design with respect to the proton beams. The main features of the detector relevant for this analysis are briefly described here. Charged particle trajectories are measured by a silicon pixel and strip tracker, covering the pseudorapidity range $|\eta| < 2.5$. The inner tracker is immersed in a 3.8 T magnetic field provided by

a superconducting solenoid of 6 m in diameter that also encompasses several calorimeters. A lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadronic calorimeter surround the tracking volume and cover the region $|\eta| < 3$. Quartz fibre and steel hadron forward calorimeters extend the coverage to $|\eta| \leq 5$. Muons are identified in gas ionisation detectors embedded in the steel return yoke of the magnet. The data for this analysis are recorded using a two-level trigger system. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

3. Data and simulated samples

Signal events corresponding to top quark pairs that decay to lepton + jets final states are expected to contain one isolated lepton (electron or muon) together with at least four jets, two of which originate from b quark fragmentation. Such events are referred to separately as e + jets or μ + jets, respectively, or when combined as ℓ + jets. Background events containing a single isolated lepton and four reconstructed jets arise mainly from processes that produce events containing a single top quark, processes that produce multijet events in association with a W boson that decays leptonically (W + jets), or Drell–Yan processes accompanied by multiple jets (DY + jets) when one of the leptons is misidentified as a jet or goes undetected. Multijet processes can also mimic lepton + jets final states, if a jet is reconstructed as an electromagnetic shower or, more unlikely, if a nonprompt muon from a hadron decay in flight fulfils all identification criteria of a prompt muon.

Simulated Monte Carlo (MC) samples, interfaced with GEANT4 [17], are used to account for detector resolution and acceptance effects, as well as to estimate the contribution from background processes that have characteristics similar to lepton + jets final states in $t\bar{t}$ decays. A signal $t\bar{t}$ sample, which also provides a reference for the SM (see Eq. (5)), is simulated using MADGRAPH v5.1.3.30 [18] with matrix elements having up to three extra partons in the final state. The parton distribution function (PDF) set CTEQ6L1 [19] is used when simulating this reference $t\bar{t}$ sample. The MADGRAPH generator is interfaced with PYTHIA v6.426 [20], tune Z2* [21], to simulate hadronisation and parton fragmentation, and also with TAUOLA v27.121.5 [22] to simulate τ lepton decays. This SM reference $t\bar{t}$ sample is simulated assuming $m_t = 172.5 \text{ GeV}$, which results in the following leading-order (LO) W boson helicity fractions for that sample:

$$F_0^{\text{SM}} = 0.6902, \quad F_L^{\text{SM}} = 0.3089, \quad F_R^{\text{SM}} = 0.0009. \quad (3)$$

Single top quark events in the s, t, and tW channels are generated using POWHEG v1.0 [23] and PYTHIA interfaced with TAUOLA, with the PDF set CTEQ6M [19]. Background W + jets and DY + jets processes are simulated using MADGRAPH with the PDF set CTEQ6L1, followed by PYTHIA for fragmentation and hadronisation. Finally, background multijet processes are simulated using the PYTHIA event generator.

Corrections are applied to the simulated samples so that resolutions, energy scales, and efficiencies as functions of p_T and η of jets [24] and leptons [25] measured in data are well described. The effect of multiple pp collisions occurring in the same bunch crossing (pileup) is also taken into account in the simulation.

The data samples selected for this measurement were recorded using inclusive single-lepton triggers, which require at least one isolated electron (muon) with $p_T > 27$ (24) GeV, used to define the e + jets (μ + jets) data sample.

The decay products of candidate top quarks are reconstructed using the CMS particle-flow (PF) algorithm, described in detail

elsewhere [26,27]. Individual charged particles identified as coming from pileup interactions are removed from the event. Effects of neutral particles from pileup interactions are mitigated by applying corrections based on event properties. Leptons are required to originate from the primary vertex of the event [28]. A lepton is determined to be isolated using a variable computed as the total transverse momentum of all particles (except the lepton itself) contained within a cone of radius 0.4, centred on the lepton direction, relative to the transverse momentum of the lepton. Electrons are identified by using a multivariate analysis (MVA) [29] based on information from the inner tracker and the ECAL. Events are selected for the $e + \text{jets}$ data sample if the identified electron has an MVA discriminant value greater than 0.9, is determined to be isolated, has $p_T > 30 \text{ GeV}$, and $|\eta| < 2.5$. Muons are identified by matching information from the inner tracker and the muon spectrometer [30]. Events are selected for the $\mu + \text{jets}$ data sample if they contain an isolated muon, $p_T > 26 \text{ GeV}$, and $|\eta| < 2.1$. Events with at least one additional isolated electron or muon are vetoed to reject backgrounds from dileptonic decay modes of $t\bar{t}$ and $DY + \text{jets}$ processes. Jets are reconstructed [24] using the anti- k_T clustering algorithm [31], with a distance parameter of 0.5. The selected or vetoed leptons described above are not allowed to be clustered into jets, to avoid ambiguities.

The event selection requires at least four reconstructed jets having $|\eta| < 2.4$, of which the four most energetic jets are required to have p_T higher than 55, 45, 35, and 20 GeV. Events with additional jets are not vetoed. The transverse momentum imbalance of the event $\vec{p}_T^{\text{miss}}$ is determined by summing the negative transverse momentum over all reconstructed particles, excluding those charged particles not associated with the primary vertex.

The transverse mass of the W boson is defined as $M_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos(\Delta\phi))}$, where p_T^ℓ is the transverse momentum of the lepton, p_T^{miss} is the magnitude of $\vec{p}_T^{\text{miss}}$, and $\Delta\phi$ is the angle in the (x, y) plane between the direction of the lepton and $\vec{p}_T^{\text{miss}}$. To reduce the multijet background and suppress dilepton events from $t\bar{t}$ processes, events are required to have $30 < M_T < 200 \text{ GeV}$. All backgrounds are further suppressed by requiring that at least two jets be identified as originating from b quarks. All jets with $p_T > 20 \text{ GeV}$ are considered as b quark candidates, including those that are not among the four most energetic.

The combined secondary vertex algorithm [32,33] tags b quark jets with an efficiency of about 70% and mistags jets originating from gluons, u, d, or s quarks with a probability of about 1%, for the typical p_T ranges (30–100 GeV) probed in $t\bar{t}$ events. Charm jets have a probability of $\approx 20\%$ of being tagged as b quark jets. The residual multijet backgrounds, already strongly suppressed by the b tagging requirement described above, are estimated by normalising simulated event samples to yields in control data samples. The control samples are defined by selection criteria which are similar to those for the signal, but which have no b tagging requirement, and have $M_T < 30 \text{ GeV}$ for the $\mu + \text{jets}$ channel or have an electron MVA discriminant value smaller than 0.5 for the $e + \text{jets}$ channel. The estimated amount of multijet events is $\approx 2\%$ of the $e + \text{jets}$ sample, and less than 1% of the $\mu + \text{jets}$ sample. The contributions of all other residual backgrounds are determined using simulation.

4. Reconstruction of the $t\bar{t}$ system and reweighting method

The reconstruction of the $t\bar{t}$ system, described in detail in Ref. [13], relies on testing the selected lepton, the measured $\vec{p}_T^{\text{miss}}$, and all selected jets for their compatibility with the top quark decay products from the leptonic ($t \rightarrow bW \rightarrow b\ell\nu$) and hadronic ($t \rightarrow bW \rightarrow b\bar{q}q'$) branches. The unmeasured component of the neutrino momentum p_z^ν is determined by requiring the $t\bar{t}$ sys-

tem to be consistent with the invariant masses of two top quarks and two W bosons. With these constraints, b jets are correctly assigned to the leptonic (hadronic) branch in about 74% (71%) of signal events. After the assignment, a kinematic fit is performed, where the momenta of the measured jets and lepton are allowed to vary within their resolutions to better comply with the mass constraints, leading to an improved determination of p_z^ν and a more accurate reconstruction of the $t\bar{t}$ system. In about 5–7% of the selected events, the fit fails to find a solution that is compatible with the constraints and such events are discarded. The number of data events passing all selection criteria, including the fit convergence, is 71 458 in the $e + \text{jets}$ sample and 70 986 in the $\mu + \text{jets}$ sample. A study using simulations normalised to the most precise theoretical cross sections available to date [34–37] indicates that the final sample composition is largely dominated by $t\bar{t}$ events, with about 82% of events from the $\ell + \text{jets}$ decay mode, $\approx 10\%$ from other decay modes (including τ leptons), and $\approx 3.5\%$ of the events from single top quark processes. The remaining events come from backgrounds not containing top quarks in the final state.

The method [13] employed to measure the W boson helicity fractions (F_L, F_0, F_R) $\equiv \vec{F}$ consists of maximising a binned Poisson likelihood function constructed using the number of observed events in data $N_{\text{data}}(i)$ and expected events from MC simulation $N_{\text{MC}}(i; \vec{F})$, in each bin i of the reconstructed $\cos\theta_{\text{rec}}^*$ distribution,

$$\mathcal{L}(\vec{F}) = \prod_i \frac{N_{\text{MC}}(i; \vec{F})^{N_{\text{data}}(i)}}{[N_{\text{data}}(i)]!} \exp[-N_{\text{MC}}(i; \vec{F})]. \quad (4)$$

While the charged lepton is easily identified in the leptonic branch of $t\bar{t}$ decays, the down-type quark jet arising from the W boson decay in the hadronic branch of $t\bar{t}$ decays can not be experimentally distinguished from the up-type quark jet. Due to this ambiguity, only the absolute value $|\cos\theta_{\text{rec}}^*|$ can be reconstructed for the hadronic branch. Hence, only the leptonic branch measurement of $\cos\theta_{\text{rec}}^*$ is used in this analysis. The expected numbers of events from background processes, $N_{W+\text{jets}}(i)$, $N_{DY+\text{jets}}(i)$, and $N_{\text{multijet}}(i)$ represent W boson production in association with multiple jets, Drell–Yan production in association with multiple jets, and production of multiple jets, which do not depend on the W boson helicity fractions. For the processes containing top quarks, the number of expected events in a given bin i is modified by reweighting each event in that bin by a factor w , defined for each decaying branch as

$$w_{\text{lep/had/single-}t}(\cos\theta_{\text{gen}}^*; \vec{F}) \equiv \left[\begin{aligned} &\frac{3}{8}F_L(1 - \cos\theta_{\text{gen}}^*)^2 \\ &+ \frac{3}{4}F_0\sin^2\theta_{\text{gen}}^* \\ &+ \frac{3}{8}F_R(1 + \cos\theta_{\text{gen}}^*)^2 \end{aligned} \right] / \left[\begin{aligned} &\frac{3}{8}F_L^{\text{SM}}(1 - \cos\theta_{\text{gen}}^*)^2 \\ &+ \frac{3}{4}F_0^{\text{SM}}\sin^2\theta_{\text{gen}}^* \\ &+ \frac{3}{8}F_R^{\text{SM}}(1 + \cos\theta_{\text{gen}}^*)^2 \end{aligned} \right], \quad (5)$$

where θ_{gen}^* is the helicity angle (specified at matrix element level) of a particular decay branch, and $F_L^{\text{SM}}, F_0^{\text{SM}}, F_R^{\text{SM}}$ are given in Eq. (3). Therefore, the number of expected events, as a function of the helicity fractions to be measured, is

Table 1

Systematic uncertainties on the measurements of the W boson helicity fractions from lepton + jets events. The cases in which the statistical precision of the limited sample size was assigned as systematic uncertainties are denoted by the symbol (*).

	e + jets		μ + jets		ℓ + jets	
	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$
JES	0.004	0.003	0.005	0.003	0.005	0.003
JER	0.001	0.002	0.004	0.003	0.003	0.003
b tagging eff.	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Lepton eff.	0.001	0.002	0.001	0.001	0.001	0.001
Single top normal.	0.002	$<10^{-3}$	0.003	0.001	0.003	0.001
W + jets bkg.	0.008	0.001	0.007	0.001	0.007	0.001
DY + jets bkg.	0.002	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Multijet bkg.	0.023	0.007	0.007	0.003	0.008	0.001
Pileup	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$
Top quark mass	0.012	0.008	0.010 (*)	0.008 (*)	0.010	0.007
$t\bar{t}$ scales	0.011	0.008 (*)	0.014	0.007 (*)	0.012	0.007
$t\bar{t}$ match. scale	0.011 (*)	0.007 (*)	0.010	0.007	0.009	0.007
$t\bar{t}$ MC and hadronisation	0.015	0.009	0.005	0.003	0.006	0.004
$t\bar{t}$ p_T reweight	0.011	0.010	$<10^{-3}$	0.001	$<10^{-3}$	0.002
Limited MC size	0.002	0.001	0.002	0.001	0.002	0.001
PDF	0.004	0.001	0.002	0.001	0.002	0.001
Total	0.037	0.020	0.024	0.014	0.023	0.014

$$\begin{aligned}
 N_{MC}(i; \vec{F}) = & N_{t\bar{t}}(i; \vec{F}) \\
 & + N_{\text{single-}t}(i; \vec{F}) \\
 & + N_{W+\text{jets}}(i) \\
 & + N_{DY+\text{jets}}(i) \\
 & + N_{\text{multijet}}(i),
 \end{aligned} \quad (6)$$

where

$$\begin{aligned}
 N_{t\bar{t}}(i; \vec{F}) = & \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t} \text{ events in bin } i} w_{\text{lep}}(\cos\theta_{\text{gen}}^*; \vec{F}) \right. \\
 & \left. \times w_{\text{had}}(\cos\theta_{\text{gen}}^*; \vec{F}) \right], \quad (7) \\
 N_{\text{single-}t}(i; \vec{F}) = & \sum_{\text{single-}t \text{ events in bin } i} w_{\text{single-}t}(\cos\theta_{\text{gen}}^*; \vec{F})
 \end{aligned}$$

represent the expected number of events fulfilling event selection criteria for processes involving top quark pair, and single top quark production, respectively. The normalisation factor $\mathcal{F}_{t\bar{t}}$ for the $t\bar{t}$ sample is a single free parameter in the fit across all bins. The expected cross section for the simulated reference $t\bar{t}$ sample is $252.9^{+13.3}_{-14.5}$ pb, calculated at NNLO and next-to-next-to-leading-log (NNLL) accuracy [34,35], and describes the data well. The fitted values of $\mathcal{F}_{t\bar{t}}$ in both e + jets and μ + jets channels are compatible with 1.00 within 3%. The overall normalisation factor for simulated single top quark events is not modified in the fit and the uncertainty in the assumed cross section is considered as a source of systematic uncertainty. Finally, the unitarity constraint ($F_L + F_0 + F_R = 1$) is imposed, so that one of the helicity fractions, namely F_R , is bound by the measurement of the other two.

The method was validated using pseudo-experiments, where the fitting procedure was performed on pseudo-data, mimicking altered helicity fractions. Linearity tests show that the fitting procedure correctly retrieves the helicity fractions of altered input values for $F_0 \in [0.50, 0.85]$ and $F_L \in [0.20, 0.50]$. Likewise the corresponding statistical uncertainties were verified using sets of statistically uncorrelated pseudo-data.

5. Systematic uncertainties

Systematic effects which could potentially bias the measurement of the W boson helicity fractions have been investigated and

their corresponding uncertainties determined, as presented in Table 1.

Residual corrections are applied in simulation to the jet energy scale (JES), to account for differences between data and simulation. The momenta of the jets in simulation are also smeared so that the jet energy resolution (JER) in simulation agrees with that in data. These corrections and smearings are propagated into $\vec{p}_T^{\text{miss}}$ to correct its momentum scale. The uncertainties [24] associated with the JES and JER corrections are also propagated to $\vec{p}_T^{\text{miss}}$, and the full analysis, including the $t\bar{t}$ reconstruction and the resulting measurements of the W boson helicity fractions, is repeated. Scale factors are used to correct the b tagging efficiency in simulation, where those corrections are shifted by their estimated uncertainties, and the full analysis repeated. Scale factors are also used to correct leptons for their identification, isolation and trigger efficiencies, which are varied within their uncertainties so as to maximise potential shape variations of the predicted $\cos\theta^*$ distributions.

To account for any possible bias of the W boson helicity measurements due to uncertainties in the normalisation of simulated backgrounds, the assumed cross section for each sample is varied individually [13]. An uncertainty of 30% is used for the normalisation of DY + jets, single top quark, and W boson production in association with light-quark or gluon jet production. Since the modelling of the simulated heavy-flavour content of the W + jets sample is known to be inaccurate, an uncertainty of $^{+100\%}_{-50\%}$ is assumed for simulated events involving a W boson produced in association with b quark jets. The impact of the DY + jets normalisation uncertainty in the analysis is small, since it corresponds to only a few percent of the sample composition. The normalisation of the multijet background is estimated from control samples and results in an uncertainty of $^{+50\%}_{-50\%}$ in the e + jets channel and $^{+40\%}_{-50\%}$ in the μ + jets channel. Shape uncertainties on the multijet background templates were investigated by comparing the distributions in several different control regions, both in MC and in data, and were found to be negligible, compared to the much larger normalisation uncertainties.

Several uncertainties from possible systematic effects related to theoretical modelling of the signal are estimated by replacing the default $t\bar{t}$ samples with alternative $t\bar{t}$ samples and repeating the entire analysis. Specifically, for the MADGRAPH interfaced with PYTHIA event generation, the default m_t value of 172.5 GeV is shifted up and down by 1 GeV; the renormalisation and fac-

Table 2

Measurements of the W boson helicity fractions from lepton + jets final states in $t\bar{t}$ decays. The helicity fractions F_0 and F_L are measured simultaneously and are strongly anti-correlated, as indicated by a correlation coefficient $\rho_{0,L}$, because F_R is derived from the unitarity condition.

Channel	$F_0 \pm (\text{stat}) \pm (\text{syst})$	$F_L \pm (\text{stat}) \pm (\text{syst})$	$F_R \pm (\text{stat}) \pm (\text{syst})$	$\rho_{0,L}$
e + jets	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$	-0.950
μ + jets	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$	-0.957
ℓ + jets	$0.681 \pm 0.012 \pm 0.023$	$0.323 \pm 0.008 \pm 0.014$	$-0.004 \pm 0.005 \pm 0.014$	-0.959

torisation scales are varied down (up) by a factor of 0.5 (2); the kinematic scale used to match jets to partons (matching threshold) is varied down (up) by factor of 0.5 (2); finally, the parton shower and hadronisation modelling is studied in a $t\bar{t}$ sample simulated with MC@NLO v3.41 [38] using the PDF set CTEQ6M and interfaced with HERWIG v6.520 [39].

Uncertainties in the helicity fractions arising from the limited size of the simulated $t\bar{t}$ samples are taken into account, both in the main analysis and in the determination of the modelling uncertainties. In the former case, these effects are added as a separate source of uncertainty. In the latter case, the systematic uncertainties in the W boson helicity are assigned to be the larger of either (i) the statistical precision of the limited sample size or (ii) the systematic shift of the central value with respect to the reference $t\bar{t}$ sample.

The shape of the p_T spectrum for top quarks, as measured by the differential cross section for top quark pairs [25,40], has been found to be softer than the predictions from MADGRAPH simulation. The effect of this mismodelling is estimated by reweighting the events in the simulated $t\bar{t}$ sample, so that the top quark p_T at parton level in the MC describes the unfolded data distribution. Further, the systematic effects due to the PDFs used to simulate the signal and background samples are estimated according to the prescriptions described in [41,42], using NNPDF21 [43] and MSTW2008lo68cl [44] PDF sets as alternatives to those used at generation. Finally, uncertainties related to the modelling of the pileup in simulated events are also taken into account.

The total systematic uncertainty is given by the sum in quadrature of all uncertainties described above.

6. Results

The measurements of the W boson helicity fractions, using $\cos\theta^*$ from the leptonic branch of $t\bar{t}$ events that decay into e + jets or μ + jets, including the full combination of these two measurements, are shown in Table 2. Within an individual channel, the helicity parameters F_0 and F_L are fit simultaneously, but they are strongly anti-correlated due to the unitarity constraint $F_L + F_0 + F_R = 1$, as indicated by the statistical correlation coefficient $\rho_{0,L}$ given in the table. The separate helicity measurements from the e + jets and μ + jets channels are combined into a single ℓ + jets measurement using the BLUE method [45,46], taking into account all uncertainties and their possible correlations. Uncertainties related to lepton efficiency, multijet background estimations, and statistical uncertainties are considered uncorrelated between the e + jets and μ + jets analyses, while all other uncertainties are assumed to be fully correlated. The combined ℓ + jets measurement of the helicity fractions is dominated by the μ + jets channel, with weights more than double those of the e + jets channel. The χ^2 of the combination is 2.13 for 2 degrees of freedom, corresponding to a probability of 34.5%. The measurement uncertainties are dominated by systematic effects that are correlated between both the e + jets and μ + jets channels. The combined F_0 and F_L values are anti-correlated with a statistical correlation coefficient $\rho_{0,L} = -0.959$. The total correlation coefficient, considering both statistical and systematic uncertainties, is found to be -0.870.

The measured helicity fractions presented in Table 2 are consistent with the SM predictions given at NNLO accuracy [5]. Fig. 2 shows, separately for the e + jets and μ + jets channels, the distributions for the cosine of the helicity angles from the leptonic branch, which are used in the helicity measurements, and the distributions of the corresponding absolute values from the hadronic branch, for comparison purposes. The simulated samples involving top quarks used in the figure were produced using the measured values for the W boson helicity fractions, as determined from the combined ℓ + jets fit. Left-handed W bosons tend to populate the region at $\cos\theta^* \approx -1$, where the charged lepton overlaps with the b quark. However, the angular separation requirement between leptons and jets removes most of the events near $\cos\theta^* = -1$. Very few events are expected in the region preferred by right-handed bosons, near $\cos\theta^* = +1$. However, due to resolution effects, the reconstructed distribution does not fall as rapidly as expected in that region, where the charged lepton and b quark have opposite directions. For these reasons, the shape of the reconstructed $\cos\theta^*$ distribution differs from that expected in the SM (Fig. 1). These features are well reproduced by the simulation, and taken into account in the measurement.

Using these results, limits on anomalous couplings are obtained by fixing the two vector couplings in Eq. (2) to their SM values, $V_L = 1$ and $V_R = 0$, and choosing the tensor couplings, $\text{Re}(g_L)$ and $\text{Re}(g_R)$, as free parameters. The combined ℓ + jets measurement of the W boson helicity fractions F_0 and F_L is reinterpreted in terms of the tensor couplings, $\text{Re}(g_L)$ and $\text{Re}(g_R)$, using the relationships between the W boson helicity fractions given in Ref. [8].

The W boson helicity measurements are displayed in the (F_0, F_L) plane in Fig. 3 (left), together with their one-dimensional statistical (inner-tick mark) and total (outer-tick mark) error bars. The full two-dimensional confidence level (CL) contours corresponding to 68% (dashed line) and 95% (solid line) probabilities are also displayed for the combined measurement. The SM prediction is shown as a star and lies within the 68% CL contour. The corresponding regions in the $(\text{Re}(g_L), \text{Re}(g_R))$ plane, allowed at 68% (dark contour) and 95% CL (light contour), are shown in Fig. 3 (right), together with the SM value. They are derived from Fig. 3 (left), using the relationships between the W boson helicity fractions and the anomalous couplings given in Ref. [8]. A region near $\text{Re}(g_L) = 0$ and $\text{Re}(g_R) \gg 0$, allowed by the fit but excluded by the CMS single top quark production measurement [47], is not shown.

If the right-handed component F_R is bound to zero, consistently with the SM within the precision of the current measurement, the combined ℓ + jets measurement amounts to $F_0 = 0.661 \pm 0.006(\text{stat}) \pm 0.021(\text{syst})$. In this case, F_L is obtained via the unitarity constraint and yields $F_L = 0.339 \pm 0.006(\text{stat}) \pm 0.021(\text{syst})$.

7. Summary

A measurement of the W boson helicity fractions in top quark pair events decaying in the e + jets and μ + jets channels has been presented, using proton–proton collision data at $\sqrt{s} = 8$ TeV, and corresponding to an integrated luminosity of 19.8 fb^{-1} . The helicity fractions F_0 and F_L are measured with a precision of

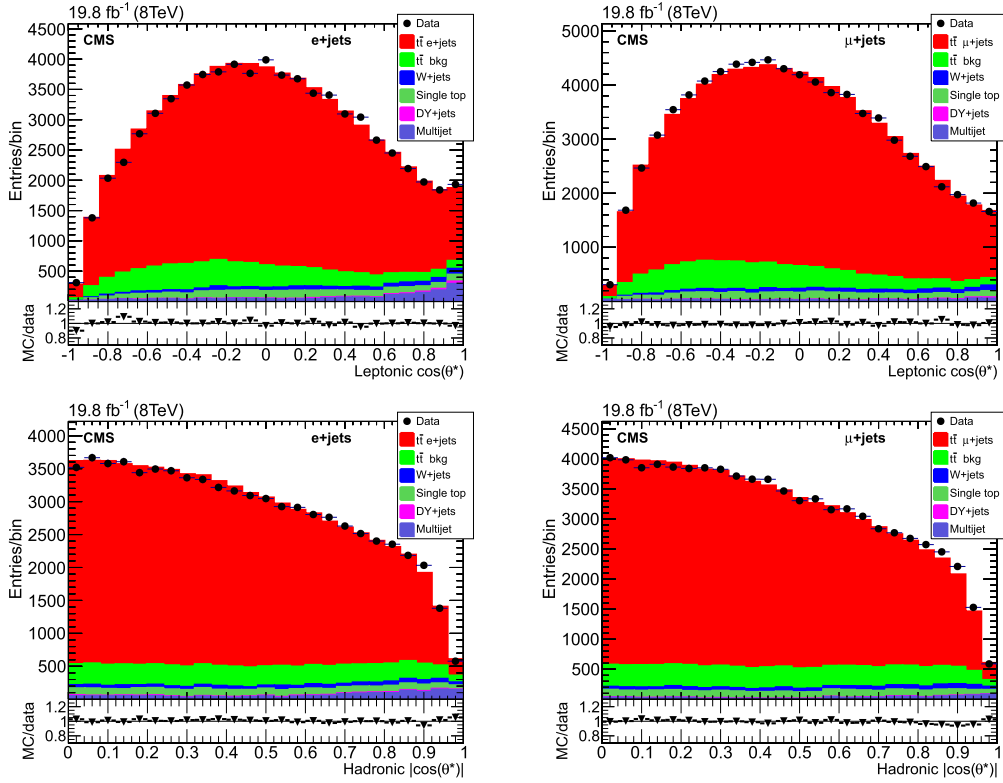


Fig. 2. Distributions for the cosine of the helicity angle in the leptonic (upper row) and hadronic (lower row) branches, for the $e + \text{jets}$ (left) and $\mu + \text{jets}$ (right) decay channels. The combined $\ell + \text{jets}$ post-fit measurements of the helicity fractions were used in the simulation of $t\bar{t}$ and single top quark events. The data are displayed as solid points, simulated samples of $t\bar{t}$ (signal) processes and the contribution from background processes as histograms. At the bottom of each plot, the ratio between MC simulation and data is displayed. The error bars correspond to the statistical uncertainties.

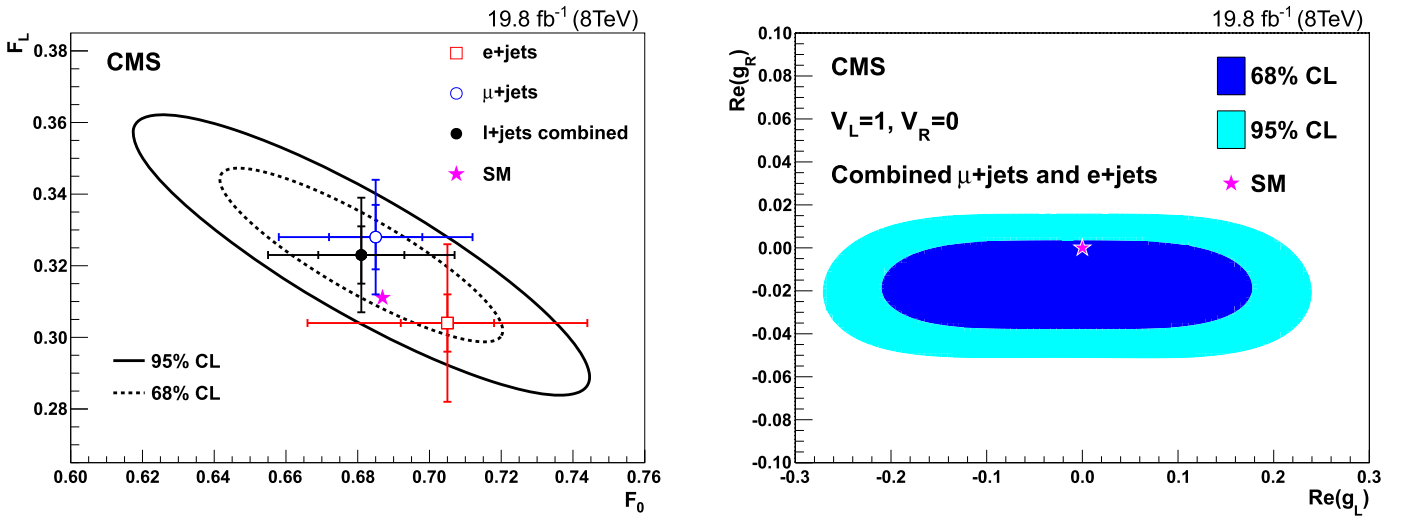


Fig. 3. Left: the measured W boson helicity fractions in the (F_0, F_L) plane. The dashed and solid ellipses enclose the allowed two-dimensional 68% and 95% CL regions, for the combined $\ell + \text{jets}$ measurement, taking into account the correlations on the total (including systematic) uncertainties. The error bars give the one-dimensional 68% CL interval for the separate F_0 and F_L measurements, with the inner-tick (outer-tick) mark representing the statistical (total) uncertainty. Right: the corresponding allowed regions for the real components of the anomalous couplings g_L and g_R at 68% and 95% CL, for $V_L = 1$ and $V_R = 0$. A region near $\text{Re}(g_L) = 0$ and $\text{Re}(g_R) \gg 0$, allowed by the fit but excluded by the CMS single top quark production measurement, is omitted. The SM predictions are shown as stars.

better than 5%, yielding the most accurate experimental determination of the W boson helicity fractions in $t\bar{t}$ processes to date. The measured W boson helicity fractions are $F_0 = 0.681 \pm 0.012(\text{stat}) \pm 0.023(\text{syst})$, $F_L = 0.323 \pm 0.008(\text{stat}) \pm 0.014(\text{syst})$, and $F_R = -0.004 \pm 0.005(\text{stat}) \pm 0.014(\text{syst})$, with a correlation coefficient of -0.87 between F_0 and F_L , and they are consistent with the expectations from the standard model.

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 NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (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 Alfred 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 the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Mobility Plus programme of the Ministry of Science and Higher Education (Poland); the OPUS programme of the National Science Center (Poland); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References

- [1] J.A. Aguilar-Saavedra, J. Carvalho, N. Castro, A. Onofre, F. Veloso, Probing anomalous Wtb couplings in top pair decays, *Eur. Phys. J. C* 50 (2007) 519, <http://dx.doi.org/10.1140/epjc/s10052-007-0289-4>, arXiv:hep-ph/0605190.
- [2] C. Bernardo, N.F. Castro, M.C.N. Fiolhais, H. Gonçalves, A.G. Guerra, M. Oliveira, A. Onofre, Studying the Wtb vertex structure using recent LHC results, *Phys. Rev. D* 90 (2014) 113007, <http://dx.doi.org/10.1103/PhysRevD.90.113007>, arXiv:1408.7063.
- [3] G.A. González-Sprinberg, J. Vidal, The top quark right coupling in the tbW vertex, *Eur. Phys. J. C* 75 (2015) 615, <http://dx.doi.org/10.1140/epjc/s10052-015-3844-4>, arXiv:1510.02153.
- [4] M. Fabbrichesi, M. Pinamonti, A. Tonerio, Limits on anomalous top quark gauge couplings from Tevatron and LHC data, *Eur. Phys. J. C* 74 (2014) 3193, <http://dx.doi.org/10.1140/epjc/s10052-014-3193-8>, arXiv:1406.5393.
- [5] A. Czarnecki, J.G. Körner, J.H. Piclum, Helicity fractions of W bosons from top quark decays at NNLO in QCD, *Phys. Rev. D* 81 (2010) 111503(R), <http://dx.doi.org/10.1103/PhysRevD.81.111503>, arXiv:1005.2625.
- [6] J.A. Aguilar-Saavedra, A minimal set of top anomalous couplings, *Nucl. Phys. B* 812 (2009) 181, <http://dx.doi.org/10.1016/j.nuclphysb.2008.12.012>, arXiv:0811.3842.
- [7] J.A. Aguilar-Saavedra, A minimal set of top-Higgs anomalous couplings, *Nucl. Phys. B* 821 (2009) 215, <http://dx.doi.org/10.1016/j.nuclphysb.2009.06.022>, arXiv:0904.2387.
- [8] J.A. Aguilar-Saavedra, J. Bernabeu, W polarisation beyond helicity fractions in top quark decays, *Nucl. Phys. B* 840 (2010) 349, <http://dx.doi.org/10.1016/j.nuclphysb.2010.07.012>, arXiv:1005.5382.
- [9] V.M. Abazov, et al., D0 Collaboration, Measurement of the W boson helicity in top quark decays using 5.4fb^{-1} of $p\bar{p}$ collision data, *Phys. Rev. D* 83 (2011) 032009, <http://dx.doi.org/10.1103/PhysRevD.83.032009>, arXiv:1011.6549.
- [10] T. Aaltonen, et al., CDF Collaboration, Measurement of W -boson polarization in top-quark decay using the full CDF Run II data set, *Phys. Rev. D* 87 (2012) 031104(R), <http://dx.doi.org/10.1103/PhysRevD.87.031104>, arXiv:1211.4523.
- [11] T. Aaltonen, et al., CDF and D0 Collaborations, Combination of CDF and D0 measurements of the W boson helicity in top quark decays, *Phys. Rev. D* 85 (2012) 071106(R), <http://dx.doi.org/10.1103/PhysRevD.85.071106>, arXiv:1202.5272.
- [12] ATLAS Collaboration, Measurement of the W boson polarization in top quark decays with the ATLAS detector, *J. High Energy Phys.* 06 (2012) 088, [http://dx.doi.org/10.1007/JHEP06\(2012\)088](http://dx.doi.org/10.1007/JHEP06(2012)088), arXiv:1205.2484.
- [13] CMS Collaboration, Measurement of the W -boson helicity in top-quark decays from $t\bar{t}$ production in lepton + jets events in pp collisions at $\sqrt{s} = 7\text{TeV}$, *J. High Energy Phys.* 10 (2013) 167, [http://dx.doi.org/10.1007/JHEP10\(2013\)167](http://dx.doi.org/10.1007/JHEP10(2013)167), arXiv:1308.3879.
- [14] CMS Collaboration, Measurement of the W boson helicity in events with a single reconstructed top quark in pp collisions at $\sqrt{s} = 8\text{TeV}$, *J. High Energy Phys.* 01 (2015) 053, [http://dx.doi.org/10.1007/JHEP01\(2015\)053](http://dx.doi.org/10.1007/JHEP01(2015)053), arXiv:1410.1154.
- [15] ATLAS Collaboration, Search for anomalous couplings in the Wtb vertex from the measurement of double differential angular decay rates of single top quarks produced in the t -channel with the ATLAS detector, *J. High Energy Phys.* 04 (2016) 023, [http://dx.doi.org/10.1007/JHEP04\(2016\)023](http://dx.doi.org/10.1007/JHEP04(2016)023), arXiv:1510.03764.
- [16] 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>.
- [17] S. Agostinelli, et al., GEANT4 Collaboration, 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).
- [18] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [19] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* 07 (2002) 012, <http://dx.doi.org/10.1088/1126-6708/2002/07/012>, arXiv:hep-ph/0201195.
- [20] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [21] CMS Collaboration, Jet and underlying event properties as a function of charged-particle multiplicity in proton–proton collisions at $\sqrt{s} = 7\text{TeV}$, *Eur. Phys. J. C* 73 (2013) 2674, <http://dx.doi.org/10.1140/epjc/s10052-013-2674-5>, arXiv:1310.4554.
- [22] N. Davidson, G. Nanava, C. Przedziński, E. Richter-Wąs, Z. Wąs, Universal interface of TAUOLA: technical and physics documentation, *Comput. Phys. Commun.* 183 (2012) 821, <http://dx.doi.org/10.1016/j.cpc.2011.12.009>, arXiv:1002.0543.
- [23] S. Alioli, P. Nason, C. Oleari, E. Re, NLO vector-boson production matched with shower in POWHEG, *J. High Energy Phys.* 07 (2008) 060, <http://dx.doi.org/10.1088/1126-6708/2008/07/060>, arXiv:0805.4802.
- [24] 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.
- [25] CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8\text{TeV}$, *Eur. Phys. J. C* 75 (2015) 542, <http://dx.doi.org/10.1140/epjc/s10052-015-3709-x>, arXiv:1505.04480.
- [26] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss} , CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, <http://cdsweb.cern.ch/record/1194487>.
- [27] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010, <http://cdsweb.cern.ch/record/1247373>.
- [28] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <http://dx.doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [29] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8\text{TeV}$, *J. Instrum.* 10 (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [30] CMS Collaboration, The performance of the CMS muon detector in proton–proton collisions at $\sqrt{s} = 7\text{TeV}$ at the LHC, *J. Instrum.* 8 (2013) P11002, <http://dx.doi.org/10.1088/1748-0221/8/11/P11002>, arXiv:1306.6905.
- [31] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [32] 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.

- [33] CMS Collaboration, Performance of b tagging at $\sqrt{s} = 8$ TeV in multijet, $t\bar{t}$ and boosted topology events, CMS Physics Analysis Summary CMS-PAS-BTV-13-001, 2013, <http://cdsweb.cern.ch/record/1581306>.
- [34] A. Ferroglia, B.D. Pecjak, L.L. Yang, Top-quark pair production at high invariant mass: an NNLO soft plus virtual approximation, J. High Energy Phys. 09 (2013) 032, [http://dx.doi.org/10.1007/JHEP09\(2013\)032](http://dx.doi.org/10.1007/JHEP09(2013)032), arXiv:1306.1537.
- [35] H.T. Li, C.S. Li, D.Y. Shao, L.L. Yang, H.X. Zhu, Top-quark pair production at small transverse momentum in hadronic collisions, Phys. Rev. D 88 (2013) 074004, <http://dx.doi.org/10.1103/PhysRevD.88.074004>, arXiv:1307.2464.
- [36] N. Kidonakis, Differential and total cross sections for top pair and single top production, presented at XX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2012), Bonn, Germany, 2012, arXiv:1205.3453.
- [37] 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.
- [38] S. Frixione, B.R. Webber, Matching NLO QCD computations and parton shower simulations, J. High Energy Phys. 06 (2002) 029, <http://dx.doi.org/10.1088/1126-6708/2002/06/029>, arXiv:hep-ph/0204244.
- [39] G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour, B.R. Webber, HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes), J. High Energy Phys. 01 (2001) 010, <http://dx.doi.org/10.1088/1126-6708/2001/01/010>, arXiv:hep-ph/0011363.
- [40] CMS Collaboration, Measurement of differential top-quark pair production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 73 (2013) 2339, <http://dx.doi.org/10.1140/epjc/s10052-013-2339-4>, arXiv:1211.2220.
- [41] S. Alekhin, et al., The PDF4LHC Working Group interim report, arXiv:1101.0536, 2011.
- [42] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNulty, T. Sjöstrand, R.S. Thorne, The PDF4LHC Working Group interim recommendations, arXiv:1101.0538, 2011.
- [43] R.D. Ball, V. Bertone, F. Cerutti, L.D. Debbio, S. Forte, A. Guffanti, J.I. La Torre, J. Rojo, M. Ubiali, NNPDF, 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.
- [44] 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.
- [45] L. Lyons, D. Gibaut, P. Clifford, How to combine correlated estimates of a single physical quantity, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 270 (1988) 110, [http://dx.doi.org/10.1016/0168-9002\(88\)90018-6](http://dx.doi.org/10.1016/0168-9002(88)90018-6).
- [46] A. Valassi, Combining correlated measurements of several different physical quantities, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 500 (2003) 391, [http://dx.doi.org/10.1016/S0168-9002\(03\)00329-2](http://dx.doi.org/10.1016/S0168-9002(03)00329-2).
- [47] CMS Collaboration, Measurement of the t -channel single-top-quark production cross section and of the $|V_{tb}|$ CKM matrix element in pp collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 06 (2014) 090, [http://dx.doi.org/10.1007/JHEP06\(2014\)090](http://dx.doi.org/10.1007/JHEP06(2014)090), arXiv:1403.7366.

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Treberer-Treberspur, W. Waltenberger, C.-E. Wulz¹

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, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang²

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöffbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, S. De Visscher, C. Delaere, M. Delcourt, L. Forthomme, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

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

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁴, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^{a,5}, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁶

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen⁷, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁸, M. Finger Jr.⁸

Charles University, Prague, Czechia

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran^{9,10}, T. Elkafrawy¹¹, A. Ellithi Kamel¹², A. Mahrous¹³

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

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Streblor, Y. Yilmaz, A. Zabi

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

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁴, X. Coubez, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin¹⁵, K. Skovpen, 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, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁶, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

T. Toriashvili¹⁷

Georgian Technical University, Tbilisi, Georgia

D. Lomidze

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov¹⁶

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

M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl¹⁵

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

M. Aldaya Martin, C. Asawatangtrakuldee, I. Asin, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁸, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Gallo¹⁹, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel²⁰, H. Jung, A. Kalogeropoulos, O. Karacheban²⁰, M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, K. Goebel, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo¹⁵, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Fries, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, I. Katkov¹⁶, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

N. Filipovic*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Hungary***G. Bencze, C. Hajdu, P. Hidas, D. Horvath²¹, F. Sikler, V. Veszpremi, G. Vesztergombi²², A.J. Zsigmond***Wigner Research Centre for Physics, Budapest, Hungary***N. Beni, S. Czellar, J. Karancsi²³, A. Makovec, J. Molnar, Z. Szillasi***Institute of Nuclear Research ATOMKI, Debrecen, Hungary***M. Bartók²², P. Raics, Z.L. Trocsanyi, B. Ujvari***University of Debrecen, Debrecen, Hungary***S. Bahinipati, S. Choudhury²⁴, P. Mal, K. Mandal, A. Nayak²⁵, D.K. Sahoo, N. Sahoo, S.K. Swain***National Institute of Science Education and Research, Bhubaneswar, India***S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia***Panjab University, Chandigarh, India***Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma***University of Delhi, Delhi, India***R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur***Saha Institute of Nuclear Physics, Kolkata, India***P.K. Behera***Indian Institute of Technology Madras, Madras, India***R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁵, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar***Bhabha Atomic Research Centre, Mumbai, India***T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar***Tata Institute of Fundamental Research-A, Mumbai, India***S. Banerjee, S. Bhowmik²⁶, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁶, G. Majumder, K. Mazumdar, B. Parida, T. Sarkar²⁶, N. Wickramage²⁷***Tata Institute of Fundamental Research-B, Mumbai, India***S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, A. Rane, S. Sharma***Indian Institute of Science Education and Research (IISER), Pune, India***H. Bakhshiansohi, H. Behnamian, S. Chenarani²⁸, E. Eskandari Tadavani, S.M. Etesami²⁸, A. Fahim²⁹, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali***Institute for Research in Fundamental Sciences (IPM), Tehran, Iran***M. Felcini, M. Grunewald***University College Dublin, Dublin, Ireland*

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,15}, R. Venditti^{a,b}, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b,15}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^{a,b,15}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁵

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

L. Brianza, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b,15}, B. Marzocchi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Pigazzini, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d,15}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,15}, M. Merola^a, P. Paolucci^{a,15}, C. Sciacca^{a,b}, F. Thyssen

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^{a,15}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b,15}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, A. Magnani^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^{a,31}, P. Azzurri^{a,15}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,31}, R. Dell’Orso^a, S. Donato^{a,c}, G. Fedi, A. Giassi^a, M.T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, G. D’imperio^{a,b,15}, D. Del Re^{a,b,15}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c,15}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, C. La Licata^{a,b}, A. Schizzi^{a,b}, A. Zanetti^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, A. Lee

Chonbuk National University, Jeonju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, S.B. Oh, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, D. Kim, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³³, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpitneyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, 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, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

R. Chistov⁴¹, V. Rusinov, E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan, A. Leonidov³⁸, S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, V. Klyukhin, O. Kodolova, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic⁴³, P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, 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, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, E. Di Marco⁴⁴, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁵, M.J. Kortelainen, K. Kousouris, M. Krammer¹, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli⁴⁵, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁷, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns⁴⁸, G.I. Veres²², N. Wardle, A. Zagozdinska³⁶, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁴⁹, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁵⁰, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci⁵¹, S. Damarasekin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁵², O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵³, K. Ozdemir⁵⁴, S. Ozturk⁵¹, A. Polatoz, D. Sunar Cerci⁵⁵, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, E.A. Yetkin⁶⁰, T. Yetkin⁶¹

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶²

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶³, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, R. Lane, C. Laner, R. Lucas⁶³, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁹, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁵, T. Virdee¹⁵, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁶, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶⁷, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶⁸, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, Z. Wu, M. Zakaria, J. Zhang

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

B. Bilki⁶⁹, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, J. Bowen, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, J. Luo, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, D. Benedetti, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷³, V. Krutelyov, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderø, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁵ Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.

⁶ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁷ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

⁸ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁹ Also at Suez University, Suez, Egypt.

¹⁰ Now at British University in Egypt, Cairo, Egypt.

¹¹ Also at Ain Shams University, Cairo, Egypt.

¹² Also at Cairo University, Cairo, Egypt.

¹³ Now at Helwan University, Cairo, Egypt.

¹⁴ Also at Université de Haute Alsace, Mulhouse, France.

¹⁵ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

¹⁶ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

¹⁷ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁸ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

¹⁹ Also at University of Hamburg, Hamburg, Germany.

²⁰ Also at Brandenburg University of Technology, Cottbus, Germany.

²¹ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²² Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

²³ Also at University of Debrecen, Debrecen, Hungary.

²⁴ Also at Indian Institute of Science Education and Research, Bhopal, India.

- ²⁵ Also at Institute of Physics, Bhubaneswar, India.
- ²⁶ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁷ Also at University of Ruhuna, Matara, Sri Lanka.
- ²⁸ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁹ Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- ³⁰ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ³¹ Also at Università degli Studi di Siena, Siena, Italy.
- ³² Also at Purdue University, West Lafayette, USA.
- ³³ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³⁴ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ³⁵ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ³⁶ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ³⁷ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁸ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁹ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ⁴⁰ Also at University of Florida, Gainesville, USA.
- ⁴¹ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴² Also at California Institute of Technology, Pasadena, USA.
- ⁴³ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴⁴ Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
- ⁴⁵ Also at National Technical University of Athens, Athens, Greece.
- ⁴⁶ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ⁴⁷ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁴⁸ Also at Riga Technical University, Riga, Latvia.
- ⁴⁹ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁵⁰ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ⁵¹ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵² Also at Mersin University, Mersin, Turkey.
- ⁵³ Also at Cag University, Mersin, Turkey.
- ⁵⁴ Also at Piri Reis University, Istanbul, Turkey.
- ⁵⁵ Also at Adiyaman University, Adiyaman, Turkey.
- ⁵⁶ Also at Ozyegin University, Istanbul, Turkey.
- ⁵⁷ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁵⁸ Also at Marmara University, Istanbul, Turkey.
- ⁵⁹ Also at Kafkas University, Kars, Turkey.
- ⁶⁰ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁶¹ Also at Yildiz Technical University, Istanbul, Turkey.
- ⁶² Also at Hacettepe University, Ankara, Turkey.
- ⁶³ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁶⁴ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁶⁵ Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ⁶⁶ Also at Utah Valley University, Orem, USA.
- ⁶⁷ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁶⁸ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ⁶⁹ Also at Argonne National Laboratory, Argonne, USA.
- ⁷⁰ Also at Erzincan University, Erzincan, Turkey.
- ⁷¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁷² Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁷³ Also at Kyungpook National University, Daegu, Republic of Korea.