



# Search for single production of vector-like quarks decaying into a b quark and a W boson in proton–proton collisions at $\sqrt{s} = 13$ TeV



The CMS Collaboration <sup>\*</sup>

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 28 January 2017

Received in revised form 21 June 2017

Accepted 10 July 2017

Available online 15 July 2017

Editor: M. Doser

### Keywords:

CMS

Physics

## ABSTRACT

A search is presented for a heavy vector-like quark, decaying into a b quark and a W boson, which is produced singly in association with a light flavor quark and a b quark. The analysis is performed using a data sample of proton–proton collisions at a center-of-mass energy of  $\sqrt{s} = 13$  TeV collected at the LHC in 2015. The data set used in the analysis corresponds to an integrated luminosity of  $2.3 \text{ fb}^{-1}$ . The search is carried out using events containing one electron or muon, at least one b-tagged jet with large transverse momentum, at least one jet in the forward region of the detector, and missing transverse momentum. No excess over the standard model prediction is observed. Upper limits are placed on the production cross section of heavy exotic quarks: a T quark with a charge of  $2/3$ , and a Y quark with a charge of  $-4/3$ . For Y quarks with coupling of 0.5 and  $B(Y \rightarrow bW) = 100\%$ , the observed (expected) lower mass limits are 1.40 (1.0) TeV. This is the most stringent limit to date on the single production of the Y vector-like quark.

© 2017 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

## 1. Introduction

The standard model (SM) of particle physics has been exceptionally successful in describing phenomena at the subatomic scale. The observation of a Higgs boson with a mass of 125 GeV and with properties consistent with the SM expectations [1–3] completed the SM. However, in the absence of enormous order-dependent cancellations, also known as fine-tuning, large SM quantum corrections would shift the bare Higgs boson mass to values far beyond the electroweak scale. New physics is required to stabilize the Higgs boson mass naturally at the electroweak scale, i.e. without invoking fine-tuning.

Many natural extensions of the SM have been proposed in recent decades. Some of these models postulate the existence of vector-like quarks (VLQs) [4–6], which are colored fermions with left- and right-handed chiral states both transforming in the same way under the gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$ . The VLQs do not acquire masses through the Yukawa coupling to the Higgs field, and could cancel loop corrections from the SM top quark to the Higgs boson mass.

Searches for VLQs have already been performed in various decay modes using proton–proton collisions at  $\sqrt{s} = 8$  TeV. These searches were primarily focused on the pair production mechanism and they ruled out VLQs with masses up to approximately

0.90 TeV [7–10]. The VLQ single production mechanism is coupling-dependent, and it could become the dominant contribution to the cross section at high VLQ masses. The strength of the VLQ–b–W coupling can be approximately characterized by a single dimensionless parameter that varies from 0 to  $\sqrt{2}$  [11], where the latter would correspond to a coupling of full electroweak strength.

In this paper, we present a search for the single production of a heavy vector-like quark that decays into a b quark and a W boson using the 2015 LHC data set. This signature can arise from either a Y or a T quark with a charge of  $-4/3$  or  $2/3$ , respectively, produced in association with a light flavor quark and a b quark. The leading order Feynman diagram for Y and T quark production is shown in Fig. 1. The outgoing light flavor quark  $q'$  in the upper part of the diagram produces a jet in the forward region of the detector, which is a distinct signature of single production.

The Y quark is expected to decay with a branching fraction ( $B$ ) of 100% into a b quark and a W boson [12], while the T quark can also decay into  $tH$  and  $tZ$  via a flavor changing neutral current. Searches with the 2015 LHC data set for single production of a vector-like T quark decaying to  $tH$  and  $tZ$  have been performed by the CMS Collaboration [13–15]. If the T quark is a singlet, then it is expected to decay into  $bW$  50% of the time.

The ATLAS Collaboration published a search for single production of Y and T quarks decaying into  $bW$  using 8 TeV proton–proton collisions [16]. The analysis presented here is the first such search using 13 TeV proton–proton data, and sets the most stringent limits to date on the production cross section for a single Y or T quark.

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

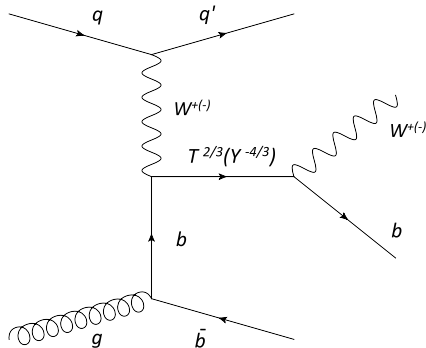


Fig. 1. Leading order Feynman diagram for singly produced  $Y$  or  $T$  quarks.

The search is carried out based on events containing one electron or muon, at least one  $b$ -tagged jet with large transverse momentum ( $p_T$ ), at least one jet in the forward region of the detector, and missing transverse momentum.

## 2. CMS detector and event samples

The essential feature of the CMS detector is the superconducting solenoid, 6 m in diameter and 13 m in length, which provides an axial magnetic field of 3.8 T. Within the solenoid volume a multi-layered silicon pixel and strip tracker is used to measure the trajectories of charged particles with pseudorapidity  $|\eta| < 2.5$ . Outside of the tracker system, an electromagnetic calorimeter (ECAL) made of lead tungstate crystals and a hadron calorimeter (HCAL) made of brass and scintillators cover the region  $|\eta| < 3.0$ . The region  $3.0 < |\eta| < 5.0$  is covered by the forward hadronic calorimeter, which is made primarily of steel and quartz fibers. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the solenoid, and covering the region  $|\eta| < 2.4$ . 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. [17].

The data used for this analysis were recorded during the 2015 data taking period in proton–proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $2.3 \text{ fb}^{-1}$ . The electron data sample was collected using a trigger that required at least one isolated electron with  $|\eta| < 2.5$  and  $p_T > 27 \text{ GeV}$ . The muon data sample was collected using a trigger that required at least one isolated muon with  $|\eta| < 2.1$  and  $p_T > 20 \text{ GeV}$ .

The VLQ signal efficiencies and background contributions are estimated using Monte Carlo (MC) samples. They are validated using background enriched data samples. The  $t\bar{t}$ -jets,  $t$ - and  $tW$ -channel single top-quark production and the  $WW$  processes are simulated using POWHEG v2 [18–20]. Single top quark production via  $s$ -channel and the  $WZ$  process are simulated with MADGRAPH5\_AMC@NLO v2 [21]. Inclusive boson production ( $W$ +jets and  $Z$ +jets) is simulated with MADGRAPH v5 [22]. PYTHIA 8.212 [23, 24] is used for parton shower development and hadronization and to simulate QCD multijet events.

The VLQ processes considered in this paper are generated using the tree-level MC event generator MADGRAPH v5 for VLQ masses in the range from 0.70 to 1.80 TeV, in steps of 100 GeV. The VLQ width is set to 10 GeV for all masses. The NNPDF3.0 [25] parton distribution functions (PDFs) are used for both signal and SM MC processes to model the momentum distribution of the colliding partons inside the protons.

The cross sections used to normalize the SM processes are calculated to next-to-leading order (NLO) or to next-to-next-to-leading order (NNLO), where the latter is available [26–28]. For the

signal, the NLO cross sections are taken from Refs. [29,30]. For the  $t\bar{t}$ -jets,  $tW$ -channel single top-quark, and  $WW$  SM processes, NNLO cross sections are used, while NLO cross sections are applied to the remaining processes.

All generated events are processed through the CMS detector simulation based on GEANT4 [31]. Additional minimum bias events, generated with PYTHIA 8.212, are superimposed on the hard-scattering events to simulate multiple proton–proton interactions (pileup) within the neighboring bunch crossings. The simulated events are weighted to reproduce the distribution of the number of pileup interactions, 20 on average, observed in data.

## 3. Event reconstruction

All physics objects in the event are reconstructed using a particle-flow (PF) algorithm [32,33], which uses information from all subsystems to reconstruct photons, electrons, muons, and charged and neutral hadrons. Charged particle tracks are used to reconstruct the interaction vertices. The vertex with the highest sum of squared  $p_T$  of all associated tracks is taken as the primary vertex of the hard collision. Filters are applied to reject events where electronic noise or proton-beam backgrounds mimic energy deposits in the detector.

Electron candidates are reconstructed by combining the tracking information with energy deposits in the ECAL in the range  $|\eta| < 2.5$  (excluding the range  $1.4442 < |\eta| < 1.566$ , which is a transition region between endcap and barrel calorimeters). Tight identification criteria are applied to select well-reconstructed electron candidates. Candidates are identified [34] using information on the shower-shape, the track quality and the spatial match between the track and the electromagnetic cluster, the fraction of total cluster energy in the HCAL, and the resulting level of activity in the surrounding tracker and calorimeter regions. The energy resolution for electrons with  $p_T > 40 \text{ GeV}$ , measured using  $Z \rightarrow ee$  decays, is on average 1.7% in the ECAL central region of the detector [34].

Muon candidates are identified using track segments reconstructed separately from hits in the silicon tracking system and in the muon system. To identify muon candidates, the track segments must be consistent with muons originating from the primary vertex and satisfying tight identification requirements. The matching of the muon and silicon track segments results in a relative  $p_T$  resolution of 1.3–2.0% in the central region of the detector for muons with  $20 < p_T < 100 \text{ GeV}$ , and for muons with  $p_T$  up to 1 TeV the resolution is 10% or better [35].

Lepton (electron or muon) reconstruction and trigger efficiencies are evaluated as a function of  $p_T$  and  $|\eta|$  in both data and simulation, using a “tag-and-probe” method [36] with recorded and simulated samples of dileptonic  $Z$  events.

An isolation variable is employed to suppress leptons originating from QCD processes. We define a relative isolation as the sum of the  $p_T$  of particle tracks found in the tracker and energy deposits found in the calorimeters within a cone  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  (0.4) around the trajectory of the electron (muon), divided by the lepton  $p_T$ . Relative isolation is corrected for the effects of pileup, and is required to be less than 0.15 for muons, and less than 0.4 (0.6) for electrons in the barrel (endcap) region.

Particles reconstructed by the PF algorithm are clustered into jets by using the direction of each particle at the interaction vertex. Charged hadrons found by the PF algorithm that are associated with pileup vertices are not considered. Particles that are identified as isolated leptons are removed from the jet clustering procedure. Jets are reconstructed with the anti- $k_T$  algorithm [37,38] with a

distance parameter of 0.4. An event-by-event jet-area-based correction [39,40] is applied to remove, on a statistical basis, neutral pileup contribution that is not already removed by the charged-hadron subtraction procedure described above. Jet energy corrections are applied to each jet, as a function of  $p_T$  and  $\eta$ , to correct for the calorimeter response [41].

The missing transverse momentum is defined as the negative vector sum of the transverse momenta of all the particles found by the PF algorithm, and its magnitude is referred to as  $E_T^{\text{miss}}$ . The decay of a heavy quark into a leptonically decaying W boson and a b quark is expected to exhibit genuine missing transverse momentum because of the undetected neutrino from the W decay. A missing transverse momentum threshold is applied to the selected events, and the missing transverse momentum vector is used in the mass reconstruction.

To identify jets originating from a b quark (b-tagged jets), the combined secondary vertex (CSV) algorithm is used [42,43]. This tagging algorithm combines variables that can distinguish b quark jets from those originating from light flavors, such as information on track impact parameter significance and secondary vertex properties. The variables are combined using a likelihood ratio technique to compute a b tagging discriminator. We use the CSV medium operating point [42], which achieves a b tagging efficiency of approximately 70% and a mistag rate of 1%. Data-to-Simulation efficiency and mistag rate scale factors account for the small differences observed between data and simulation. We use these scale factors as a function of jet  $p_T$  and  $\eta$  [42] to correct simulated events.

#### 4. Event selection and search strategy

The signal event selection requires exactly one lepton with  $p_T > 40$  GeV and  $|\eta| < 2.1$ . Events with additional leptons having  $p_T > 10$  GeV and  $|\eta| < 2.5$  and passing relatively loose isolation and identification requirements are rejected to suppress dileptonic events.

Events are required to have at least two jets, one in the central and one in the forward region of the detector. The central jet is required to have  $p_T > 200$  GeV and  $|\eta| < 2.4$  and be b-tagged. When there is more than one central jet satisfying the above criteria, the leading central jet is used to reconstruct the mass of the VLQ. The forward jet ( $2.4 < |\eta| < 5.0$ ) must have  $p_T > 30$  GeV.

In the decay of a singly produced VLQ, the b quark and the W boson tend to be produced with the transverse momenta pointing in opposite directions. Hence, the azimuthal angle between the central b jet and the lepton  $\ell$  is required to satisfy  $\Delta\phi(\ell, b) > 2$ . In addition, the lepton is required to be separated from any jets with  $p_T > 40$  GeV produced in the event. When a hadronic jet is found within  $\Delta R(\ell, \text{jet}) < 1.5$ , the event is rejected. Since W boson originating from heavy VLQ decay has significant  $p_T$ , events are required to have substantial  $E_T^{\text{miss}} (> 50$  GeV) due to the undetected neutrino from the W boson decay. The transverse mass,  $M_T$ , formed by the lepton and  $E_T^{\text{miss}}$  system is required to satisfy  $M_T < 130$  GeV to suppress  $t\bar{t}$  dilepton events, which can mimic the signal when one of the leptons escapes detection.

Finally, events are required to have  $S_T > 500$  GeV, where  $S_T$  is defined as the scalar sum of the transverse momenta of the lepton, the leading central jet, and the missing transverse momentum. This requirement reduces the signal efficiency by less than 10% for the VLQ mass range considered in this paper.

The invariant mass of the heavy quark candidate,  $M_{\text{inv}}$ , is reconstructed from its decay products: the lepton, the leading central jet, and the neutrino, where the  $x, y$ -components of the neutrino momentum are given by the missing transverse momentum, while the  $z$ -component is determined by constraining the

invariant mass of the lepton and neutrino to the W boson mass value. The solution with the smallest value is considered as the  $z$ -component. This method is used only when the solution of the relevant quadratic equation is real, otherwise the  $z$ -component is set to zero.

The single VLQ production  $Y/T \rightarrow bW$  would result in a peak in the  $M_{\text{inv}}$  distribution at the mass of the VLQ. The experimental mass resolution is 12–15% and is independent of the VLQ mass.

#### 5. Background modeling

The dominant background processes in this search are the production of  $t\bar{t}$  and W+jets events. The modeling of these processes is validated by studying background-enriched samples.

To verify the modeling of the  $t\bar{t}$  process, we select events with the lepton and  $E_T^{\text{miss}}$  fulfilling the signal selection criteria, and at least 2 b-tagged jets with the leading (sub-leading) jet satisfying the requirement of  $p_T > 70$  (30) GeV. We also remove the  $\Delta R(\ell, \text{jet})$ ,  $\Delta\phi(\ell, b)$  and forward jet requirements to enrich the sample with  $t\bar{t}$  events.

The top quark  $p_T$  spectrum from the  $t\bar{t}$  simulation is known to be mismodeled and is reweighted using the empirical function described in Ref. [44]. After this correction, the data points at large values of all relevant kinematic distributions are consistent within systematic uncertainties. Distributions of  $S_T$  and the invariant mass of the bW system in the  $t\bar{t}$  sample are shown in Fig. 2.

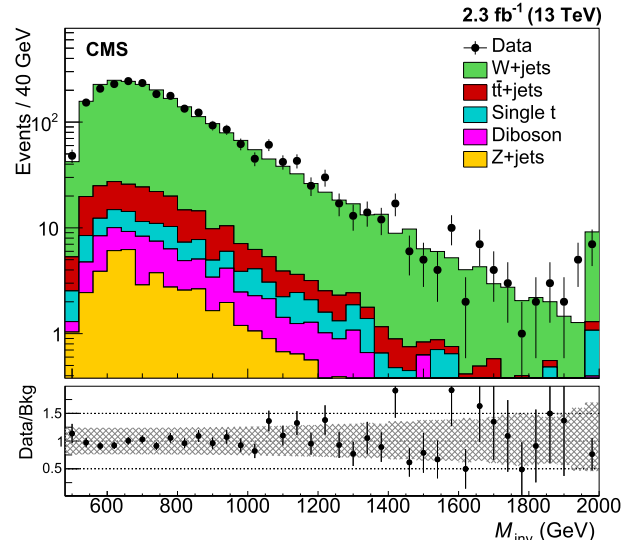
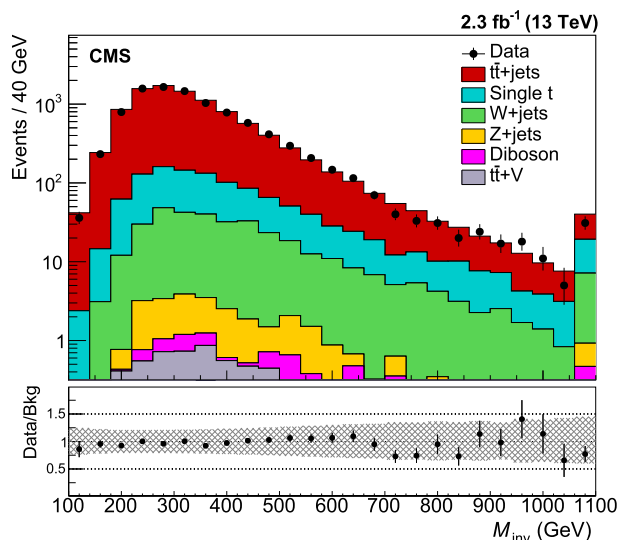
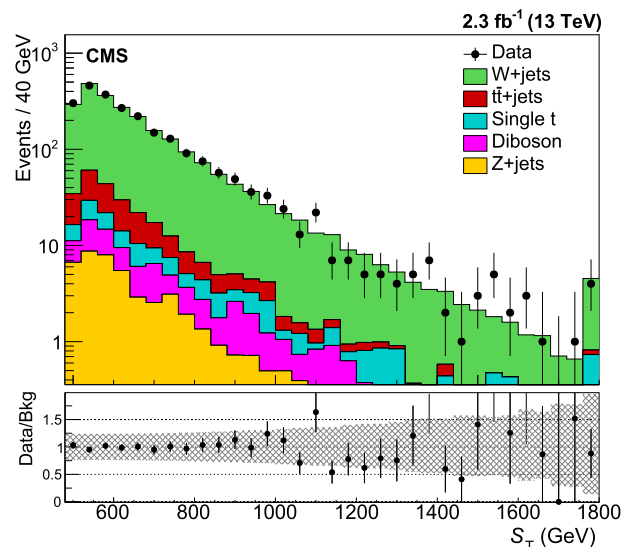
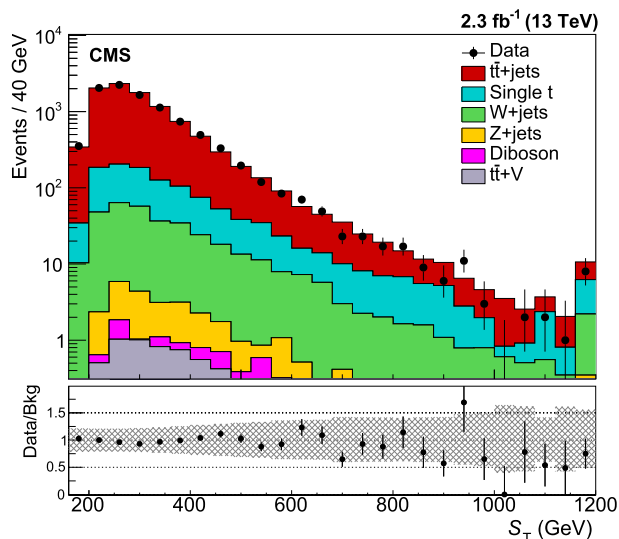
The W+jets-enriched control sample requirement is identical to the signal event selection except that events with b-tagged jets are vetoed. We observe that in the W+jets simulated sample, the number of events at large jet  $p_T$  distributions is overestimated as compared with the distributions measured in data. We derive a correction for the W+jets simulation as a function of the  $H_T$  variable, defined as the scalar sum of the transverse momenta of all jets with  $p_T > 30$  GeV. The data to simulation ratio of the  $H_T$  distribution is well described by a 2-parameter linear fit with a negative slope. A correction to the modeling of the W+jets  $H_T$  spectrum is made using the results of the fit. After the correction is applied, good agreement in the modeling of all kinematic variables is observed. Distributions of  $S_T$  and the invariant mass of the bW system in the W+jets sample are shown in Fig. 3.

#### 6. Systematic uncertainties

We divide the systematic uncertainties into two categories: uncertainties that impact only the rate of background and signal predictions, and uncertainties that affect both the rate and the shape of the fitted  $M_{\text{inv}}$  spectra. The shape uncertainties affecting the  $M_{\text{inv}}$  distribution are modeled by varying the nuisance parameters that characterize the associated systematic effects up and down by one standard deviation.

The uncertainty in the integrated luminosity is 2.7% [45]. We assign the uncertainties for the normalization of the SM background processes as the uncertainties on corresponding CMS cross section measurements at 13 TeV, which are 5.6% for  $t\bar{t}$  [46], 14.7% for single top quark [47], and 9.2% for W+jets [48], where in the last case we also account separately for uncertainties in the W+heavy-flavor contributions [49,50].

To account for the MC mismodeling correction in the W+jets sample, we derive a two-sided uncertainty band using the  $H_T$  correction procedure. To account for the MC mismodeling correction in the  $t\bar{t}$  sample, we derive a two-sided uncertainty band using the top  $p_T$  reweighting procedure. One side of the band is obtained by removing the correction, and the other side is obtained by applying the procedure twice. The uncertainties due to these corrections increase with the rise of the top quark  $p_T$  and  $H_T$ , which leads to



**Fig. 2.** Kinematic distributions in the  $t\bar{t}$ -enriched control sample:  $S_T$  (top) and  $M_{inv}$  (bottom). The last bin includes overflow events. The statistical and systematic uncertainties are represented by the hatched band on the ratio plot.

**Fig. 3.** Kinematic distributions in the W+jets-enriched control sample:  $S_T$  (top) and  $M_{inv}$  (bottom). The last bin includes overflow events. The statistical and systematic uncertainties are represented by the hatched band on the ratio plot.

the widening of the uncertainty band at large  $S_T$  and  $M_{inv}$ , as can be seen in Figs. 2 and 3.

In addition, the reconstruction efficiency of forward jets has been observed to be larger in the simulation than in the data. The efficiency as a function of  $\eta$  is corrected to match the data using the W+jets-enriched sample with 0 b-tagged jets, and validated using the  $t\bar{t}$ -enriched sample with two b-tagged jets. An uniform rate uncertainty of  $\pm 15\%$  is assigned to cover the forward jet mismodelling in simulation.

Trigger and lepton identification efficiencies in simulation are corrected as functions of lepton  $p_T$  and  $\eta$  using decays of Z bosons to leptons in data. The associated uncertainty of about 2% is the statistical uncertainty in the data.

The shape uncertainties include uncertainties in the jet energy scale, jet energy resolution, b tagging efficiency, pileup, PDFs, as well as factorization and renormalization scales. These uncertainties are treated as uncorrelated.

The uncertainty related to the modeling of pileup is evaluated by varying the inelastic cross section by  $\pm 5\%$  relative to the nominal value of 69 mb [51]. Uncertainties in renormalization and

factorization scales are taken into account by varying both scales simultaneously up and down by a factor of two. Uncertainties arising from the choice of PDFs are taken into account according to the PDF4LHC procedure [52].

The systematic uncertainties are summarized in Table 1.

## 7. Limit calculation and results

Good agreement between the event yields in the data and in the SM prediction is observed within uncertainties, as shown in Table 2. The sum of the SM backgrounds and a hypothesized signal for the combined electron and muon channels is fitted to the observed spectrum of  $M_{inv}$ . The fit uses a binned likelihood method, where the binning of the distributions is chosen in such a way that the statistical uncertainty in the MC estimation of total background per bin is always less than 20%. Contributions from the SM processes are allowed to float independently within their systematic uncertainties, using log-normal priors [53,54]. The nuisance parameters describing the shape uncertainties are constrained using Gaussian priors. The shapes of the  $M_{inv}$  distributions for backgrounds and signal are parametrized and varied according to the

**Table 1**  
Summary of the systematic uncertainties associated with the simulated backgrounds and the signal events. The value quoted represents the expected change in the event yield in the signal region due to the systematic uncertainty.

Source		W+jets	$t\bar{t}$	Single top	Signal
Integrated luminosity	rate	2.7%	2.7 %	2.7 %	2.7 %
Jet energy scale	shape	5%	6%	5%	3%
Jet energy resolution	shape	2%	1%	1%	2%
b tagging efficiency	shape	3%	5%	5%	5%
Multiple interactions	shape	1%	1%	1%	1%
Lepton efficiency	rate	2%	2%	2%	2%
Trigger efficiency	rate	2%	2%	2%	2%
Cross section	rate	9.2%	5.6%	14.7%	—
Top quark $p_T$ reweighting	shape	—	28%	—	—
W+jets $H_T$ reweighting	shape	5.3%	—	—	—
Renormalization/factorization scales	shape	14%	16%	16%	—
PDF	shape	5.5%	2.3%	8.5%	6.7%
Forward jet reweighting	rate	15%	15%	15%	15%

**Table 2**  
Data, background, and possible signal pre-fit event yields corresponding to  $2.3 \text{ fb}^{-1}$  of integrated luminosity. The signal sample is the  $M(Y) = 1.0 \text{ TeV}$  mass point using the NLO cross section [30]. The percentage in the signal column indicates the signal efficiency. The background uncertainties include both the statistical and the systematic pre-fit components.

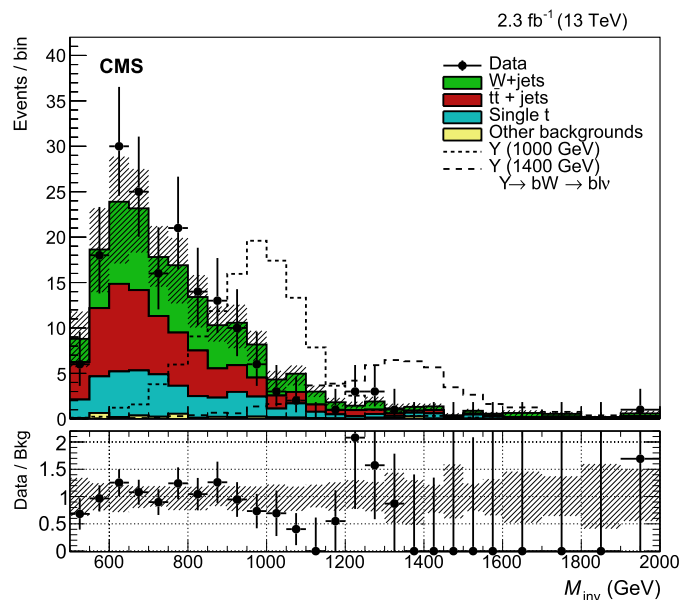
Channel	W+jets	$t\bar{t}$	Single t	QCD	Z+jets	Diboson	Y(1.0 TeV)	Total bkg.	Data
Electron	$44 \pm 12$	$28 \pm 11$	$20 \pm 5$	<1	$1.5 \pm 1.5$	$1.3 \pm 0.5$	54 (1.3%)	$95 \pm 17$	78
Muon	$52 \pm 14$	$34 \pm 13$	$27 \pm 6$	<1	<1	$1.7 \pm 0.6$	60 (1.4%)	$115 \pm 20$	95

nuisance parameters. The post-fit  $M_{\text{inv}}$  distribution, with the shape and background normalizations corresponding to the maximum likelihood values, is presented in Fig. 4. All corrections derived from the background-enriched regions are propagated to the signal region and appropriate systematic uncertainties are assigned.

Upper limits at 95% confidence level (CL) on the production cross section of the  $Y/T \rightarrow bW$  process are computed using a Bayesian approach [55], where the likelihood is marginalized with respect to the nuisance parameters representing systematic uncertainties. The expected limit is calculated by resampling the data from the background distribution. The 95% CL expected and observed upper limits are listed in Table 3 and shown in Fig. 5. The observed limits at high VLQ mass reflect a  $2\sigma$  deficit of events above 1.0 TeV in the  $M_{\text{inv}}$  distribution. The limits are derived assuming a narrow width for the VLQ. The VLQ width is proportional to the square of the coupling, and is negligible compared to the experimental resolution for couplings below 0.5, for the range of VLQ masses considered in this paper. In the framework of the model considered, Y quarks with a coupling of 0.5 and  $\mathcal{B}(Y \rightarrow bW) = 100\%$  are excluded in the mass range from 0.85 to 1.40 TeV. This result may be compared with the expected region of excluded masses, which extends up to 1.0 TeV. In the case of T quarks with a coupling of 0.5, the theoretical cross section, the selection efficiency and the  $M_{\text{inv}}$  distribution are the same as those for the production and decay of Y quarks, but the expected decay branching fraction  $\mathcal{B}(T \rightarrow bW)$  is 50%, only half that expected for  $\mathcal{B}(Y \rightarrow bW)$ . Thus mass exclusion limits similar to those achieved for the Y quark would only be obtained for  $\mathcal{B}(T \rightarrow bW) = 100\%$ .

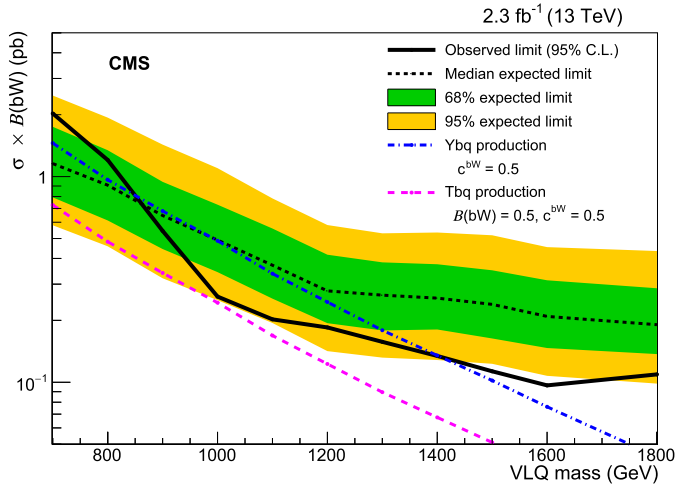
## 8. Summary

A search has been performed for single production of a vector-like quark decaying into a b quark and a W boson in the electron/muon + jets channels. The mass of the vector-like quark is reconstructed by forming the invariant mass of the leading b-tagged jet, electron or muon, and missing transverse momentum in the event, and a fit to the invariant mass spectrum is performed. No evidence of an excess due to new physics is observed. Upper limits at 95% CL are set on the cross sections for single production of vector-like Y and T quarks in the mass range from 0.70



**Fig. 4.** The invariant mass  $M_{\text{inv}}$  distribution of heavy quark candidates, reconstructed from their decay products: the lepton, the leading central jet, and the neutrino. The distribution is obtained after the fit, assuming the background-only hypothesis. The dashed histograms show the event distributions expected for a Y quark with masses of 1.0 TeV and 1.4 TeV, coupling of 0.5 and  $\mathcal{B}(Y \rightarrow bW) = 100\%$ . The statistical and systematic uncertainties are represented by the hatched band on the ratio plot. In the last bin the data overflow event is an electron channel event with a mass of 2.22 TeV.

to 1.80 TeV. In the framework of the model considered, Y quarks with a coupling of 0.5 and  $\mathcal{B}(Y \rightarrow bW) = 100\%$  are excluded in the mass range from 0.85 to 1.40 TeV. This result may be compared with the expected region of excluded masses, which extends up to 1.0 TeV. These results represent the most stringent limits to date on the single production of a vector-like Y quark. In the case of T quarks with a coupling of 0.5, the theoretical cross section, the selection efficiency and the  $M_{\text{inv}}$  distribution are the same as those for the production and decay of Y quarks, but the expected decay branching fraction  $\mathcal{B}(T \rightarrow bW)$  is 50%, only half that expected for



**Fig. 5.** Expected and observed limits on the single VLQ production ( $pp \rightarrow Ybq$  and  $pp \rightarrow Tbq$ ) cross section together with the one and two standard deviation uncertainty bands.

**Table 3**

The 95% CL expected and observed upper limits (UL) on the single VLQ production cross section, assuming  $\mathcal{B}(VLQ \rightarrow bW) = 100\%$ .

VLQ mass (TeV)	Expected UL (pb)	Observed UL (pb)
0.70	$1.16^{+0.68}_{-0.37}$	2.03
0.80	$0.91^{+0.43}_{-0.30}$	1.20
0.90	$0.65^{+0.29}_{-0.21}$	0.54
1.0	$0.49^{+0.24}_{-0.15}$	0.26
1.10	$0.37^{+0.19}_{-0.12}$	0.20
1.20	$0.28^{+0.14}_{-0.09}$	0.18
1.30	$0.27^{+0.11}_{-0.09}$	0.16
1.40	$0.26^{+0.11}_{-0.08}$	0.13
1.50	$0.24^{+0.11}_{-0.08}$	0.11
1.60	$0.21^{+0.11}_{-0.06}$	0.10
1.70	$0.20^{+0.10}_{-0.06}$	0.10
1.80	$0.19^{+0.09}_{-0.05}$	0.11

$\mathcal{B}(Y \rightarrow bW)$ . Thus mass exclusion limits similar to those achieved for the  $Y$  quark would only be obtained for  $\mathcal{B}(T \rightarrow bW) = 100\%$ .

## Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI

(Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP-Center, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

## References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, <http://dx.doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, <http://dx.doi.org/10.1016/j.physletb.2012.08.021>, arXiv:1207.7235.
- [3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in  $pp$  collisions at  $\sqrt{s} = 7$  and 8 TeV, J. High Energy Phys. 06 (2013) 081, [http://dx.doi.org/10.1007/JHEP06\(2013\)081](http://dx.doi.org/10.1007/JHEP06(2013)081), arXiv:1303.4571.
- [4] P. Lodone, Vector-like quarks in a 'composite' Higgs model, J. High Energy Phys. 12 (2008) 029, <http://dx.doi.org/10.1088/1126-6708/2008/12/029>, arXiv:0806.1472.
- [5] M. Perelstein, M.E. Peskin, A. Pierce, Top quarks and electroweak symmetry breaking in little Higgs models, Phys. Rev. D 69 (2004) 075002, <http://dx.doi.org/10.1103/PhysRevD.69.075002>, arXiv:hep-ph/0310039.
- [6] R. Contino, T. Kramer, M. Son, R. Sundrum, Warped/composite phenomenology simplified, J. High Energy Phys. 05 (2007) 074, <http://dx.doi.org/10.1088/1126-6708/2007/05/074>, arXiv:hep-ph/0612180.
- [7] CMS Collaboration, Search for vectorlike charge 2/3 T quarks in proton-proton collisions at  $\sqrt{s} = 8$  TeV, Phys. Rev. D 93 (2016) 012003, <http://dx.doi.org/10.1103/PhysRevD.93.012003>, arXiv:1509.04177.
- [8] CMS Collaboration, Search for pair-produced vectorlike B quarks in proton-proton collisions at  $\sqrt{s} = 8$  TeV, Phys. Rev. D 93 (2016) 112009, <http://dx.doi.org/10.1103/PhysRevD.93.112009>, arXiv:1507.07129.
- [9] ATLAS Collaboration, Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, J. High Energy Phys. 08 (2015) 105, [http://dx.doi.org/10.1007/JHEP08\(2015\)105](http://dx.doi.org/10.1007/JHEP08(2015)105), arXiv:1505.04306.
- [10] ATLAS Collaboration, Search for vectorlike B quarks in events with one isolated lepton, missing transverse momentum and jets at  $\sqrt{s} = 8$  TeV with the ATLAS detector, Phys. Rev. D 91 (2015) 112011, <http://dx.doi.org/10.1103/PhysRevD.91.112011>, arXiv:1503.05425.
- [11] A. De Simone, O. Matsedonskyi, R. Rattazzi, A. Wulzer, A first top partner hunter's guide, J. High Energy Phys. 04 (2013) 1304, [http://dx.doi.org/10.1007/JHEP04\(2013\)004](http://dx.doi.org/10.1007/JHEP04(2013)004), arXiv:1211.5663.
- [12] J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Perez-Victoria, A handbook of vectorlike quarks: mixing and single production, Phys. Rev. D 88 (2013) 094010, <http://dx.doi.org/10.1103/PhysRevD.88.094010>, arXiv:1306.0572.

- [13] CMS Collaboration, Search for single production of a heavy vector-like T quark decaying to a Higgs boson and a top quark with a lepton and jets in the final state, *Phys. Lett. B* 771 (2017) 80, <http://dx.doi.org/10.1016/j.physletb.2017.05.019>, arXiv:1612.00999.
- [14] CMS Collaboration, Search for electroweak production of a vector-like quark decaying to a top quark and a Higgs boson using boosted topologies in fully hadronic final states, *J. High Energy Phys.* 04 (2017) 136, [http://dx.doi.org/10.1007/JHEP04\(2017\)136](http://dx.doi.org/10.1007/JHEP04(2017)136), arXiv:1612.05336.
- [15] CMS Collaboration, Search for single production of vector-like quarks decaying to a Z boson and a top or a bottom quark in proton–proton collisions at  $\sqrt{s} = 13\text{TeV}$ , *J. High Energy Phys.* 05 (2017) 029, [http://dx.doi.org/10.1007/JHEP05\(2017\)029](http://dx.doi.org/10.1007/JHEP05(2017)029), arXiv:1701.07409.
- [16] ATLAS Collaboration, Search for single production of vector-like quarks decaying into  $Wb$  in  $pp$  collisions at  $\sqrt{s} = 8\text{TeV}$  with the ATLAS detector, *Phys. J. C* 76 (2016), <http://dx.doi.org/10.1140/epjc/s10052-016-4281-8>, arXiv:1602.05606.
- [17] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [18] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2004) 040, <http://dx.doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [19] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [20] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, [http://dx.doi.org/10.1007/JHEP06\(2010\)043](http://dx.doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [21] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [22] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, *J. High Energy Phys.* 06 (2011) 128, [http://dx.doi.org/10.1007/JHEP06\(2011\)128](http://dx.doi.org/10.1007/JHEP06(2011)128), arXiv:1106.0522.
- [23] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [24] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* 191 (2015) 159, <http://dx.doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [25] R.D. Ball, V. Bertone, S. Carrazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.I. Latorre, J. Rojo, M. Ubiali, Parton distributions for the LHC run II, *J. High Energy Phys.* 04 (2015) 040, [http://dx.doi.org/10.1007/JHEP04\(2015\)040](http://dx.doi.org/10.1007/JHEP04(2015)040), arXiv:1410.8849.
- [26] T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi,  $W^+W^-$  production at hadron colliders in NNLO QCD, *Phys. Rev. Lett.* 113 (2014) 212001, <http://dx.doi.org/10.1103/PhysRevLett.113.212001>, arXiv:1408.5243.
- [27] M. Czakon, A. Mitov, NNLO corrections to top pair production at hadron colliders: the quark–gluon reaction, *J. High Energy Phys.* 01 (2013) 080, [http://dx.doi.org/10.1007/JHEP01\(2013\)080](http://dx.doi.org/10.1007/JHEP01(2013)080), arXiv:1210.6832.
- [28] N. Kidonakis, Next-to-next-to-leading-order collinear and soft gluon corrections for  $t$ -channel single top quark production, *Phys. Rev. D* 83 (2011) 091503, <http://dx.doi.org/10.1103/PhysRevD.83.091503>, arXiv:1103.2792.
- [29] J. Campbell, R.K. Ellis, F. Tramontano, Single top production and decay at next-to-leading order, *Phys. Rev. D* 70 (2004) 094012, <http://dx.doi.org/10.1103/PhysRevD.70.094012>, arXiv:hep-ph/0408158.
- [30] G. Panico, O. Matsedonskyi, A. Wulzer, On the interpretation of top partners searches, *J. High Energy Phys.* 12 (2014) 097, [http://dx.doi.org/10.1007/JHEP12\(2014\)097](http://dx.doi.org/10.1007/JHEP12(2014)097), arXiv:1409.0100.
- [31] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, *Nucl. Instrum. Methods A* 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [32] CMS Collaboration, Particle–flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{\text{miss}}$ , CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009), URL <http://cdsweb.cern.ch/record/1194487>.
- [33] CMS Collaboration, Commissioning of the particle–flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-001 (2010), URL <http://cdsweb.cern.ch/record/1247373>.
- [34] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at  $\sqrt{s} = 8\text{TeV}$ , *J. Instrum.* 10 (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [35] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <http://dx.doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [36] CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at  $\sqrt{s} = 7\text{TeV}$ , *J. High Energy Phys.* 01 (2011) 080, [http://dx.doi.org/10.1007/JHEP01\(2011\)080](http://dx.doi.org/10.1007/JHEP01(2011)080), arXiv:1012.2466.
- [37] M. Cacciari, G.P. Salam, Dispelling the  $N^3$  myth for the  $k_T$  jet-finder, *Phys. Lett. B* 641 (2006) 57, <http://dx.doi.org/10.1016/j.physletb.2006.08.037>, arXiv:hep-ph/0512210.
- [38] M. Cacciari, G.P. Salam, G. Soyez, The anti- $k_T$  jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [39] M. Cacciari, G.P. Salam, G. Soyez, The catchment area of jets, *J. High Energy Phys.* 04 (2008) 005, <http://dx.doi.org/10.1088/1126-6708/2008/04/005>, arXiv:0802.1188.
- [40] M. Cacciari, G.P. Salam, Pileup subtraction using jet areas, *Phys. Lett. B* 659 (2008) 119, <http://dx.doi.org/10.1016/j.physletb.2007.09.077>, arXiv:0707.1378.
- [41] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, *J. Instrum.* 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [42] CMS Collaboration, Identification of b quark jets at the CMS experiment in the LHC Run 2, CMS Physics Analysis Summary CMS-PAS-BTV-15-001 (2015), URL <https://cds.cern.ch/record/2138504?ln=en>.
- [43] CMS Collaboration, Identification of b-quark jets with the CMS experiment, *J. Instrum.* 8 (2011) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [44] CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at  $\sqrt{s} = 8\text{TeV}$ , *Eur. Phys. J. C* 75 (2015) 542, <http://dx.doi.org/10.1140/epjc/s10052-015-3709-x>, arXiv:1505.04480.
- [45] CMS Collaboration, CMS luminosity measurement for the 2015 data taking period, CMS Physics Analysis Summary CMS-PAS-LUM-15-001 (2016), URL <https://cds.cern.ch/record/2138682>.
- [46] CMS Collaboration, Measurement of the  $t\bar{t}$  production cross section in the dilepton channel in pp collisions at  $\sqrt{s} = 8\text{TeV}$ , *J. High Energy Phys.* 02 (2014) 024, [http://dx.doi.org/10.1007/JHEP02\(2014\)024](http://dx.doi.org/10.1007/JHEP02(2014)024), arXiv:1312.7582.
- [47] CMS Collaboration, Measurement of the inclusive cross section of single top-quark production in the  $t$ -channel at 13 TeV, *Phys. Lett. B* (2017), arXiv:1610.00678, In proofs.
- [48] CMS Collaboration, Measurement of inclusive W and Z boson production cross sections in pp collisions at  $\sqrt{s} = 13\text{TeV}$ , CMS Physics Analysis Summary CMS-PAS-SMP-15-004 (2015), URL <https://cds.cern.ch/record/2093537>.
- [49] CMS Collaboration, Measurement of associated W+charm production in pp collisions at  $\sqrt{s} = 7\text{TeV}$ , *J. High Energy Phys.* 02 (2014) 013, [http://dx.doi.org/10.1007/JHEP02\(2014\)013](http://dx.doi.org/10.1007/JHEP02(2014)013), arXiv:1310.1138.
- [50] CMS Collaboration, Measurement of the production cross section of the W boson in association with two b jets in pp collisions at  $\sqrt{s} = 8\text{TeV}$ , *Eur. Phys. J. C* 77 (2017) 92, <http://dx.doi.org/10.1140/epjc/s10052-016-4573-z>, arXiv:1608.07561.
- [51] ATLAS Collaboration, Measurement of the inelastic proton–proton cross section at  $\sqrt{s} = 13\text{TeV}$  with the ATLAS detector at the LHC, *Phys. Rev. Lett.* 117 (2016) 182002, <http://dx.doi.org/10.1103/PhysRevLett.117.182002>, arXiv:1606.02625.
- [52] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, *J. Phys. G* 43 (2016) 023001, <http://dx.doi.org/10.1088/0954-3899/43/2/023001>, arXiv:1510.03865.
- [53] W.T. Eadie, D. Drijard, F.E. James, M. Roos, B. Sadoulet, *Statistical Methods in Experimental Physics*, vol. 6, North Holland, Amsterdam, 1971, pp. 79–80. See.
- [54] F. James, *Statistical Methods in Experimental Physics*, 2nd ed., World Scientific, Singapore, 2006, pp. 83–87. See.
- [55] J. Ott, Theta – theta-auto testing documentation, URL <http://www-ekp.physik.uni-karlsruhe.de/~ott/theta/theta-auto/>, 2012.

## The CMS Collaboration

### A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, J. Strauss, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik, Wien, Austria*

O. Dvornikov, V. Makarenko, V. Mossolov, J. Suarez Gonzalez, V. Zykunov

*Institute for Nuclear Problems, Minsk, Belarus*

N. Shumeiko

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

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

*Universiteit Antwerpen, Antwerpen, Belgium*

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

*Vrije Universiteit Brussel, Brussel, Belgium*

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

H. Bakhshiansohi, C. Beluffi<sup>3</sup>, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

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

N. Beliy

*Université de Mons, Mons, Belgium*

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

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>4</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>5</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>4</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

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



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

*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

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

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>6</sup>

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen<sup>7</sup>, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, M. Ruan, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

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

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

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

*Universidad de Los Andes, Bogota, Colombia*

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

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

Z. Antunovic, M. Kovac

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

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

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

*Charles University, Prague, Czech Republic*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

E. El-khateeb<sup>9</sup>, S. Elgammal<sup>10</sup>, A. Mohamed<sup>11</sup>

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

M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

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

P. Eerola, J. Pekkanen, M. Voutilainen

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

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

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

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

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

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

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

J.-L. Agram<sup>12</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>12</sup>, X. Coubez, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove

*Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, France*

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>13</sup>, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

T. Toriashvili<sup>14</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>8</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

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

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

V. Cherepanov, G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl<sup>15</sup>

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras<sup>16</sup>, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>17</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>18</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>18</sup>, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker,

W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>18</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>15</sup>, T. Peiffer, A. Perieanu, J. Poehlsen, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann<sup>15</sup>, S.M. Heindl, U. Husemann, I. Katkov<sup>13</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

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

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

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

*University of Ioánnina, Ioánnina, Greece*

N. Filipovic, G. Pasztor

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

G. Bencze, C. Hajdu, D. Horvath<sup>19</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>20</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

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

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>20</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Hungary*

J.R. Komaragiri

*Indian Institute of Science (IISc), India*

S. Bahinipati<sup>22</sup>, S. Bhowmik<sup>23</sup>, S. Choudhury<sup>24</sup>, P. Mal, K. Mandal, A. Nayak<sup>25</sup>, D.K. Sahoo<sup>22</sup>, N. Sahoo, S.K. Swain

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

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

*University of Delhi, Delhi, India*

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

*Saha Institute of Nuclear Physics, Kolkata, India*

P.K. Behera

*Indian Institute of Technology Madras, Madras, India*

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>15</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

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

S. Banerjee, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>23</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>23</sup>, N. Wickramage<sup>26</sup>

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

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

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

S. Chenarani<sup>27</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>27</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>28</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>29</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<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>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</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,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,15</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

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

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

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

G. Abbiendi<sup>a</sup>, C. Battilana, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, 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>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b,15</sup>

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

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

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

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

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

G. Barbagli <sup>a</sup>, V. Ciulli <sup>a,b</sup>, C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, L. Russo <sup>a,30</sup>, G. Sguazzoni <sup>a</sup>, D. Strom <sup>a</sup>, L. Viliani <sup>a,b,15</sup>

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

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

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera <sup>15</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli <sup>a,b</sup>, F. Ferro <sup>a</sup>, M.R. Monge <sup>a,b</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>

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

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

L. Brianza <sup>a,b,15</sup>, F. Brivio <sup>a,b</sup>, V. Ciriolo, M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b,15</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>, R.A. Manzoni <sup>a,b</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</sup>, S. Pigazzini <sup>a,b</sup>, S. Ragazzi <sup>a,b</sup>, T. Tabarelli de Fatis <sup>a,b</sup>

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

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

S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, G. De Nardo, S. Di Guida <sup>a,d,15</sup>, M. Esposito <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>, F. Fienga <sup>a,b</sup>, A.O.M. Iorio <sup>a,b</sup>, G. Lanza <sup>a</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,15</sup>, P. Paolucci <sup>a,15</sup>, C. Sciacca <sup>a,b</sup>, F. Thyssen <sup>a</sup>

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

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

<sup>c</sup> Università della Basilicata, Potenza, Italy

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

P. Azzi <sup>a,15</sup>, L. Benato <sup>a,b</sup>, D. Bisello <sup>a,b</sup>, A. Boletti <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, A. Carvalho Antunes De Oliveira <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>, S. Fantinel <sup>a</sup>, F. Fanzago <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, F. Gonella <sup>a</sup>, S. Lacaprara <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, J. Pazzini <sup>a,b</sup>, N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Zanetti <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>

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

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

<sup>c</sup> Università di Trento, Trento, Italy

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

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

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

L. Alunni Solestizi <sup>a,b</sup>, G.M. Bilei <sup>a</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>, G. Mantovani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>

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

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

K. Androsov <sup>a,30</sup>, P. Azzurri <sup>a,15</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,30</sup>, R. Dell'Orso <sup>a</sup>, S. Donato <sup>a,c</sup>, G. Fedi, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,30</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,31</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>

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

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

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

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, M. Cipriani <sup>a,b</sup>, D. Del Re <sup>a,b,15</sup>, M. Diemoz <sup>a</sup>, S. Gelli <sup>a,b</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, B. Marzocchi <sup>a,b</sup>, P. Meridiani <sup>a</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, F. Preiato <sup>a,b</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>

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

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

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c,15</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>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b</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>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P. Traczyk<sup>a,b</sup>

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

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

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

S. Belforte<sup>a</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, A. Zanetti<sup>a</sup>

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

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

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

*Kyungpook National University, Daegu, Republic of Korea*

A. Lee

*Chonbuk National University, Jeonju, Republic of Korea*

H. Kim

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

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

*Hanyang University, Seoul, Republic of Korea*

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

*Korea University, Seoul, Republic of Korea*

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

*Seoul National University, Seoul, Republic of Korea*

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

*University of Seoul, Seoul, Republic of Korea*

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

*Sungkyunkwan University, Suwon, Republic of Korea*

V. Dudenas, A. Juodagalvis, J. Vaitkus

*Vilnius University, Vilnius, Lithuania*

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>32</sup>, F. Mohamad Idris<sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>34</sup>, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

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

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

*Universidad Iberoamericana, Mexico City, Mexico*

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

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

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

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler

*University of Canterbury, Christchurch, New Zealand*

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

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

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

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszuk<sup>35</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura,  
M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho,  
M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas,  
O. Toldaiev, D. Vadrucchio, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev,  
A. Malakhov, V. Matveev<sup>36,37</sup>, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov,  
V. Smirnov, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, V. Murzin, V. Oreshkin, V. Sulimov,  
A. Vorobyev

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

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

*Institute for Nuclear Research, Moscow, Russia*

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

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

A. Bylinkin<sup>37</sup>

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

R. Chistov<sup>40</sup>, M. Danilov<sup>40</sup>, S. Polikarpov

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

V. Andreev, M. Azarkin<sup>37</sup>, I. Dremin<sup>37</sup>, M. Kirakosyan, A. Leonidov<sup>37</sup>, A. Terkulov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>41</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin

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

V. Blinov<sup>42</sup>, Y. Skovpen<sup>42</sup>, D. Shtol<sup>42</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

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

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

P. Adzic<sup>43</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

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

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizán García

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco<sup>44</sup>, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer<sup>15</sup>, M.J. Kortelainen, K. Kousouris, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic<sup>45</sup>, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi<sup>46</sup>, M. Rovere, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas<sup>47</sup>, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns<sup>48</sup>, G.I. Veres<sup>20</sup>, M. Verweij, N. Wardle, H.K. Wöhri, A. Zagozdinska<sup>35</sup>, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*



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

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov<sup>49</sup>, V.R. Tavolaro, K. Theofilatos, R. Wallny

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

T.K. Aarrestad, C. AMSler<sup>50</sup>, L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

*Universität Zürich, Zurich, Switzerland*

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

*National Central University, Chung-Li, Taiwan*

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

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

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

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

A. Adiguzel, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>51</sup>, E.E. Kungal<sup>52</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>53</sup>, K. Ozdemir<sup>54</sup>, S. Ozturk<sup>55</sup>, A. Polatoz, B. Tali<sup>56</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Cukurova University – Physics Department, Science and Art Faculty, Turkey*

B. Bilin, S. Bilmis, B. Isildak<sup>57</sup>, G. Karapinar<sup>58</sup>, M. Yalvac, M. Zeyrek

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

E. Gülmez, M. Kaya<sup>59</sup>, O. Kaya<sup>60</sup>, E.A. Yetkin<sup>61</sup>, T. Yetkin<sup>62</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak, S. Sen<sup>63</sup>

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold<sup>64</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>65</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas<sup>64</sup>, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko<sup>49</sup>, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>66</sup>, T. Virdee<sup>15</sup>, J. Wright, S.C. Zenz

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

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

*Baylor University, Waco, USA*

R. Bartek, A. Dominguez

*Catholic University of America, United States*

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

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, USA*

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

*Brown University, Providence, USA*

R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi

*University of California, Davis, Davis, USA*

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

*University of California, Los Angeles, USA*

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

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>67</sup>, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

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

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

*California Institute of Technology, Pasadena, USA*

M.B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

*Carnegie Mellon University, Pittsburgh, USA*

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

*University of Colorado Boulder, Boulder, USA*

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

*Cornell University, Ithaca, USA*

D. Winn

*Fairfield University, Fairfield, USA*

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir<sup>†</sup>, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, 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, A. Whitbeck, Y. Wu

*Fermi National Accelerator Laboratory, Batavia, USA*

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

*University of Florida, Gainesville, USA*

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

*Florida International University, Miami, USA*

A. Ackert, T. Adams, A. Askew, S. Bein, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, A. Santra, R. Yohay

*Florida State University, Tallahassee, USA*

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

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, K. Jung, I.D. Sandoval Gonzalez, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

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

B. Bilki<sup>68</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>69</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>70</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

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

*Johns Hopkins University, Baltimore, USA*

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

*The University of Kansas, Lawrence, USA*

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

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, G.Y. Jeng<sup>71</sup>, R.G. Kellogg, T. Kolberg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, A. Apyan, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang

*Massachusetts Institute of Technology, Cambridge, USA*

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

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

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

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

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

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

*Northeastern University, Boston, USA*

S. Bhattacharya, O. Charaf, K.A. Hahn, A. Kumar, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>36</sup>, M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

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

*The Ohio State University, Columbus, USA*

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

*Princeton University, Princeton, USA*

S. Malik

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, J.F. Schulte, X. Shi, J. Sun, F. Wang, W. Xie

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, USA*

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

*Rice University, Houston, USA*

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

*University of Rochester, Rochester, USA*

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

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

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

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>72</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon<sup>73</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

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

N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P.R. Duerdo, J. Faulkner, E. Garpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*

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

*Vanderbilt University, Nashville, USA*

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

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, USA*

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

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

† Deceased.

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

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

<sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France.

<sup>4</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>5</sup> Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>6</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>7</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

<sup>8</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>9</sup> Now at Ain Shams University, Cairo, Egypt.

<sup>10</sup> Now at British University in Egypt, Cairo, Egypt.

<sup>11</sup> Also at Zewail City of Science and Technology, Zewail, Egypt.

<sup>12</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>13</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>14</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>15</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>16</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>17</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>18</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>19</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>20</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>21</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>22</sup> Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

<sup>23</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>24</sup> Also at Indian Institute of Science Education and Research, Bhopal, India.

<sup>25</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>26</sup> Also at University of Ruhuna, Matara, Sri Lanka.

<sup>27</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>28</sup> Also at Yazd University, Yazd, Iran.

<sup>29</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>30</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>31</sup> Also at Purdue University, West Lafayette, USA.

<sup>32</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

<sup>33</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>34</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

<sup>35</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>36</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>37</sup> Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

<sup>38</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>39</sup> Also at University of Florida, Gainesville, USA.

<sup>40</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.

<sup>41</sup> Also at California Institute of Technology, Pasadena, USA.

- <sup>42</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>43</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>44</sup> Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
- <sup>45</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>46</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>47</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>48</sup> Also at Riga Technical University, Riga, Latvia.
- <sup>49</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>50</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>51</sup> Also at Istanbul Aydin University, Istanbul, Turkey.
- <sup>52</sup> Also at Mersin University, Mersin, Turkey.
- <sup>53</sup> Also at Cag University, Mersin, Turkey.
- <sup>54</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>55</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>56</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>57</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>58</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>59</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>60</sup> Also at Kafkas University, Kars, Turkey.
- <sup>61</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>62</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>63</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>64</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>65</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>66</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>67</sup> Also at Utah Valley University, Orem, USA.
- <sup>68</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>69</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>70</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>71</sup> Also at University of Sydney, Sydney, Australia.
- <sup>72</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>73</sup> Also at Kyungpook National University, Daegu, Korea.