



# Search for new physics in top quark production in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration\*

CERN

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**Abstract** A search for new physics in top quark production is performed in proton-proton collisions at 13 TeV. The data set corresponds to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  collected in 2016 with the CMS detector. Events with two opposite-sign isolated leptons (electrons or muons), and b quark jets in the final state are selected. The search is sensitive to new physics in top quark pair production and in single top quark production in association with a W boson. No significant deviation from the standard model expectation is observed. Results are interpreted in the framework of effective field theory and constraints on the relevant effective couplings are set, one at a time, using a dedicated multivariate analysis. This analysis differs from previous searches for new physics in the top quark sector by explicitly separating  $tW$  from  $t\bar{t}$  events and exploiting the specific sensitivity of the  $tW$  process to new physics.

## 1 Introduction

Because of its large mass, close to the electroweak (EW) symmetry breaking scale, the top quark is predicted to play an important role in several new physics scenarios. If the new physics scale is in the available energy range of the CERN LHC, the existence of new physics could be directly observed via the production of new particles. Otherwise, new physics could affect standard model (SM) interactions indirectly, through modifications of SM couplings or enhancements of rare SM processes. In this case, it is useful to introduce a model independent approach to parametrize and constrain possible deviations from SM predictions, independently of the fundamental theory of new physics.

Several searches for new physics in the top quark sector including new non-SM couplings of the top quark have been performed at the Tevatron and LHC colliders [1–4, 4–10]. Most of the previous analyses followed the anomalous coupling approach in which the SM Lagrangian is extended for possible new interactions. Another powerful framework

to parametrize deviations with respect to the SM prediction is the effective field theory (EFT) [11, 12]. Constraints obtained on anomalous couplings can be translated to the effective coupling bounds [1, 13]. Several groups have performed global fits of top quark EFT to unfolded experimental data from the Tevatron and LHC colliders [14, 15]. Due to the limited access to data and details of the associated uncertainties, correlations between various cross section measurements and related uncertainties are neglected in a global fit on various unfolded measurements. On the other hand, EFT operators could affect backgrounds for some processes constructively or destructively while cross sections are measured with the SM assumptions for background processes. Inside the CMS Collaboration and with direct access to data, all mentioned points could be considered properly.

In this paper, the EFT approach is followed to search for new physics in the top quark sector in the dilepton final states. In Refs. [13, 16], all dimension-six operators that contribute to top quark pair ( $t\bar{t}$ ) production and single top quark production in association with a W boson ( $tW$ ) are investigated. The operators and the related effective Lagrangians, which are relevant for dilepton final states, can be written as [12]:

$$O_{\phi q}^{(3)} = (\phi^+ \tau^i D_\mu \phi)(\bar{q} \gamma^\mu \tau^i q),$$

$$L_{\text{eff}} = \frac{C_{\phi q}^{(3)}}{\sqrt{2}\Lambda^2} g v^2 \bar{b} \gamma^\mu P_L t W_\mu^- + \text{h.c.}, \quad (1)$$

$$O_{tW} = (\bar{q} \sigma^{\mu\nu} \tau^i t) \tilde{\phi} W_{\mu\nu}^i,$$

$$L_{\text{eff}} = -2 \frac{C_{tW}}{\Lambda^2} v \bar{b} \sigma^{\mu\nu} P_R t \partial_\nu W_\mu^- + \text{h.c.}, \quad (2)$$

$$O_{tG} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{\phi} G_{\mu\nu}^a,$$

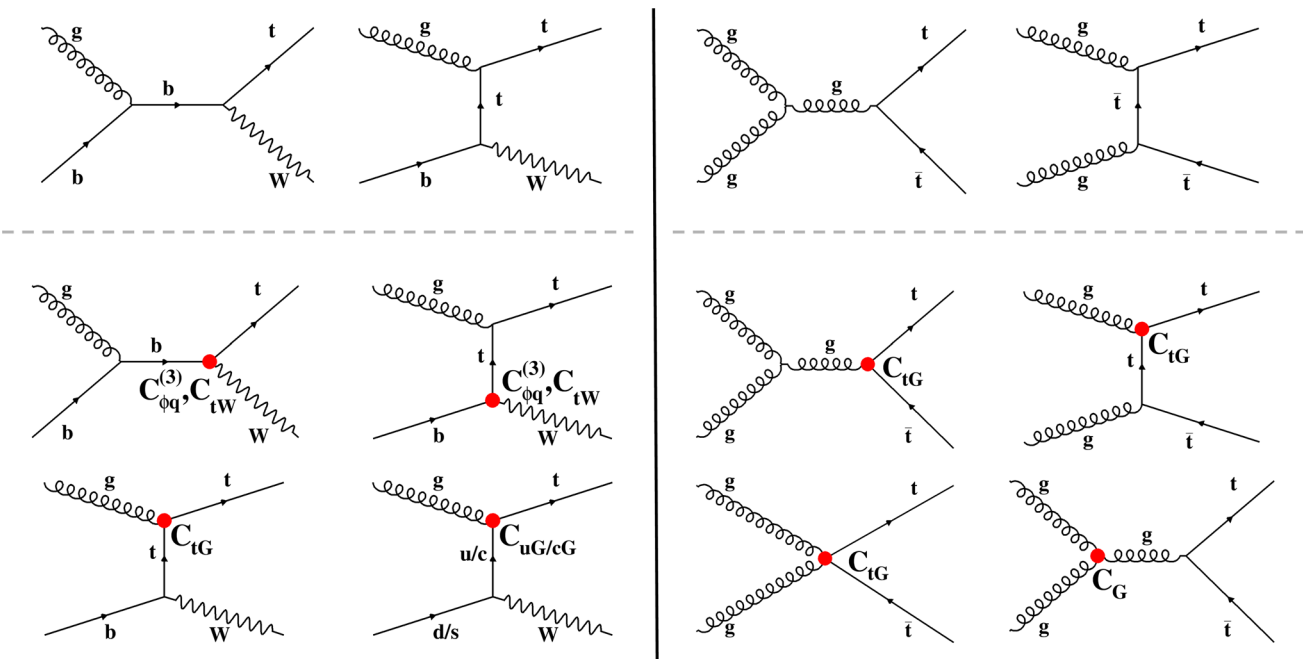
$$L_{\text{eff}} = \frac{C_{tG}}{\sqrt{2}\Lambda^2} v (\bar{t} \sigma^{\mu\nu} \lambda^a t) G_{\mu\nu}^a + \text{h.c.}, \quad (3)$$

$$O_G = f_{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu},$$

$$L_{\text{eff}} = \frac{C_G}{\Lambda^2} f_{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}, \quad (4)$$

$$O_{u(c)G} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \tilde{\phi} G_{\mu\nu}^a,$$

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



**Fig. 1** Representative Feynman diagrams for the  $tW$  (left panel) and  $t\bar{t}$  (right panel) production at leading order. The upper row presents the SM diagrams, the middle and lower rows present diagrams corresponding to the  $O_{\phi q}^{(3)}$ ,  $O_{tW}$ ,  $O_{tG}$ ,  $O_G$  and  $O_{u/cG}$  contributions

$$L_{\text{eff}} = \frac{C_{u(c)G}}{\sqrt{2}\Lambda^2} v (\bar{u} (\bar{c}) \sigma^{\mu\nu} \lambda^a t) G_{\mu\nu}^a + \text{h.c.}, \tag{5}$$

where  $D_\mu = \partial_\mu - i g_s \frac{1}{2} \lambda^a G_\mu^a - i g \frac{1}{2} \tau^i W_\mu^i - i g' Y B_\mu$ ,  $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g \epsilon_{ijk} W_\mu^j W_\nu^k$ ,  $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c$ ,  $\sigma^{\mu\nu} = \frac{1}{2} [\gamma^\mu, \gamma^\nu]$ ,  $P_{L,R} = \frac{1}{2} (1 \mp \gamma^5)$ , and the symbols  $q$ ,  $t$  and  $\phi$  ( $\tilde{\phi} = \epsilon \phi^*$ ) in the operators represent the left-handed quark doublet, the right-handed top quark singlet, and the Higgs boson doublet fields, respectively. The parameters  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$ ,  $C_G$  and  $C_{u(c)G}$  stand for the dimensionless Wilson coefficients, also called effective couplings. The variable  $\Lambda$  represents the energy scale beyond which new physics becomes relevant. A detailed description of the operators is given in Refs. [13, 16, 17]. In this analysis, four-fermion operators involved in  $t\bar{t}$  production are not probed. Up to order  $\Lambda^{-2}$ , the  $tW$  and  $t\bar{t}$  production cross sections and most of the differential observables considered in this analysis do not receive CP-odd contributions. Therefore, we only probe CP-even operators with real coefficients. The operators  $O_{\phi q}^{(3)}$  and  $O_{tW}$  modify the SM interaction between the W boson, top quark, and b quark (Wtb). We consider the EFT effects in the production of top quarks not in their decays [18]. The operator  $O_{tG}$  is called the chromomagnetic dipole moment operator of the top quark and can arise from various models of new physics [19, 20]. The triple-gluon field strength operator  $O_G$  represents the only genuinely gluonic CP conserving term that can appear at dimension six within an effective strong interaction Lagrangian. Although it is

shown that jet production at the LHC can set a tight constraint on the  $C_G$  [21],  $t\bar{t}$  production is also considered as a promising channel [22, 23]. The operators  $O_{uG}$  and  $O_{cG}$  lead to flavor-changing neutral current (FCNC) interactions of the top quark and contribute to  $tW$  production. The effect of introducing new couplings  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$  and  $C_{u(c)G}$  can be investigated in  $tW$  production. The chromomagnetic dipole moment operator of the top quark also affects  $t\bar{t}$  production. In the case of  $C_G$  coupling, only  $t\bar{t}$  production is modified. It should be noted that the  $O_{tW}$  and  $O_{tG}$  operators with imaginary coefficients lead to CP-violating effects. Representative Feynman diagrams for SM and new physics contributions in  $tW$  and  $t\bar{t}$  production are shown in Fig. 1.

A variety of limits have been set on the Wtb anomalous coupling through single top quark  $t$ -channel production and measurements of the W boson polarization from top quark decay by the D0 [1], ATLAS [2, 3] and CMS [4, 5] Collaborations. Direct limits on the top quark chromomagnetic dipole moment have been obtained by the CMS Collaboration at 7 and 13 TeV using top quark pair production events [6, 10]. Searches for top quark FCNC interactions have been performed at the Tevatron [7, 8] and LHC [4, 9] via single top quark production and limits are set on related anomalous couplings.

In this paper, a search for new physics in top quark production using an EFT framework is reported. This is the first such search for new physics that uses the  $tW$  process. Final states with two opposite-sign isolated leptons (electrons or muons) in association with jets identified as originating from

the fragmentation of a bottom quark (“bjets”) are analyzed. The search is sensitive to new physics contributions to  $t\bar{t}$  and  $t\bar{t}$  production, and the six effective couplings,  $C_G$ ,  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$ ,  $C_{uG}$ , and  $C_{cG}$ , are constrained assuming one non-zero effective coupling at a time. The effective couplings affect both the rate of  $t\bar{t}$  and  $tW$  production and the kinematic distributions of final state particles. For the  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$ , and  $C_G$  effective couplings, the deviation from the SM prediction is dominated by the interference term between SM and new physics diagrams, which is linear with respect to the effective coupling. Therefore, the kinematic distributions of the final-state particles vary as a function of the Wilson coefficients. For small effective couplings the kinematic distributions approach those predicted by the SM. On the other hand, the new physics terms due to the  $C_{uG}$  and  $C_{cG}$  effective couplings do not interfere with the SM  $tW$  process, and the kinematic distributions of final-state particles are determined by the new physics terms independently of the SM prediction. In this analysis, we use the rates of  $tW$  and  $t\bar{t}$  production to probe the  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$ , and  $C_G$  effective couplings. Variations in both rate and kinematic distributions of final-state particles are employed to probe the  $C_{uG}$  and  $C_{cG}$  effective couplings. The analysis utilizes proton-proton (pp) collision data collected by the CMS experiment in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ .

The paper is structured as follows. In Sect. 2, a description of the CMS detector is given and the simulated samples used in the analysis are detailed. The event selection and the SM background estimation are presented in Sect. 3. Section 4 presents a description of the signal extraction procedure. An overview of the systematic uncertainty treatment is given in Sect. 5. Finally, the constraints on the effective couplings are presented in Sect. 6, and a summary is given in Sect. 7.

## 2 The CMS detector and event simulation

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. 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. [24].

The Monte Carlo (MC) samples for the  $t\bar{t}$ ,  $tW$  and diboson ( $VV = WW, WZ, ZZ$ ) SM processes are simulated using

the POWHEG-BOX event generator (v1 for  $tW$ , v2 for  $t\bar{t}$  and diboson) [25–28] at the next-to-leading order (NLO), interfaced with PYTHIA (v8.205) [29] to simulate parton showering and to match soft radiations with the contributions from the matrix elements. The PYTHIA tune CUETP8M1 [30] is used for all samples except for the  $t\bar{t}$  sample, for which the tune CUETP8M2 [31] is used. The NNPDF3.0 [32] set of the parton distribution functions (PDFs) is used. The  $t\bar{t}$  and  $tW$  samples are normalized to the next-to-next-to-leading order (NNLO) and approximate NNLO cross section calculations, respectively [33,34]. In order to better describe the transverse momentum ( $p_T$ ) distribution of the top quark in  $t\bar{t}$  events, the top quark  $p_T$  spectrum simulated with POWHEG is reweighted to match the differential top quark  $p_T$  distribution at NNLO quantum chromodynamics (QCD) accuracy and including EW corrections calculated in Ref. [35]. Other SM background contributions, from Drell–Yan (DY),  $t\bar{t}+V$ ,  $t\bar{t}+\gamma$ , and  $W+\gamma$  processes, are simulated at NLO using the MADGRAPH5\_AMC@NLO (v2.2.2) event generator [36–38], interfaced with PYTHIA v8 for parton showering and hadronization. The events include the effects of additional pp interactions in the same or nearby bunch crossings (pileup) and are weighted according to the observed pileup distribution in the analyzed data. The CMS detector response is simulated using GEANT4 (v9.4) [39,40], followed by a detailed trigger simulation. Simulated events are reconstructed with the same algorithms as used for data.

In order to calculate the total cross sections for the  $t\bar{t}$  and  $tW$  processes and generate events in the presence of new effective interactions, the operators of Eqs. 1–5 have been implemented in the universal FEYNRULES output (UFO) format [41] through the FEYNRULES package [42]. The output EFT model is used in the MADGRAPH5\_AMC@NLO (v2.2.2) event generator [36,37]. If we allow for the presence of one operator at a time, the total cross section up to  $\mathcal{O}(\Lambda^{-4})$  can be parametrized as

$$\sigma = \sigma_{\text{SM}} + C_i \sigma_i^{(1)} + C_i^2 \sigma_i^{(2)}, \quad (6)$$

where the  $C_i$ s are effective couplings introduced in Eqs. 1–5. Here,  $\sigma_i^{(1)}$  is the contribution to the cross section due to the interference term between the SM diagrams and diagrams with one EFT vertex. The cross section  $\sigma_i^{(2)}$  is the pure new physics contribution. We use the most precise available SM cross section prediction, which are  $\sigma_{\text{SM}}^{t\bar{t}} = 832_{-29}^{+20}$  (scales)  $\pm 35$  (PDF +  $\alpha_S$ ) pb and  $\sigma_{\text{SM}}^{tW} = 71.7 \pm 1.8$  (scales)  $\pm 3.4$  (PDF +  $\alpha_S$ ) pb for  $t\bar{t}$  and  $tW$  production, respectively [33,34], where the  $\alpha_S$  is strong coupling constant. The first uncertainty reflects the uncertainties in the factorization and renormalization scales. In the framework of EFT, the  $\sigma_i^{(1)}$  and  $\sigma_i^{(2)}$  terms have been calculated at NLO accuracy for all of the operators, except  $O_G$  [16,43,44]. At the time the work for this paper was concluded, there was no

**Table 1** Contribution to the cross section due to the interference between the SM diagrams and diagrams with one EFT vertex ( $\sigma_i^{(1)}$ ), and the pure new physics ( $\sigma_i^{(2)}$ ) for  $t\bar{t}$  and  $tW$  production [in pb] for the various effective couplings for  $\Lambda = 1$  TeV. The respective  $K$  factors ( $\sigma_i^{\text{NLO}}/\sigma_i^{\text{LO}}$ ) are also shown

Channel	Contribution	$C_G$	$C_{\phi q}^{(3)}$	$C_{tW}$	$C_{tG}$	$C_{uG}$	$C_{cG}$
$t\bar{t}$	$\sigma_i^{(1)\text{--LO}}$	31.9 pb	–	–	137 pb	–	–
	$K^{(1)}$	–	–	–	1.48	–	–
	$\sigma_i^{(2)\text{--LO}}$	102.3 pb	–	–	16.4 pb	–	–
	$K^{(2)}$	–	–	–	1.44	–	–
$tW$	$\sigma_i^{(1)\text{--LO}}$	–	6.7 pb	–4.5 pb	3.3 pb	0	0
	$K^{(1)}$	–	1.32	1.27	1.27	0	0
	$\sigma_i^{(2)\text{--LO}}$	–	0.2 pb	1 pb	1.2 pb	16.2 pb	4.6 pb
	$K^{(2)}$	–	1.31	1.18	1.06	1.27	1.27

available UFO model including the  $O_G$  operator at the NLO. The values of  $\sigma_i^{(1)}$  and  $\sigma_i^{(2)}$  for various effective couplings at LO and available  $K$  factors are given in Table 1.

### 3 Event selection and background estimation

The event selection for this analysis is similar to the one used in Ref. [10]. The events of interest are recorded by the CMS detector using a combination of dilepton and single-lepton triggers. Single-lepton triggers require at least one isolated electron (muon) with  $p_T > 27$  (24) GeV. The dilepton triggers select events with at least two leptons with loose isolation requirements and  $p_T$  for the leading and sub-leading leptons greater than 23 and 12 (17 and 8) GeV for the  $ee$  ( $\mu\mu$ ) final state. In the  $e\mu$  final state, in the case of the leading lepton being an electron, the events are triggered if the electron-muon pair has a  $p_T$  greater than 23 and 8 GeV for the electron and muon, respectively. In the case of the leading lepton being a muon, the trigger thresholds are 23 and 12 GeV for the muon and electron, respectively [45].

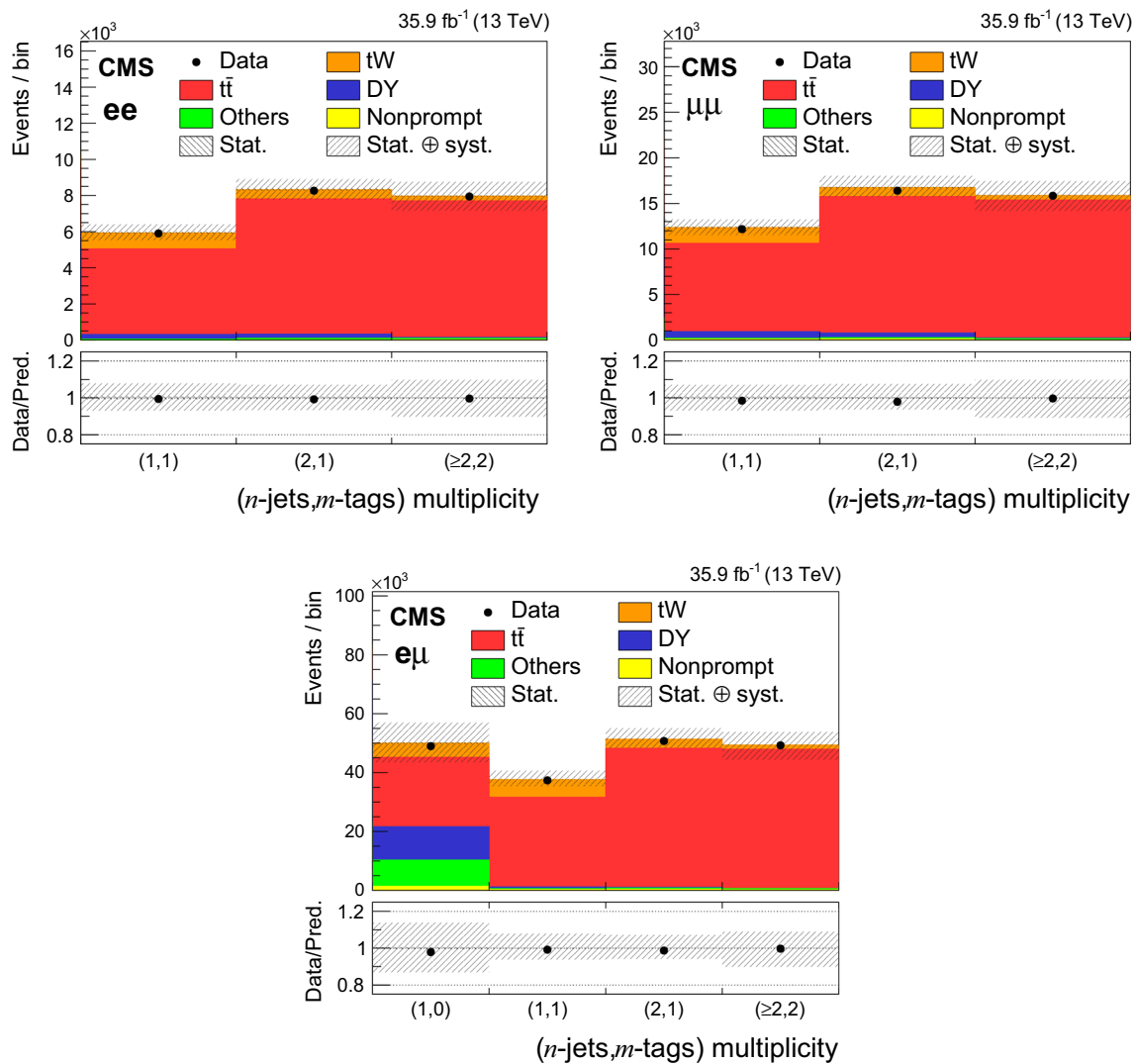
Offline, the particle-flow (PF) algorithm [46] aims to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. Electron candidates are reconstructed using tracking and ECAL information [47]. Requirements on electron identification variables based on shower shape and track-cluster matching are further applied to the reconstructed electron candidates, together with isolation criteria [10, 47]. Electron candidates are selected with  $p_T > 20$  GeV and  $|\eta| < 2.4$ . Electron candidates within the range  $1.444 < |\eta| < 1.566$ , which corresponds to the transition region between the barrel and endcap regions of the ECAL, are not considered. Information from the tracker and the muon spectrometer are combined in a global fit to reconstruct muon candidates [48]. Muon candidates are further required to have a high-quality fit including a minimum number of hits in both systems, and to be isolated [10, 48]. The muons used in this analysis are selected inside the fiducial region of

the muon spectrometer,  $|\eta| < 2.4$ , with a minimum  $p_T$  of 20 GeV.

The PF candidates are clustered into jets using the anti- $k_T$  algorithm with a distance parameter of 0.4 [49–51]. Jets are calibrated in data and simulation, accounting for energy deposits of particles from pileup [52]. Jets with  $p_T > 30$  GeV and  $|\eta| < 2.4$  are selected; loose jets are defined as jets with the  $p_T$  range between 20 and 30 GeV. Jets originating from the hadronization of  $b$  quarks are identified using the combined secondary vertex algorithm [53]; this algorithm combines information from track impact parameters and secondary vertices identified within a given jet. The chosen working point provides a signal identification efficiency of approximately 68% with a probability to misidentify light-flavor jets as  $b$ -jets of approximately 1% [53]. The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection on the plane perpendicular to the proton beams axis of the negative vector sum of the momenta of all reconstructed PF candidates in the event [54]. Corrections to the jet energies are propagated to  $\vec{p}_T^{\text{miss}}$ . Its magnitude is referred to as  $p_T^{\text{miss}}$ .

Events are required to have at least two leptons (electrons or muons) with opposite sign and with an invariant mass above 20 GeV. The leading lepton must fulfill  $p_T > 25$  GeV. For the same-flavor lepton channels, to suppress the DY background, the dilepton invariant mass must not be within 15 GeV of the  $Z$  boson mass and a minimal value (of 60 GeV) on  $p_T^{\text{miss}}$  is applied.

The events are divided into the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels according to the flavors of the two leptons with the highest  $p_T$  and are further categorized in different bins depending on the number of jets (“ $n$ -jets”) and number  $b$ -tagged jets (“ $m$ -tags”) in the final state. The largest number of  $tW$  events is expected in the category with exactly one  $b$ -tagged jet (1-jet, 1-tag) followed by the category with two jets, of which one is a  $b$ -jet (2-jets, 1-tag). Events in the categories with more than two jets and exactly two  $b$ -tagged jets are dominated by the  $t\bar{t}$  process ( $\geq 2$ -jets, 2-tags). Categories with zero  $b$ -jets are dominated by DY events in the  $ee$  and  $\mu\mu$  channels and



**Fig. 2** The observed number of events and SM background predictions in the search regions of the analysis for the  $ee$  (upper left),  $\mu\mu$  (upper right), and  $e\mu$  (lower) channels. The hatched bands correspond to the quadratic sum of statistical and systematic uncertainties in the event

yield for the SM background predictions. The ratios of data to the sum of the predicted yields are shown at the bottom of each plot. The narrow hatched bands represent the contribution from the statistical uncertainty in the MC simulation

are not used in the analysis. However, in the  $e\mu$  channel, the contamination of DY events is lower and a significant number of tW events is present in the category with one jet and zero b-tagged jets (1-jet,0-tag). The latter category is included in this analysis. In Fig. 2, the data in the ten search regions are shown together with the SM background predictions.

The contributions of SM processes leading to two prompt leptons in the final state are estimated from simulated samples and are normalised to the integrated luminosity of the data. These contributions originate mainly from  $t\bar{t}$ , tW and DY production. Other SM processes, such as diboson,  $t\bar{t}+V$  and  $t\bar{t}+\gamma$  have significantly smaller contributions.

To correct the DY simulation for the efficiency of the  $p_T^{\text{miss}}$  threshold and for the mismodeling of the heavy-flavour con-

tent, scale factors are derived using the ratio of the numbers of simulated events inside and outside the dilepton invariant mass window, 76–106 GeV. The observed event yield inside the window is scaled to estimate the DY background outside the mass window [55].

The nonprompt lepton backgrounds which contain fake lepton(s) from a misreconstructed  $\gamma$  or jet(s) are also considered. The contribution of misidentified or converted  $\gamma$  events from the  $W\gamma$  process is estimated from MC simulation. The contribution from  $W$ +jets and multijet processes is estimated by a data-based technique using events with same-sign leptons. The method is based on the assumption that the probability of assigning positive or negative charge to the fake lepton is equal. Therefore, the background contribution from

**Table 2** Number of expected events from  $tW$ ,  $t\bar{t}$  and  $DY$  production, from the remaining backgrounds (other), total background contribution and observed events in data after all selections for the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels and for different  $(n\text{-jets}, m\text{-tags})$  categories. The uncer-

tainties correspond to the statistical contribution only for the individual background predictions and to the quadratic sum of the statistical and systematic contributions for the total background predictions

Channel	$(n\text{-jets}, m\text{-tags})$	Prediction					Data
		$tW$	$t\bar{t}$	$DY$	Other	Total yield	
$ee$	(1,1)	$884 \pm 8$	$4741 \pm 15$	$258 \pm 50$	$53 \pm 5$	$5936 \pm 470$	5902
	(2,1)	$518 \pm 6$	$7479 \pm 19$	$241 \pm 53$	$94 \pm 5$	$8331 \pm 597$	8266
	$(\geq 2, 2)$	$267 \pm 4$	$7561 \pm 18$	$46 \pm 24$	$99 \pm 4$	$7973 \pm 819$	7945
$e\mu$	(1,0)	$4835 \pm 20$	$23557 \pm 35$	$11352 \pm 277$	$10294 \pm 72$	$50038 \pm 6931$	48973
	(1,1)	$6048 \pm 22$	$30436 \pm 38$	$561 \pm 66$	$629 \pm 13$	$37673 \pm 2984$	37370
	(2,1)	$3117 \pm 16$	$47206 \pm 48$	$278 \pm 48$	$781 \pm 9$	$51382 \pm 3714$	50725
	$(\geq 2, 2)$	$1450 \pm 10$	$47310 \pm 46$	$32 \pm 22$	$598 \pm 9$	$49391 \pm 5010$	49262
$\mu\mu$	(1,1)	$1738 \pm 12$	$9700 \pm 21$	$744 \pm 90$	$183 \pm 5$	$12366 \pm 879$	12178
	(2,1)	$989 \pm 9$	$14987 \pm 27$	$501 \pm 75$	$275 \pm 5$	$16751 \pm 1276$	16395
	$(\geq 2, 2)$	$508 \pm 6$	$15136 \pm 26$	$82 \pm 24$	$163 \pm 5$	$15889 \pm 1714$	15838

**Table 3** Summary of the observables used to probe the effective couplings in various  $(n\text{-jets}, m\text{-tags})$  categories in the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels

Eff. coupling	Channel	Categories				
		1-jet, 0-tag	1-jet, 1-tag	2-jets, 1-tag	>2-jets, 1-tag	$\geq 2$ -jets, 2-tags
$C_G$	$ee$	–	Yield	Yield	–	Yield
	$e\mu$	Yield	Yield	Yield	–	Yield
	$\mu\mu$	–	Yield	Yield	–	Yield
$C_{\phi q}^{(3)}, C_{tW}, C_{tG}$	$ee$	–	NN <sub>11</sub>	NN <sub>21</sub>	–	Yield
	$e\mu$	NN <sub>10</sub>	NN <sub>11</sub>	NN <sub>21</sub>	–	Yield
	$\mu\mu$	–	NN <sub>11</sub>	NN <sub>21</sub>	–	Yield
$C_{uG}, C_{cG}$	$ee$	–	NN <sub>FCNC</sub>	–	–	–
	$e\mu$	–	NN <sub>FCNC</sub>	–	–	–
	$\mu\mu$	–	NN <sub>FCNC</sub>	–	–	–

fake leptons in the final selection (opposite-sign sample) can be estimated from the corresponding sample with same-sign leptons. In this latter same-sign event sample, the remaining small contribution from prompt-lepton backgrounds is subtracted from data using MC samples.

After all selections, the expected numbers of events from  $tW$ ,  $t\bar{t}$ ,  $DY$ , and remaining background contributions mentioned above, as well as the total number of background events are reported in Table 2 for the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels and for the various  $(n\text{-jets}, m\text{-tags})$  categories. We find generally very good agreement between data and predictions, within the uncertainties of the data.

#### 4 Signal extraction using neural networks tools

The purpose of the analysis is to search for deviations from the SM predictions in the  $tW$  and  $t\bar{t}$  production due to new physics, parametrized with the presence of new effective cou-

plings. In order to investigate the effect of the non-zero effective couplings, it is important to find suitable variables with high discrimination power between the signal and the background. Depending on the couplings, the total yield or the distribution of the output of a neural network (NN) algorithm is employed, as summarized in Table 3. The NN algorithm used in this analysis is a multilayer perceptron [56].

All the effective couplings introduced in Sect. 1 can contribute to  $tW$  production except the triple gluon field strength operator,  $O_G$  which only affects  $t\bar{t}$  production. As observed in previous analysis [22] and confirmed here, the top quark  $p_T$  distribution is sensitive to the triple-gluon field-strength operator. The kinematic distributions of final-state particles show less discrimination power than the top quark  $p_T$  distribution. In addition, they vary with the value of  $C_G$  and approach the SM prediction for decreasing values of  $C_G$ . Therefore, we use the total yield in various categories to constrain the  $C_G$  effective coupling.

The deviation from the SM  $t\bar{W}$  production because of the interference between the SM and the  $O_{tG}$ ,  $O_{\phi q}^{(3)}$ , and  $O_{tW}$  operators is of the order of  $1/\Lambda^2$ . It is assumed that the new physics scale  $\Lambda$  is larger than the scale we probe. Therefore,  $1/\Lambda^4$  contributions from the new physics terms are small compared to the contribution from the interference term. The operator  $O_{\phi q}^{(3)}$  is similar to the SM  $Wtb$  operator and leads to a rescaling of the SM  $Wtb$  vertex [13]. The  $O_{tW}$  and  $O_{tG}$  operators lead to the right-handed  $Wtb$  interaction and a tensor-like  $ttg$  interaction, respectively, which are absent in the SM at the first order. Their effects have been investigated via the various kinematic distributions of the final-state particles considered in this analysis and are found to be not distinguishable from the SM  $t\bar{W}$  and  $t\bar{t}$  processes for unconstrained values of the effective couplings within the current precision on data. After the selection described in Section 3, the dominant background comes from  $t\bar{t}$  production, with a contribution of about 90%. In order to observe deviations from SM  $t\bar{W}$  production in the presence of the  $O_{\phi q}^{(3)}$ ,  $O_{tW}$ , and  $O_{tG}$  effective operators, we need to separate  $t\bar{W}$  events from the large number of  $t\bar{t}$  events. Two independent NNs are trained to separate  $t\bar{t}$  events (the background) and  $t\bar{W}$  events (considered as the signal) in the (1-jet, 1-tag) ( $NN_{11}$ ) and (2-jets, 1-tag) ( $NN_{21}$ ) categories, which have significant signal contributions [57]. For the  $e\mu$  channel, another NN is used for the (1-jet, 0-tag) ( $NN_{10}$ ) category, in which the  $t\bar{t}$ ,  $WW$ , and  $DY$  events are combined and are considered as the background. A comparison between the observed data and the SM background prediction of the NN output shape in various ( $n$ -jets,  $m$ -tags) categories is shown for the  $ee$  and  $\mu\mu$  channels in Fig. 3 and for the  $e\mu$  channel in Fig. 4 (left column).

The presence of the  $O_{uG}$  and  $O_{cG}$  operators changes the initial-state particle (see Fig. 1), and leads to different kinematic distributions for the final-state particles, compared to the SM  $t\bar{W}$  process. For these FCNC operators, new physics effects on final-state particle distributions are expected to be distinguishable from SM processes. In order to search for new physics due to the  $O_{uG}$  and  $O_{cG}$  effective operators, an NN ( $NN_{FCNC}$ ) is used to separate SM backgrounds ( $t\bar{t}$  and  $t\bar{W}$  events together) and new physics signals for events with exactly one b-tagged jet with no requirement on the number of light-flavor jets ( $n$ -jets, 1-tag). The comparison of the NN output for data, SM background and signal ( $t\bar{W}$  events via FCNC interactions) is shown in Fig. 4 (right column) for the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels.

The various input variables for training the NN introduced above are described below and are shown in Table 4.

- $M_{\ell\ell}$  (where  $\ell = e$  or  $\mu$ ), invariant mass of dilepton system;
- $p_T^{\ell\ell}$ ,  $p_T$  of dilepton system;

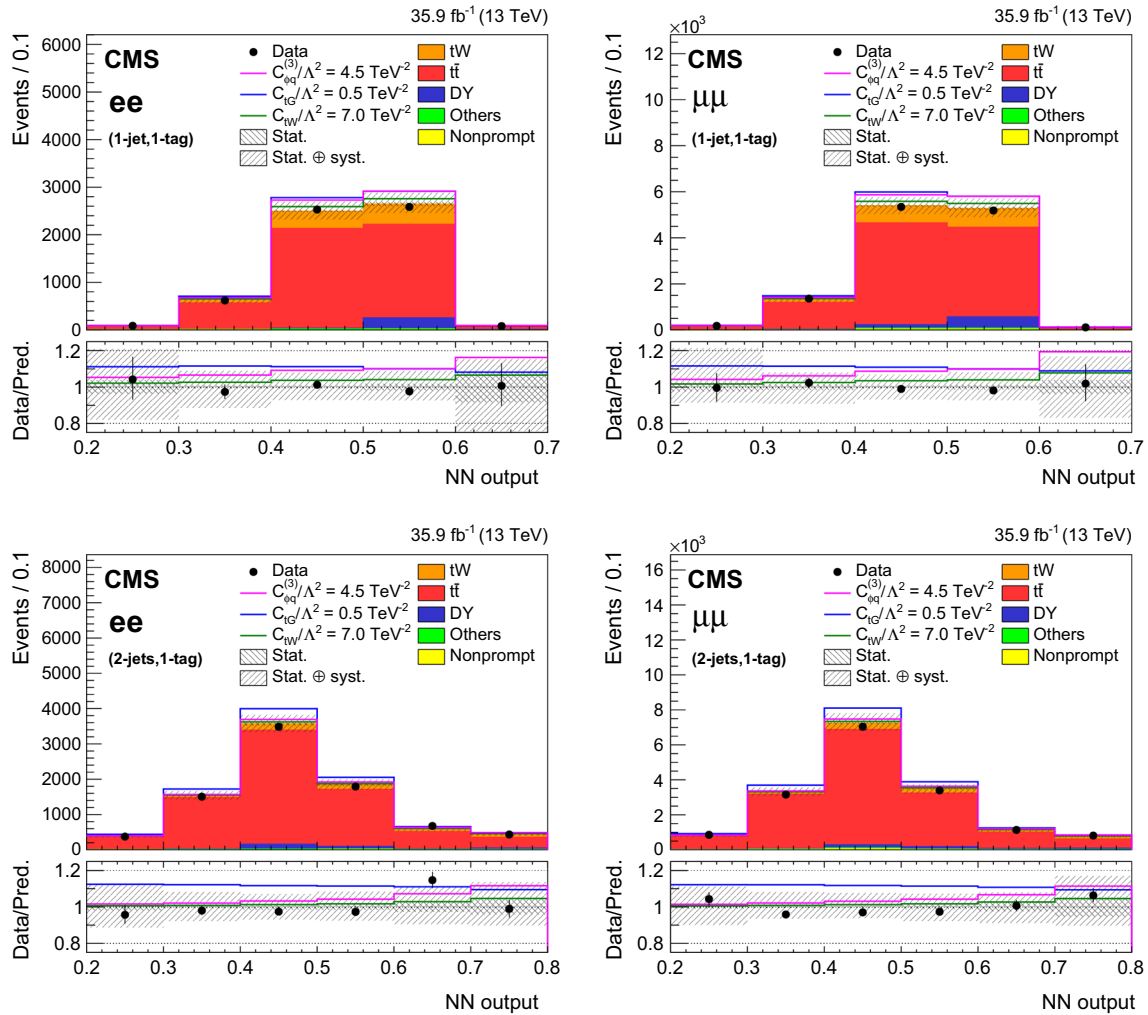
- $\Delta p_T(\ell_1, \ell_2)$ ,  $p_T^{\text{leading lepton}} - p_T^{\text{sub-leading lepton}}$ ;
- $p_T^{\ell_1}$ ,  $p_T$  of leading lepton;
- $\text{Centrality}(\ell_1, \text{jet}_1)$ , scalar sum of  $p_T$  of the leading lepton and leading jet, over total energy of selected leptons and jets;
- $\text{Centrality}(\ell_1, \ell_2)$ , scalar sum of  $p_T$  of the leading and sub-leading leptons, over total energy of selected leptons and jets;
- $\Delta\Phi(\ell\ell, \text{jet}_1)$ ,  $\Delta\Phi$  between dilepton system and leading jet where  $\Phi$  is azimuthal angle;
- $p_T(\ell\ell, \text{jet}_1)$ ,  $p_T$  of dilepton and leading jet system;
- $p_T(\ell_1, \text{jet}_1)$ ,  $p_T$  of leading lepton and leading jet system;
- $\text{Centrality}(\ell\ell, \text{jet}_1)$ , scalar sum of  $p_T$  of the dilepton system and leading jet, over total energy of selected leptons and jets;
- $\Delta R(\ell_1, \ell_2)$ ,  $\sqrt{(\eta^{\ell_1} - \eta^{\ell_2})^2 + (\Phi^{\ell_1} - \Phi^{\ell_2})^2}$ ;
- $\Delta R(\ell_1, \text{jet}_1)$ ,  $\sqrt{(\eta^{\ell_1} - \eta^{\text{jet}_1})^2 + (\Phi^{\ell_1} - \Phi^{\text{jet}_1})^2}$ ;
- $M(\ell_1, \text{jet}_1)$ , invariant mass of leading lepton and leading jet;
- $M(\text{jet}_1, \text{jet}_2)$ , invariant mass of leading jet and sub-leading jet;
- $\Delta R(\ell_1, \text{jet}_2)$ ,  $\sqrt{(\eta^{\ell_1} - \eta^{\text{jet}_2})^2 + (\Phi^{\ell_1} - \Phi^{\text{jet}_2})^2}$ ;
- $\Delta R(\ell\ell, \text{jet}_1)$ ,  $\sqrt{(\eta^{\ell\ell} - \eta^{\text{jet}_1})^2 + (\Phi^{\ell\ell} - \Phi^{\text{jet}_1})^2}$ ;
- $\Delta p_T(\ell_2, \text{jet}_2)$ ,  $p_T^{\ell_2} - p_T^{\text{jet}_2}$ ;
- $M(\ell_2, \text{jet}_1)$ , invariant mass of sub-leading lepton and leading jet.

### 5 Systematic uncertainties

The normalization and shape of the signal and the backgrounds are both affected by different sources of systematic uncertainty. For each source, an induced variation can be parametrized, and treated as a nuisance parameter in the fit that is described in the next section.

A systematic uncertainty of 2.5% is assigned to the integrated luminosity and is used for signal and background rates [58]. The efficiency corrections for trigger and offline selection of leptons were estimated by comparing the efficiency measured in data and in MC simulation using  $Z \rightarrow \ell\ell$  events, based on a “tag-and-probe” method as in Ref. [59]. The scale factors obtained are varied by one standard deviation to take into account the corresponding uncertainties in the efficiency. The jet energy scale and resolution uncertainties depend on  $p_T$  and  $\eta$  of the jet and are computed by shifting the energy of each jet and propagating the variation to  $\vec{p}_T^{\text{miss}}$  coherently [60].

The uncertainty in the b tagging is estimated by varying the b tagging scale factors within one standard deviation [53]. Effects of the uncertainty in the distribution of the number of pileup interactions are evaluated by varying the effective inelastic pp cross section used to predict the num-



**Fig. 3** The NN output distributions for data and simulation for the ee (left) and  $\mu\mu$  (right) channels in 1-jet, 1-tag (upper) and 2-jets, 1-tag (lower) categories. The hatched bands correspond to the quadratic sum of the statistical and systematic uncertainties in the event yield for the sum of signal and background predictions. The ratios of data to the

sum of the predicted yields are shown at the lower panel of each graph. The narrow hatched bands represent the contribution from the statistical uncertainty in the MC simulation. In each plot, the expected distributions assuming specific values for the effective couplings (given in the legend) are shown as the solid curves

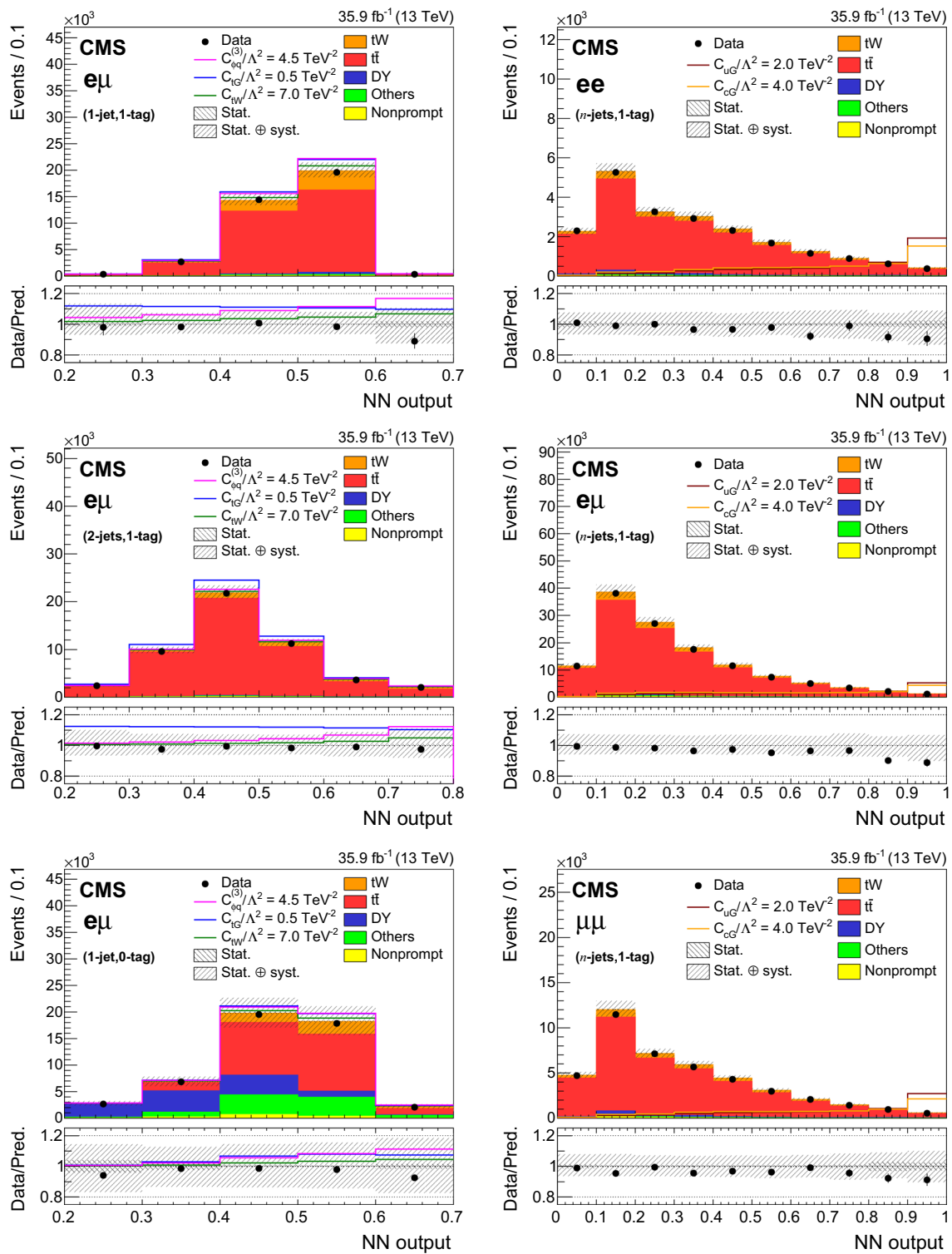
ber of pileup interactions in MC simulation by  $\pm 4.6\%$  of its nominal value [61].

The uncertainty in the DY contribution in categories with one or two b-tagged jets is considered to be 50 and 30% in the  $e\mu$  and same-flavor dilepton channels, respectively [10,57]. For the DY normalization in the (1-jet, 0-tag) category, an uncertainty of 15% is assigned [62]. In addition, systematic uncertainties related to the PDF, and to the renormalization and factorization scale uncertainty are taken into account for DY process in the (1-jet, 0-tag) category. The uncertainty in the yield of nonprompt lepton backgrounds is considered to be 50% [57]. Contributions to the background from  $t\bar{t}$  production in association with a boson, as well as diboson production, are estimated from simulation and a systematic uncertainty of 50% is conservatively assigned [63].

Various uncertainties originate from the theoretical predictions. The effect of the renormalization and factorization scale uncertainty from the  $t\bar{t}$  and  $tW$  MC generators is estimated by varying the scales used during the generation of the simulation sample independently by a factor 0.5, 1 or 2. Unphysical cases, where one scale fluctuates up while the other fluctuates down, are not considered. The top quark  $p_T$  reweighting procedure, discussed in Sect. 2, is applied on top of the nominal POWHEG prediction at NLO to account for the higher-order corrections.

The uncertainty in the PDFs for each simulated signal process is obtained using the replicas of the NNPDF 3.0 set [64]. The most recent measurement of the top quark mass by CMS yields a total uncertainty of  $\pm 0.49$  GeV [65]. We consider variations of the top quark mass due to this uncertainty and





**Fig. 4** The NN output distributions for (left) data and simulation for the  $e\mu$  channel in 1-jet, 1-tag (upper) and 2-jets, 1-tag (middle) and 1-jet, 0-tag (lower) categories; and for (right) data, simulation, and FCNC signals in the  $n$ -jets, 1-tag category used in the limit setting for the  $ee$  (upper),  $e\mu$  (middle), and  $\mu\mu$  (lower) channels. The hatched bands correspond to the quadratic sum of the statistical and systematic un-

certainties in the event yield for the sum of signal and background predictions. The ratios of data to the sum of the predicted yields are shown at the lower panel of each graph. The narrow hatched bands represent the contribution from the statistical uncertainty in the MC simulation. In each plot, the expected distributions assuming specific values for the effective couplings (given in the legend) are shown as the solid curves

**Table 4** Input variables for the NN used in the analysis in various bins of  $n$ -jets and  $m$ -tags. The symbols “×” indicate the input variables used in the four NNs

Variable	NN <sub>10</sub>	NN <sub>11</sub>	NN <sub>21</sub>	NN <sub>FCNC</sub>
$M_{\ell\ell}$	×			×
$p_T^{\ell\ell}$	×		×	×
$\Delta p_T(\ell_1, \ell_2)$	×			×
$p_T^{\ell_1}$	×		×	×
Centrality( $\ell_1, \text{jet}_1$ )	×			×
Centrality( $\ell_1, \ell_2$ )	×			×
$\Delta\Phi(\ell\ell, \text{jet}_1)$	×	×	×	
$p_T(\ell\ell, \text{jet}_1)$		×		×
$p_T(\ell_1, \text{jet}_1)$		×		
Centrality( $\ell\ell, \text{jet}_1$ )		×		
$\Delta R(\ell_1, \ell_2)$		×		
$\Delta R(\ell_1, \text{jet}_1)$		×		
$M(\ell_1, \text{jet}_1)$			×	
$M(\text{jet}_1, \text{jet}_2)$			×	
$\Delta R(\ell_1, \text{jet}_2)$			×	
$\Delta R(\ell\ell, \text{jet}_1)$			×	×
$\Delta p_T(\ell_2, \text{jet}_2)$			×	
$M(\ell_2, \text{jet}_1)$				×

they are found to be insignificant. At NLO QCD,  $t\bar{W}$  production is expected to interfere with  $t\bar{t}$  production [66]. Two schemes for defining the  $t\bar{W}$  signal in a way that distinguishes it from the  $t\bar{t}$  production have been compared in the analysis: the “diagram removal” (DR), in which all doubly resonant NLO  $t\bar{W}$  diagrams are removed, and the “diagram subtraction” (DS), where a gauge-invariant subtractive term modifies the NLO  $t\bar{W}$  cross section to locally cancel the contribution from  $t\bar{t}$  production [66–68]. The DR method is used for the nominal  $t\bar{W}$  sample and the difference with respect to the sample simulated using the DS method is taken as a systematic uncertainty. The model parameter  $h_{\text{damp}}$  in  $t\bar{t}$  POWHEG [25] that controls the matching of the matrix elements to the PYTHIA parton showers is varied from a top quark mass default value of 172.5 GeV by factors of 0.5 and 2 for estimating the uncertainties from the matching between jets from matrix element calculations and parton shower emissions. The renormalization scale for QCD emissions in the initial- and final-state radiation (ISR and FSR) is varied up and down by factors of 2 and  $\sqrt{2}$ , respectively, to account for parton shower QCD scale variation error in both  $t\bar{t}$  and  $t\bar{W}$  samples [69]. In addition, several dedicated  $t\bar{t}$  samples are used to estimate shower modeling uncertainties in both underlying event and color re-connections [10, 31, 69]. To estimate model uncertainties,  $t\bar{W}$  and  $t\bar{t}$  samples are generated with POWHEG as described in Sect. 2, varying the relevant model parameters with respect to the nominal samples.

## 6 Constraints on the effective couplings

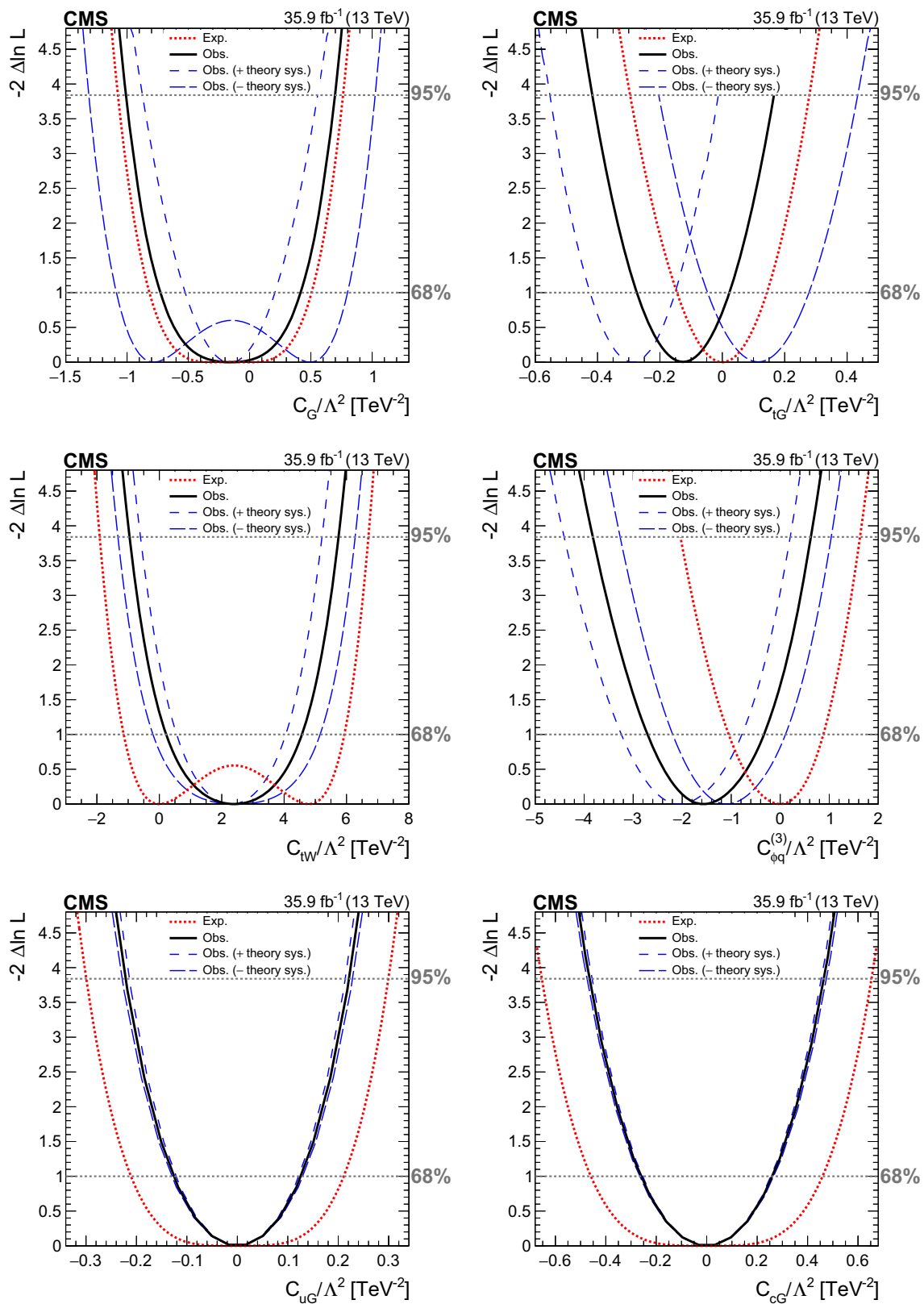
The six Wilson coefficients sensitive to new physics contributions in top quark interactions, as defined in Eqs. 1–5, are tested separately in the observed data. The event yields and the NN output distributions in each analysis category, summarized in Table 3, are used to construct a binned likelihood function. All sources of systematic uncertainty, described in Sect. 5, are taken into account as nuisance parameters in the fit. A simultaneous binned maximum-likelihood fit is performed to find the best fit value for each Wilson coefficient together with 68 and 95% confidence intervals (CIs) [70]. In this section, distributions of the log-likelihood functions are shown with one nonzero effective coupling at a time for  $\Lambda = 1$  TeV.

The SM cross section prediction for the  $t\bar{t}$  and  $t\bar{W}$  processes,  $\sigma_i^{(1)}$  and  $\sigma_i^{(2)}$  (see Table 1), are accompanied by uncertainties in scales and PDFs. These theoretical uncertainties can affect the bounds on the Wilson coefficients. In order to study this effect, the fit is performed on data, while theoretical uncertainties are varied within one standard deviation and are shown together with the nominal results in the likelihood scan plots in Fig. 5. The nominal theoretical cross sections for  $t\bar{t}$  and  $t\bar{W}$  processes are varied by [+4.8%, –5.5%] and [+5.4%, –5.4%], respectively. These variations cover the uncertainties arising from the variations of factorization and renormalization scales and PDFs [10, 34]. The scale variations for  $\sigma_i^{(1)}$  and  $\sigma_i^{(2)}$  are evaluated to be within 1–25%. We assumed that the scale uncertainty is 100% correlated among the terms  $\sigma_{\text{SM}}$ ,  $\sigma_i^{(1)}$ , and  $\sigma_i^{(2)}$ .

### 6.1 Exclusion limits on the $C_G$ effective coupling

In order to constrain the  $C_G$  coupling, the effect on the  $t\bar{t}$  rate in various ( $n$ -jets,  $m$ -tags) categories is considered. The impact of the difference between the kinematic distributions of  $t\bar{t}$  events from the  $O_G$  interaction and from the SM interactions on the acceptance is evaluated to be 3% for  $C_G \sim 1$ . This uncertainty is considered only for the  $C_G$  coupling since the top  $p_T$  spectrum is affected considerably by this operator, while other operators lead to a  $p_T$  spectrum similar to the SM prediction for unconstrained values of the probed Wilson coefficients. The fit is performed simultaneously on the observed event yields in the categories presented in Fig. 2 in the (1-jet, 1-tag), (2-jets, 1-tag), and ( $\geq 2$ -jets, 2-tags) categories for the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels. In addition, the (1-jet, 0-tag) category is included only for the  $e\mu$  channel. The main limiting factor on the constraints in the  $C_G$  coupling is the uncertainty in the signal acceptance found after maximizing the likelihood, followed by uncertainties in the integrated luminosity calibration and the trigger scale factor.

The results of the fit for the individual channels and for all channels combined are listed in the first row of Table 5.



**Fig. 5** Observed (solid) and expected (dotted) log likelihoods for the effective couplings:  $C_G$  (upper left),  $C_{IG}$  (upper right),  $C_{IW}$  (middle left),  $C_{\phi q}^{(3)}$  (middle right),  $C_{UG}$  (lower left), and  $C_{CG}$  (lower right). The

dashed curves represent fits to the observed data with the variations of normalization due to the theoretical uncertainties

**Table 5** Summary of the observed and expected allowed intervals on the effective couplings obtained in the  $ee$ ,  $e\mu$ , and  $\mu\mu$  channels, and all channels combined. All sources of systematic uncertainty, described in

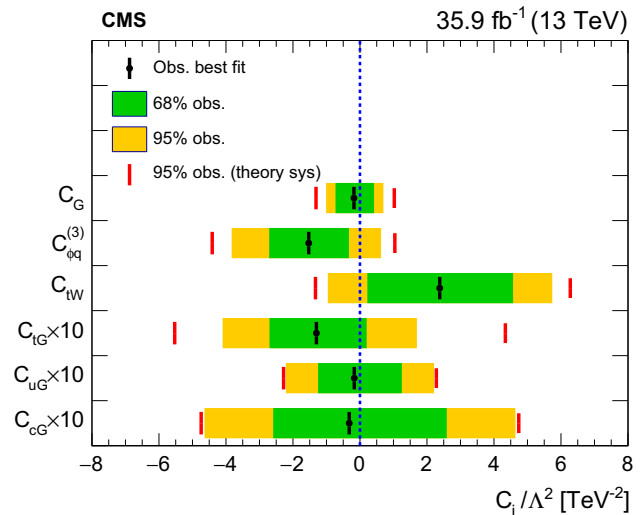
Sect. 5, are taken into account with the exception of the uncertainties on the SM cross section predictions for the  $t\bar{t}$  and  $tW$  processes

Effective coupling	Channel	Observed [ $\text{TeV}^{-2}$ ]			Expected [ $\text{TeV}^{-2}$ ]		
		Best fit	[68% CI]	[95% CI]	Best fit	[68% CI]	[95% CI]
$C_G/\Lambda^2$	$ee$	-0.14	[-0.82, 0.51]	[-1.14, 0.83]	0.00	[-0.90, 0.59]	[-1.20, 0.88]
	$e\mu$	-0.18	[-0.73, 0.42]	[-1.01, 0.70]	0.00	[-0.82, 0.51]	[-1.08, 0.77]
	$\mu\mu$	-0.14	[-0.75, 0.44]	[-1.06, 0.75]	0.00	[-0.88, 0.57]	[-1.16, 0.85]
	Combined	-0.18	[-0.73, 0.42]	[-1.01, 0.70]	0.00	[-0.82, 0.51]	[-1.07, 0.76]
$C_{\phi q}^{(3)}/\Lambda^2$	$ee$	1.12	[-1.18, 2.89]	[-4.03, 4.37]	0.00	[-2.53, 1.74]	[-6.40, 3.27]
	$e\mu$	-0.70	[-2.16, 0.59]	[-3.74, 1.61]	0.00	[-1.34, 1.12]	[-2.57, 2.15]
	$\mu\mu$	1.13	[-0.87, 2.86]	[-3.58, 4.46]	0.00	[-2.20, 1.92]	[-4.68, 3.66]
	Combined	-1.52	[-2.71, -0.33]	[-3.82, 0.63]	0.00	[-1.05, 0.88]	[-2.04, 1.63]
$C_{tW}/\Lambda^2$	$ee$	6.18	[-3.02, 7.81]	[-4.16, 8.95]	0.00	[-2.02, 6.81]	[-3.33, 8.12]
	$e\mu$	1.64	[-0.80, 5.59]	[-1.89, 6.68]	0.00	[-1.40, 6.19]	[-2.39, 7.18]
	$\mu\mu$	-1.40	[-3.00, 7.79]	[-4.23, 9.01]	0.00	[-2.18, 6.97]	[-3.63, 8.42]
	Combined	2.38	[0.22, 4.57]	[-0.96, 5.74]	0.00	[-1.14, 5.93]	[-1.91, 6.70]
$C_{tG}/\Lambda^2$	$ee$	-0.19	[-0.40, 0.02]	[-0.65, 0.22]	0.00	[-0.22, 0.21]	[-0.44, 0.41]
	$e\mu$	-0.03	[-0.19, 0.11]	[-0.34, 0.27]	0.00	[-0.17, 0.15]	[-0.34, 0.29]
	$\mu\mu$	-0.15	[-0.34, 0.02]	[-0.53, 0.19]	0.00	[-0.19, 0.18]	[-0.40, 0.35]
	Combined	-0.13	[-0.27, 0.02]	[-0.41, 0.17]	0.00	[-0.15, 0.14]	[-0.30, 0.28]
$C_{uG}/\Lambda^2$	$ee$	-0.017	[-0.22, 0.22]	[-0.37, 0.37]	0.00	[-0.29, 0.29]	[-0.42, 0.42]
	$e\mu$	-0.017	[-0.17, 0.17]	[-0.29, 0.29]	0.00	[-0.26, 0.26]	[-0.38, 0.38]
	$\mu\mu$	-0.017	[-0.17, 0.17]	[-0.29, 0.29]	0.00	[-0.27, 0.27]	[-0.38, 0.38]
	Combined	-0.017	[-0.13, 0.13]	[-0.22, 0.22]	0.00	[-0.21, 0.21]	[-0.30, 0.30]
$C_{cG}/\Lambda^2$	$ee$	-0.032	[-0.47, 0.47]	[-0.78, 0.78]	0.00	[-0.63, 0.63]	[-0.92, 0.92]
	$e\mu$	-0.032	[-0.34, 0.34]	[-0.60, 0.60]	0.00	[-0.56, 0.56]	[-0.81, 0.81]
	$\mu\mu$	-0.032	[-0.36, 0.36]	[-0.63, 0.63]	0.00	[-0.58, 0.58]	[-0.84, 0.84]
	Combined	-0.032	[-0.26, 0.26]	[-0.46, 0.46]	0.00	[-0.46, 0.46]	[-0.65, 0.65]

The results of the likelihood scans of the  $C_G$  coupling are shown in Fig. 5 (upper left plot). The likelihood scan result of the nominal fit, in which the nominal values of  $\sigma_{SM}$ ,  $\sigma_i^{(1)}$ , and  $\sigma_i^{(2)}$  terms are assumed, is shown as the thick curve. The thin dashed curves are the results of the fit to the observed data when the assumed values of the  $\sigma_{SM}$ ,  $\sigma_i^{(1)}$ , and  $\sigma_i^{(2)}$  terms are varied due to the scale and PDF uncertainties. As a second-order parametrization, given by Eq. 6 is used to fit the data, the resulting likelihood function could have two minima, as can be seen in some of the plots in Fig. 5.

### 6.2 Exclusion limits on the $C_{tG}$ , $C_{\phi q}^{(3)}$ , and $C_{tW}$ effective couplings

In order to set limits on the effective couplings  $C_{tG}$ ,  $C_{\phi q}^{(3)}$ , and  $C_{tW}$ , we utilize the NN output distributions for both data and MC expectation in the (1-jet, 1-tag) and (2-jets, 1-tag) regions and event yields in the ( $\geq 2$ -jets, 2-tags) region for the three dilepton channels. The inclusion of the ( $\geq 2$ -jets,



**Fig. 6** Observed best fits together with one and two standard deviation bounds on the top quark effective couplings. The dashed line shows the SM expectation and the vertical lines indicate the 95% CL bounds including the theoretical uncertainties

**Table 6** Estimation of the effect of the most important uncertainty sources on the observed allowed intervals of in the fit

Uncertainty	$C_G$ (%)	$C_{\phi q}^{(3)}$ (%)	$C_{tW}$ (%)	$C_{tG}$ (%)	$C_{uG}$ (%)	$C_{cG}$ (%)
Trigger	10.2	2.3	7.0	2.9	1.7	2.5
Lepton ident./isolation	7.4	1.1	1.2	23.0	<1	<1
Jet energy scale	<1	25.0	17.8	4.9	<1	<1
tW DS/DR	<1	24.2	4.4	3.0	7.6	7.8
ME/PS matching	<1	4.9	9.9	1.2	<1	<1
ISR scale	<1	5.0	5.6	<1	<1	<1
FSR scale	5.8	4.4	4.0	10.2	<1	<1
DY background	<1	7.5	5.5	21.5	<1	<1
Nonprompt background	<1	1.4	5.8	<1	<1	<1
Integrated luminosity	13.1	<1	1.1	18.8	<1	<1
Statistical	5.8	2.3	23.7	<1	72.6	73.6
MC statistical	<1	12.1	3.7	5.2	2.9	2.5

2-tags) and (2-jets, 1-tag) categories provides a constraint of the normalization and systematic uncertainties in the  $t\bar{t}$  background. In addition, the (1-jet, 0-tag) category is included for the  $e\mu$  channel to increase the signal sensitivity. The results of the likelihood scans of the  $C_{tG}$ ,  $C_{\phi q}^{(3)}$ , and  $C_{tW}$  Wilson coefficients are shown in Fig. 5 for the combination of all channels. The inclusion of the  $C_{tG}$  coupling to the  $tW$  process tightens the 2 standard deviations band by 7%. The results for the individual channels, and the combined results are listed in Table 5 (second, third, and fourth rows). The three main sources of uncertainty that affect the interval determination are uncertainties in the DY estimation, integrated luminosity, and lepton identification scale factors for  $C_{tG}$ ; jet energy scale,  $t\bar{t}$  and  $tW$  interference at NLO, and statistical uncertainty in MC samples for  $C_{\phi q}^{(3)}$ ; statistical uncertainty in data, jet energy scale, and the POWHEG matching method for  $C_{tW}$  effective couplings.

### 6.3 Exclusion limits on the $C_{uG}$ and $C_{cG}$ effective couplings

Since the  $tW$  production via FCNC interactions does not interfere with the SM  $tW$  process (with the assumption of  $|V_{td}| = |V_{ts}| = 0$ ), the FCNC signal sample is used to set upper bounds on the related Wilson coefficients. Events with exactly one b-tagged jet are included in the limit setting procedure with no requirement on the number of light-flavor jets ( $n$ -jets, 1-tag). The observed (median expected) 95% confidence level (CL) upper limits on the product of cross section times branching fractions  $\sigma(pp \rightarrow tW)\mathcal{B}(W \rightarrow \ell\nu)^2$  for the  $C_{uG}$  and  $C_{cG}$  FCNC signals for the combination of the  $ee$ ,  $\mu\mu$ , and  $e\mu$  channels are found to be 0.11 (0.20) pb and 0.13 (0.26) pb, respectively. These results are used to calculate upper limits on the Wilson coefficients  $C_{uG}$ ,  $C_{cG}$ , and on the branching fractions  $\mathcal{B}(t \rightarrow ug)$  and  $\mathcal{B}(t \rightarrow cg)$ . The limits on the  $C_{uG}$  and  $C_{cG}$  couplings are summarized in the last two

rows of Table 5, and correspond to the observed (expected) limits on  $\mathcal{B}(t \rightarrow ug) < 0.12$  (0.22)% and  $\mathcal{B}(t \rightarrow cg) < 0.53$  (1.05)% at 95% CL. The statistical uncertainty in data is the dominant source of uncertainty affecting the limits on the FCNC couplings. The second and third most important uncertainties originate from  $t\bar{t}$  and  $tW$  interferences at NLO and FSR in  $t\bar{t}$  events.

The observed best fit together with one and two standard deviation bounds on the six Wilson coefficients,  $C_{\phi q}^{(3)}$ ,  $C_{tW}$ ,  $C_{tG}$ ,  $C_G$ ,  $C_{uG}$ , and  $C_{cG}$ , obtained from the combination of all channels are shown in Fig. 6. Table 6 summarizes the effect of the most important uncertainty sources on the observed allowed intervals.

## 7 Summary

A search for new physics in top quark interactions is performed using  $t\bar{t}$  and  $tW$  events in dilepton final states. The analysis is based on data collected in  $pp$  collisions at 13 TeV by the CMS detector in 2016, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . No significant excess above the standard model background expectation is observed. For the first time, both  $t\bar{t}$  and  $tW$  production are used simultaneously in a model independent search for effective couplings. The six effective couplings,  $C_G$ ,  $C_{tG}$ ,  $C_{tW}$ ,  $C_{\phi q}^{(3)}$ ,  $C_{uG}$ , and  $C_{cG}$  are constrained using a dedicated multivariate analysis. The constraints presented, obtained by considering one operator at a time, are a useful first step toward more global approaches.

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## CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik, Vienna, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth<sup>1</sup>, V. M. Ghete, J. Hrubec, M. Jeitler<sup>1</sup>, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerp, Belgium

E. A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

### Vrije Universiteit Brussel, Brussels, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

### Université Libre de Bruxelles, Brussels, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, A. Grebenyuk, A. K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov<sup>2</sup>, D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F. L. Alves, G. A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles



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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, E. Coelho, E. M. Da Costa, G. G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, L. J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E. J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

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

**Beihang University, Beijing, China**

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>, L. Yuan

**Institute of High Energy Physics, Beijing, China**

M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, Y. Chen, C. H. Jiang, D. Leggat, H. Liao, Z. Liu, S. M. Shaheen<sup>6</sup>, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang<sup>6</sup>, J. Zhao

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

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S. J. Qian, D. Wang

**Tsinghua University, Beijing, China**

Y. Wang

**Universidad de Los Andes, Bogotá, Colombia**

C. Avila, A. Cabrera, C. A. Carrillo Montoya, L. F. Chaparro Sierra, C. Florez, C. F. González Hernández, M. A. Segura Delgado

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

**Faculty of Science, University of Split, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov<sup>7</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Finger<sup>8</sup>, M. Finger Jr.<sup>8</sup>

**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin

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

H. Abdalla<sup>9</sup>, A. Mohamedj<sup>10</sup>, E. Salama<sup>11,12</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik, A. Carvalho Antunes De Oliveira, R. K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Havukainen, J. K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

M. Besancon, F. Couderc, M. Dejaradin, D. Denegri, J. L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M. Ö. Sahin, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France**

A. Abdulsalam<sup>13</sup>, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J. B. Sauvan, Y. Sirois, A. G. Stahl Leiton, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>14</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E. C. Chabert, V. Cherepanov, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov<sup>15</sup>, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>16</sup>

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>8</sup>

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

C. Autermann, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M. P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

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

A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

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

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>17</sup>

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A. A. Bin Anuar, K. Borras<sup>18</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M. M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo<sup>19</sup>, A. Geiser, J. M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>20</sup>, R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich,

V. Myronenko, S. K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G. P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, C. E. N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, B. Vormwald, I. Zoi

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M. A. Harrendorf, F. Hartmann<sup>17</sup>, S. M. Heindl, U. Husemann, I. Katkov<sup>15</sup>, S. Kudella, S. Mitra, M. U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H. J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

**National and Kapodistrian University of Athens, Athens, Greece**

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

**National Technical University of Athens, Athens, Greece**

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Giannios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F. A. Triantis, D. Tsitsonis

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**

M. Bartók<sup>21</sup>, M. Csanad, N. Filipovic, P. Major, M. I. Nagy, G. Pasztor, O. Surányi, G. I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>22</sup>, Á. Hunyadi, F. Sikler, T. Á. Vámi, V. Veszpremi, G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

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

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J. R. Komaragiri, P. C. Tiwari

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

S. Bahinipati<sup>24</sup>, C. Kar, P. Mal, K. Mandal, A. Nayak<sup>25</sup>, S. Roy Chowdhury, D. K. Sahoo<sup>24</sup>, S. K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, A. Mehta, K. Sandeep, S. Sharma, J. B. Singh, A. K. Viridi, G. Walia

**University of Delhi, Delhi, India**

A. Bhardwaj, B. C. Choudhary, R. B. Garg, M. Gola, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah, R. Sharma

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

R. Bhardwaj<sup>26</sup>, M. Bharti<sup>26</sup>, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>26</sup>, D. Bhowmik, S. Dey, S. Dutt<sup>26</sup>, S. Dutta, S. Ghosh, M. Maity<sup>27</sup>, K. Mondal, S. Nandan, A. Purohit, P. K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar<sup>27</sup>, M. Sharan, B. Singh<sup>26</sup>, S. Thakur<sup>26</sup>

**Indian Institute of Technology Madras, Madras, India**

P. K. Behera, A. Muhammad

**Bhabha Atomic Research Centre, Mumbai, India**

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D. K. Mishra, P. K. Netrakanti, L. M. Pant, P. Shukla, P. Suggiseti

**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, M. A. Bhat, S. Dugad, G. B. Mohanty, N. Sur, R. Verma

**Tata Institute of Fundamental Research-B, Mumbai, India**

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

S. Chenarani<sup>28</sup>, E. Eskandari Tadavani, S. M. Etesami<sup>28</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>29</sup>, M. Zeinali

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F. R. Cavallo<sup>a</sup>, S. S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G. M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,30</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F. L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A. M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Florence, Italy**

G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, G. Latino, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,31</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

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

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genoa, Italy**

F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milan, Italy**

A. Benaglia<sup>a</sup>, A. Beschi<sup>b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,17</sup>, S. Di Guida<sup>a,b,17</sup>, M. E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Zuolo<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Naples, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Rome, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, A. Di Crescenzo<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, G. Galati<sup>a</sup>, A. O. M. Iorio<sup>a,b</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,17</sup>, P. Paolucci<sup>a,17</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Y. Hoh, S. Lacaprara<sup>a</sup>, P. Lujan, M. Margoni<sup>a,b</sup>, A. T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, M. Presilla<sup>b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, A. Tiko, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S. P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G. M. Bilei<sup>a</sup>, C. Cecchi<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M. A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedi<sup>a</sup>, F. Fiori<sup>a,c</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M. T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>32</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P. G. Verdini<sup>a</sup>

**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Rome, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy, Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, A. Cappati<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, S. Cometti, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M. M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G. L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, R. Salvatico<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>, G. Della Ricca<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kyungpook National University, Daegu, Korea**

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

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

H. Kim, D. H. Moon, G. Oh

**Hanyang University, Seoul, Korea**

B. Francois, J. Goh<sup>33</sup>, T. J. Kim

**Korea University, Seoul, Korea**

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

**Sejong University, Seoul, Korea**

H. S. Kim

**Seoul National University, Seoul, Korea**

J. Almond, J. Kim, J. S. Kim, H. Lee, K. Lee, K. Nam, S. B. Oh, B. C. Radburn-Smith, S. h. Seo, U. K. Yang, H. D. Yoo, G. B. Yu

**University of Seoul, Seoul, Korea**

D. Jeon, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, J. Lee, I. Yu

**Riga Technical University, Riga, Latvia**V. Veckalns<sup>34</sup>**Vilnius University, Vilnius, Lithuania**

V. Dudenas, A. Juodagalvis, J. Vaitkus

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**Z. A. Ibrahim, M. A. B. Md Ali<sup>35</sup>, F. Mohamad Idris<sup>36</sup>, W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J. F. Benitez, A. Castaneda Hernandez, J. A. Murillo Quijada

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**H. Castilla-Valdez, E. De La Cruz-Burelo, M. C. Duran-Osuna, I. Heredia-De La Cruz<sup>37</sup>, R. Lopez-Fernandez, J. Mejia Guisao, R. I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez**Universidad Iberoamericana, Mexico City, Mexico**

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

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

J. Eysermans, I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

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

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P. H. Butler

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

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

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szeleper, P. Traczyk, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski, A. Byszuk<sup>38</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak**Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev<sup>39,40</sup>, P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**V. Golovtsov, Y. Ivanov, V. Kim<sup>41</sup>, E. Kuznetsova<sup>42</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev**Institute for Nuclear Research, Moscow, Russia**

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

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

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

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**R. Chistov<sup>43</sup>, M. Danilov<sup>43</sup>, D. Philippov, E. Tarkovskii**P.N. Lebedev Physical Institute, Moscow, Russia**V. Andreev, M. Azarkin, I. Dremin<sup>40</sup>, M. Kirakosyan, A. Terkulov**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>44</sup>, L. Dudko, V. Klyukhin, O. Kodolova, N. Korneeva, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin**Novosibirsk State University (NSU), Novosibirsk, Russia**A. Barnyakov<sup>45</sup>, V. Blinov<sup>45</sup>, T. Dimova<sup>45</sup>, L. Kardapoltsev<sup>45</sup>, Y. Skovpen<sup>45</sup>**Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**National Research Tomsk Polytechnic University, Tomsk, Russia**

A. Babaev, S. Baidali, V. Okhotnikov

**Faculty of Physics and VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**P. Adzic<sup>46</sup>, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic<sup>47</sup>, J. Milosevic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J. A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M. S. Soares, A. Triossi

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J. F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J. M. Vizán García

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

I. J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P. J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

**Department of Physics, University of Ruhuna, Matara, Sri Lanka**

N. Wickramage

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita<sup>48</sup>, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, G. M. Innocenti, A. Jafari, P. Janot, O. Karacheban<sup>20</sup>, J. Kieseler, A. Kornmayer, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo<sup>17</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F. M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>49</sup>, A. Stakia, J. Steggemann, D. Treille, A. Tsiros, A. Vartak, M. Verzetti, W. D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>50</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

**ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R. A. Manzoni, M. Marionneau, M. T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, D. Ruini, D. A. Sanz Becerra, M. Schönenberger, L. Shchutska, V. R. Tavolaro, K. Theofilatos, M. L. Vesterbacka Olsson, R. Wallny, D. H. Zhu

**Universität Zürich, Zurich, Switzerland**

T. K. Aarrestad, C. Amsler<sup>51</sup>, D. Brzhechko, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

**National Central University, Chung-Li, Taiwan**

T. H. Doan, R. Khurana, C. M. Kuo, W. Lin, S. S. Yu

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

P. Chang, Y. Chao, K. F. Chen, P. H. Chen, W.-S. Hou, Y. F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

**Physics Department, Science and Art Faculty, Çukurova University, Adana, Turkey**

A. Bat, F. Boran, S. Cerci<sup>52</sup>, S. Damarseekin, Z. S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos<sup>53</sup>, C. Isik, E. E. Kangal<sup>54</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir<sup>55</sup>, A. Polatoz, D. Sunar Cerci<sup>52</sup>, U. G. Tok, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

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

B. Isildak<sup>56</sup>, G. Karapinar<sup>57</sup>, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

I. O. Atakisi, E. Gülmez, M. Kaya<sup>58</sup>, O. Kaya<sup>59</sup>, S. Ozkorucuklu<sup>60</sup>, S. Tekten, E. A. Yetkin<sup>61</sup>

**Istanbul Technical University, Istanbul, Turkey**

M. N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen<sup>62</sup>

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

B. Grynyov

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Ball, J. J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, D. M. Newbold<sup>63</sup>, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V. J. Smith, J. Taylor, A. Titterton

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K. W. Bell, A. Belyaev<sup>64</sup>, C. Brew, R. M. Brown, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams, W. J. Womersley

**Imperial College, London, United Kingdom**

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash<sup>65</sup>, A. Nikitenko<sup>7</sup>, V. Palladino, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee<sup>17</sup>, N. Wardle, D. Winterbottom, J. Wright, S. C. Zenz



**Brunel University, Uxbridge, United Kingdom**

J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, C. K. Mackay, A. Morton, I. D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, USA**

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

**Catholic University of America, Washington DC, USA**

R. Bartek, A. Dominguez

**The University of Alabama, Tuscaloosa, USA**

A. Buccilli, S. I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, USA**

D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

**Brown University, Providence, USA**

G. Benelli, B. Burkley, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J. M. Hogan<sup>66</sup>, K. H. M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir<sup>67</sup>, R. Syarif, E. Usai, D. Yu

**University of California, Davis, Davis, USA**

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

**University of California, Los Angeles, USA**

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, S. Erhan, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

**University of California, Riverside, Riverside, USA**

E. Bouvier, K. Burt, R. Clare, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O. R. Long, M. Olmedo Negrete, M. I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

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

J. G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, S. Wang, J. Yoo

**California Institute of Technology, Pasadena, USA**

D. Anderson, A. Bornheim, J. M. Lawhorn, N. Lu, H. B. Newman, T. Q. Nguyen, J. Pata, M. Spiropulu, J. R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R. Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

M. B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

**University of Colorado Boulder, Boulder, USA**

J. P. Cumalat, W. T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K. A. Ulmer, S. R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J. R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S. M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V. D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M. J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J. M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, A. Savoy-Navarro<sup>68</sup>, B. Schneider, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, 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

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R. D. Field, S. V. Gleyzer, B. M. Joshi, J. Konigsberg, A. Korytov, K. H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

**Florida International University, Miami, USA**

Y. R. Joshi, S. Linn

**Florida State University, Tallahassee, USA**

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K. F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

**Florida Institute of Technology, Melbourne, USA**

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

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

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C. E. Gerber, D. A. Hangal, D. J. Hofman, K. Jung, J. Kamin, C. Mills, M. B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

**The University of Iowa, Iowa City, USA**

M. Alhusseini, B. Bilki<sup>69</sup>, W. Clarida, K. Dilsiz<sup>70</sup>, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>71</sup>, Y. Onel, F. Ozok<sup>72</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

**Johns Hopkins University, Baltimore, USA**

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, W. T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao

**The University of Kansas, Lawrence, USA**

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J. D. Tapia Takaki, Q. Wang

**Kansas State University, Manhattan, USA**

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D. R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

A. Baden, O. Baron, A. Belloni, S. C. Eno, Y. Feng, C. Ferraioli, N. J. Hadley, S. Jabeen, G. Y. Jeng, R. G. Kellogg, J. Kunkle, A. C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y. H. Shin, A. Skuja, S. C. Tonwar, K. Wong

**Massachusetts Institute of Technology, Cambridge, USA**

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, R. Bi, S. Brandt, W. Busza, I. A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, M. Klute, D. Kovalskyi, Y.-J. Lee, P. D. Luckey, B. Maier, A. C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G. S. F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T. W. Wang, B. Wyslouch

**University of Minnesota, Minneapolis, USA**

A. C. Benvenuti<sup>†</sup>, R. M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M. A. Wadud

**University of Mississippi, Oxford, USA**

J. G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, USA**

E. Avdeeva, K. Bloom, D. R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J. E. Siado, G. R. Snow, B. Stieger

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

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roobahani

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D. M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, USA**

S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K. A. Hahn, N. Odell, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

**University of Notre Dame, Notre Dame, USA**

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>39</sup>, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

**The Ohio State University, Columbus, USA**

J. Alimena, L. Antonelli, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T. Y. Ling, W. Luo, B. L. Winer

**Princeton University, Princeton, USA**

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M. T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

**University of Puerto Rico, Mayagüez, USA**

S. Malik, S. Norberg

**Purdue University, West Lafayette, USA**

A. Barker, V. E. Barnes, S. Das, L. Gutay, M. Jones, A. W. Jung, A. Khatiwada, B. Mahakud, D. H. Miller, N. Neumeister, C. C. Peng, S. Piperov, H. Qiu, J. F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, USA**

T. Cheng, J. Dolen, N. Parashar

**Rice University, Houston, USA**

Z. Chen, K. M. Ecklund, S. Freed, F. J. M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

**University of Rochester, Rochester, USA**

A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, J. L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khkhunaishvili, E. Ranken, P. Tan, R. Taus

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

B. Chiarito, J. P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

**University of Tennessee, Knoxville, USA**

H. Acharya, A. G. Delannoy, J. Heideman, G. Riley, S. Spanier

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

O. Bouhali<sup>73</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>74</sup>, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

**Texas Tech University, Lubbock, USA**

N. Akchurin, J. Damgov, F. De Guio, P. R. Duerdo, S. Kunori, K. Lamichhane, S. W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

**Vanderbilt University, Nashville, USA**

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

R. Harr, P. E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

**University of Wisconsin-Madison, Madison, WI, USA**

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber<sup>75</sup>, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W. H. Smith, N. Woods

**† Deceased**

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at University of Chinese Academy of Sciences, Beijing, China
- 7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Zewail City of Science and Technology, Zewail, Egypt
- 11: Also at British University in Egypt, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 16: Also at Tbilisi State University, Tbilisi, Georgia
- 17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 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 Physics, University of Debrecen, Debrecen, Hungary
- 22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 24: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 25: Also at Institute of Physics, Bhubaneswar, India
- 26: Also at Shoolini University, Solan, India
- 27: Also at University of Visva-Bharati, Santiniketan, India
- 28: Also at Isfahan University of Technology, Isfahan, Iran
- 29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy

- 31: Also at Università degli Studi di Siena, Siena, Italy
- 32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 33: Also at Kyung Hee University, Department of Physics, Seoul, Korea
- 34: Also at Riga Technical University, Riga, Latvia
- 35: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 36: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 37: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 38: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 39: Also at Institute for Nuclear Research, Moscow, Russia
- 40: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 41: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 42: Also at University of Florida, Gainesville, USA
- 43: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 44: Also at California Institute of Technology, Pasadena, USA
- 45: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 46: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 47: Also at University of Belgrade, Belgrade, Serbia
- 48: Also at INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy
- 49: Also at National and Kapodistrian University of Athens, Athens, Greece
- 50: Also at Universität Zürich, Zurich, Switzerland
- 51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 52: Also at Adiyaman University, Adiyaman, Turkey
- 53: Also at Istanbul Aydın University, Istanbul, Turkey
- 54: Also at Mersin University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, 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 University, Istanbul, Turkey
- 61: Also at Istanbul Bilgi 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 Monash University, Faculty of Science, Clayton, Australia
- 66: Also at Bethel University, St. Paul, USA
- 67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 68: Also at Purdue University, West Lafayette, USA
- 69: Also at Beykent University, Istanbul, Turkey
- 70: Also at Bingol University, Bingol, Turkey
- 71: Also at Sinop University, Sinop, Turkey
- 72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 73: Also at Texas A&M University at Qatar, Doha, Qatar
- 74: Also at Kyungpook National University, Daegu, Korea
- 75: Also at University of Hyderabad, Hyderabad, India