Search for Top-Quark Partners with Charge 5/3 in the Same-Sign Dilepton Final State

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

Citation

As Published
http://dx.doi.org/10.1103/PhysRevLett.112.171801

Publisher
American Physical Society

Version
Final published version

Accessed
Wed Jan 16 17:18:28 EST 2019

Citable Link
http://hdl.handle.net/1721.1/88726

Terms of Use
Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.

Detailed Terms
Search for Top-Quark Partners with Charge 5/3 in the Same-Sign Dilepton Final State

S. Chatrchyan et al.*

(CMS Collaboration)

(Received 9 December 2013; published 30 April 2014)

A search for the production of heavy partners of the top quark with charge 5/3 is performed in events with a pair of same-sign leptons. The data sample corresponds to an integrated luminosity of 19.5 fb⁻¹ and was collected at √s = 8 TeV by the CMS experiment. No significant excess is observed in the data above the expected background, and the existence of top-quark partners with masses below 800 GeV is excluded at a 95% confidence level, assuming they decay exclusively to tW. This is the first limit on these particles from the LHC, and it is significantly more restrictive than previous limits.

DOI: 10.1103/PhysRevLett.112.171801

PACS numbers: 14.65.Jk, 12.60.-i, 13.85.Qk

Various extensions of the standard model (SM) address the hierarchy problem, caused by the quadratic divergences in the quantum-loop corrections to the Higgs boson mass, by proposing new heavy particles. Since the largest correction arises from the top-quark loop, a class of these models, based on composite Higgs scenarios [1–4], predicts the existence of heavy partners of the top quark to explain the cancellation of this correction. These “top-quark partners” are expected to have masses close to the electroweak symmetry breaking scale and thus would be accessible at the CERN Large Hadron Collider (LHC), located near Geneva, Switzerland. They may also have exotic charge (5e/3, where 5 is the charge of the electron) and in this case would not contribute to the coupling of the Higgs boson to gluons [5]. Searches for such top-quark partners explore parameter space that is not excluded by the recent observation of a Higgs boson with properties consistent with those of the SM Higgs particle [6–14]. Theoretical predictions suggest that searches in the mass region from 500 GeV to 1.5 TeV present the greatest potential for discovery at the LHC [2,15].

This Letter presents a search for exotic top-quark partners using LHC pp collision data collected by the Compact Muon Solenoid (CMS) experiment at a center-of-mass energy √s = 8 TeV. The analysis is based on a data sample corresponding to an integrated luminosity of 19.5 fb⁻¹. We look for the T5/3, an exotic top-quark partner with charge 5e/3. We assume that the T5/3 is pair produced via either gluon fusion or quark annihilation and decays via T5/3 → tW⁺ followed by t → W⁺b (charge conjugate modes are implied throughout this Letter). Single T5/3 production is not considered because it is more model dependent and presents a different event topology [2].

We focus on the dilepton final state wherein, for one or both of the T5/3, its two W bosons both decay into leptons, which will have the same charge. Because of the presence of the two bottom quarks and the possibility of hadronic decays for one of the top-quark partners, this final state also includes significant jet activity. The leptons considered in this analysis are electrons and muons. The presence of leptons with the same electric charge (same-sign leptons) distinguishes this process from tt, making the contribution of the latter comparable to backgrounds with much smaller cross sections: tW, tWW, tZ, WW, and same-sign WW. Because of its large cross section, tt still contributes to the overall background through instrumental effects such as charge misidentification in dilepton decays, as well as through tt events where the W boson from one top quark decays leptonically and the second lepton arises from a b-quark decay. Additional processes that contribute to the expected background include QCD multijets, W/Z+jets, and dibosons (WZ and ZZ). A previous search using a signature of same-sign leptons, multiple jets, and missing transverse energy was performed by the CDF experiment and excludes T5/3 masses below 365 GeV at the 95% confidence level (C.L.) [16]. The CDF Collaboration also set a limit on the production of exotic quarks with charge −4e/3 [17].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux return yoke outside the solenoid. In addition, the CMS detector has extensive forward calorimetry. A more detailed description of the CMS detector can be found elsewhere [18].

Simulation of the pair production of top-quark partners was performed with the MADGRAPH 5.1.1 [19] event generator, and 12 samples corresponding to values of the
Additional low-rate SM processes were also considered: superimposing minimum bias interactions (obtained using interactions in each beam crossing (pileup) were modeled by each electron candidate is measured using three different reject electrons produced by photon conversions. The charge of each electron candidate is measured using three different rejection algorithms: the standard CMS track reconstruction algorithm [29] and the Gaussian sum filter algorithm [30], optimized to take into account the possible emission of bremsstrahlung photons in the silicon tracker. The third measurement is based on the relative position of the calorimeter cluster and the projected track from the pixel detector. All three measurements are required to be consistent with the electron hypothesis. Muon candidates are required to be reconstructed by both the silicon tracker and the muon system, and the combined fit of the track must be of good quality ($q^2$ per degree of freedom less than 10).

All selected leptons are required to be isolated. The isolation for each lepton is estimated by first computing the scalar sum of the transverse momenta of all neutral and charged reconstructed particle candidates, except the lepton itself, within a cone of size $\Delta R = \sqrt{ \Delta \phi^2 + (\Delta \eta)^2}$ around the lepton, where $\phi$ is the azimuthal angle. This sum is then divided by the transverse momentum ($p_T$) of the lepton to calculate the relative isolation ($I_R$). The values for the cone size and the maximum allowed $I_R$ are $0.3(0.4)$ and $I_R = 0.15(0.20)$, respectively, for electrons (muons), as determined by optimization studies for CMS top-quark related analyses. An event-by-event correction is applied to the computation of the lepton isolation in order to account for the effect of pileup. Scale factors to correct for imperfect detector simulation are obtained using the tag-and-probe method [31] for lepton identification and isolation as a function of lepton $p_T$ and $\eta$. In addition, we define a category of “loose” leptons with some of the isolation and identification requirements relaxed. The $I_R$ threshold for these leptons is increased from 0.15 to 0.60 for electrons and from 0.20 to 0.40 for muons.

For the range of $T_{5/3}$ masses accessible at $\sqrt{s} = 8$ TeV, the analysis exploits advanced techniques in jet reconstruction for identifying highly boosted top quarks and W bosons that decay hadronically. In particular, if the top quarks are highly boosted ($p_T > 400$ GeV), their decay products are collimated and merged into one jet. We use a “top-quark tagging” algorithm based on identifying jet substructure [32] to reconstruct such merged top-quark jets. Jets are clustered using the Cambridge-Aachen algorithm [33,34], as implemented in FastJet version 3 [35], with a distance parameter of $R = 0.8$ in $\eta$-$\phi$ space (CA8 jets). The CA8 top-quark jets are required to have $p_T > 400$ GeV and more than two subjets found by the top-quark tagging algorithm. The jet mass must be consistent with the mass of the top quark, and the minimum pairwise mass of the three highest $p_T$ subjets is required to be greater than 50 GeV.

The decay products of W bosons from the $T_{5/3}$ decay or from a highly boosted top quark, for which the $b$ quark is reconstructed independently, may also merge into a single jet. We use a “jet pruning” algorithm [36] to identify the hadronic decay of such W bosons. This algorithm also uses CA8 jets as inputs with the pruning parameters taken from the original theoretical papers [37,38]. CA8 W-boson jets are required to have $p_T > 200$ GeV, exactly two subjets, and their mass must be consistent with that of the W boson [39].

To account for W bosons and top quarks that are not highly boosted, jets are also reconstructed using the anti-$k_T$ algorithm [40] with a distance parameter of 0.5 (AK5). These jets are required to have $p_T > 30$ GeV. If an AK5 jet overlaps with a top-quark jet or a W-boson jet ($\Delta R < 0.8$), the AK5 jet is discarded.

All of the above categories of jets are required to have $|\eta| < 2.4$ and particle-flow jet identification [41]. Jet energy

\[ T_{5/3} \text{ mass from 350 GeV to 1 TeV were produced. The PYTHIA 6.426 [20] generator was used for parton showering, hadronization, and simulation of the underlying event. The CTEQ6L [21] parton distribution functions were used, and the PYTHIA parameters for the underlying event were set to the Z2* [22] tune. The detector response was modeled using GEANT4 [23]. The next-to-next-to-leading-order cross section for $T_{5/3}$ pair production was found using TOP++ [24] to vary from 5.3 pb at the mass of 350 GeV to 3.4 fb at the mass of 1 TeV. The uncertainty on the cross section in the mass range used for the analysis is about 5%. \]
corrections are applied to account for residual nonuniformity and nonlinearity of the detector response. Jet energies are also corrected by subtracting the average contribution of particles from pileup [42,43]. For the simulated samples, additional smearing is applied to the jet $p_T$ ($\sim 7\%$–$19\%$ depending on $\eta$) in order to reproduce the jet energy resolution observed in data. All jets must be $\Delta R \geq 0.3$ away from the selected leptons and, as mentioned above, $\Delta R \geq 0.8$ away from any other jet. A correction to account for differences in the identification efficiency of $W$-boson and top-quark jets between data and simulation is applied [44].

The signal selection, optimized to yield the best signal sensitivity, requires the following. (i) At least two isolated same-sign leptons as defined above with $p_T > 30$ GeV. Between each lepton and every top-quark jet, we require $\Delta R > 0.8$. (ii) Dilepton $Z$-boson veto: $M(\ell\ell) < 76$ GeV or $M(\ell\ell) > 106$ GeV. This selection applies only to the dilepton channel. If the muon charge is mismeasured, its momentum will also be mismeasured, so a selected muon pair from a $Z$ boson will not fall within this invariant mass range. (iii) Trilepton $Z$-boson veto: $M(\ell\ell) < 76$ GeV or $M(\ell\ell) > 106$ GeV, where $M(\ell\ell)$ is the invariant mass of either one of the selected leptons and any other same-flavor opposite-sign lepton in the event with $p_T > 15$ GeV that satisfies the loose lepton criteria. (iv) $N_{T} \geq 7$, where $N_{T}$ is the number of constituents identified in the event. For the purpose of this selection, each AK5 jet and each lepton count as one constituent. Since a $W$-boson jet is assumed to correspond to a $W$ boson, each such jet counts as two constituents, corresponding to the $W$-boson decay products. Likewise, each top-quark jet represents a top quark and counts as three constituents. (v) $H_{T} > 900$ GeV, where $H_{T}$ is the scalar sum of the $p_T$ of all selected jets and leptons in the event. With these criteria, the signal efficiency is $10\%$–$13\%$ for $T_{S/3}$ masses between 750 and 1000 GeV.

The backgrounds associated with this analysis fall into three main categories. First, they may originate from SM processes leading to prompt, same-sign dilepton signatures, including diboson production ($WZ$ and $ZZ$), $t\bar{t}W$, $t\bar{t}WW$, $t\bar{t}Z$, $W^{\pm}W^{\pm}$, and $WWW$. The contribution of these backgrounds is obtained from simulation.

The second category consists of events from processes with prompt, opposite-sign leptons, such as $t\bar{t}$ and Drell-Yan production, in which one of the leptons is misreconstructed with the wrong charge, leading to a same-sign dilepton final state. For muons in the $p_T$ range typical of the dominant backgrounds, the charge misidentification rate is extremely small (of order $10^{-4}$) and its contribution to the background is negligible [45]. For electrons, the charge misidentification probability ($\sim 10^{-5}$) is derived from a data sample dominated by Drell-Yan events obtained by selecting dileptons with an invariant mass consistent with originating from the $Z$ boson, using the ratio of same-sign $Z$-boson candidates to the total number of candidates. The number of expected same-sign events due to charge misidentification is then estimated by considering the total number of events passing the full selection but having oppositely charged leptons. These events are weighted by the charge misidentification probability parametrized as a function of the electron $p_T$ and $\eta$ to obtain the contribution of this background type.

The third category consists of events with one or more “nonprompt leptons.” This is the primary instrumental background arising from jets being misidentified as leptons and nonprompt leptons passing tight isolation selection criteria. This contribution is estimated using the “tight-loose” method described in Ref. [46]. “Tight” leptons have the same definition as those used in the analysis, whereas “loose” leptons are defined earlier. The background is estimated by using events with one or more loose leptons weighted by the ratios of the numbers of tight leptons to the numbers of loose leptons expected for prompt and nonprompt leptons. The ratio for prompt leptons is determined from Drell-Yan events where the invariant mass of the leptons is within 10 GeV of the $Z$-boson mass. The nonprompt ratio is determined from a sample enriched in background by requiring exactly one lepton, low missing transverse energy ($E_T^{\text{miss}} < 25$ GeV), low transverse mass ($M_T < 25$ GeV), and at least one jet (the “away jet”) with $p_T > 40$ GeV and $\Delta R > 1.0$ with respect to the lepton. The transverse mass is defined as $M_T \equiv \sqrt{2p_T^{\ell}E_T^{\text{miss}}(1 - \cos \Delta \phi)}$, where $\Delta \phi$ is the angle between the lepton transverse momentum ($p_T^{\ell}$) and the direction associated with $E_T^{\text{miss}}$.

The systematic uncertainties that affect the signal and background acceptance include uncertainties in the efficiency of the trigger (1%), lepton reconstruction and identification efficiency (1% per lepton), pileup, and the jet energy scale (JES). The uncertainties due to the JES and pileup are obtained by varying the respective quantities in simulation. For the signal, the JES and pileup uncertainties in the acceptance correspond to 2% and 3%, respectively. For the simulated backgrounds, they range from 3% to 6%, depending on the sample. In addition, we assign a constant 3% uncertainty due to the JES of CA8 jets for all simulated samples [44]. The dominant uncertainty in the expected event yields due to backgrounds derived from simulation is the overall normalization uncertainty. The ZZ (5.1%), WZ (17%), and $t\bar{t}W$ (32%) normalization uncertainties are taken from Refs. [26,47,48], respectively. For the other rare backgrounds, we assume a conservative normalization uncertainty of 50% [49]. An uncertainty of 20% is assigned to the background contribution from charge misidentification, based on the difference in the charge misidentification rate between Drell-Yan data and $t\bar{t}$ simulation. Following Ref. [45], we also assign a conservative additional systematic uncertainty of 50% in the estimation of backgrounds due to nonprompt leptons. This uncertainty is
TABLE I. Summary table of expected and observed numbers of events for all channels. The background is composed of the same-sign component, the contribution due to charge misidentification, and that due to misreconstructed leptons. All systematic uncertainties are included. Also shown is the expected contribution from a $T_{5/3}$ with mass of 800 GeV.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same sign</td>
<td>0.8 ± 0.2</td>
<td>1.9 ± 0.4</td>
<td>1.3 ± 0.3</td>
<td>4.0 ± 0.8</td>
</tr>
<tr>
<td>Charge misidentification</td>
<td>0.06 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>...</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>Nonprompt</td>
<td>1.9 ± 1.2</td>
<td>0.6 ± 0.9</td>
<td>0.3 ± 0.6</td>
<td>2.8 ± 1.9</td>
</tr>
<tr>
<td>Total background</td>
<td>2.7 ± 1.3</td>
<td>2.5 ± 1.0</td>
<td>1.6 ± 0.7</td>
<td>6.8 ± 2.1</td>
</tr>
<tr>
<td>Observed events</td>
<td>0</td>
<td>6</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>$T_{5/3}$</td>
<td>2.1 ± 0.1</td>
<td>4.7 ± 0.3</td>
<td>2.8 ± 0.2</td>
<td>9.7 ± 0.5</td>
</tr>
</tbody>
</table>

based on closure tests using $t\bar{t}$ and $W + jets$ simulated samples and takes into account variations due to the away jet $p_T$ and the flavor composition of the background, thus also accounting for any potential dependence on kinematic parameters that alter the background composition (such as $H_T$). We also include a 2.6% uncertainty due to the luminosity [50] for all event yields that are derived from simulation.

The final numbers of observed and expected events are reported in Table I for each of the three lepton channels ($ee$, $e\mu$, and $\mu\mu$) and their combination. Figure 1 shows the $H_T$ distribution for all channels combined.

No significant excess is observed. Exclusion limits are computed at 95% C.L. by using the ROOSTATS implementation [51] of the Bayesian approach. We use a cut-and-count method and compare the numbers of observed events with the numbers of expected signal and background events. A flat prior is used for the signal production cross section. The event yields from all lepton channels are combined when setting the limits. Upper bounds are set on the production cross section of heavy top-quark partners, assuming a 100% branching fraction (BF) for the decay $T_{5/3} \rightarrow t W$. The resulting expected and observed limits are shown in Fig. 2. The expected lower limit on the mass of the $T_{5/3}$ is 830 GeV, and the observed limit is 800 GeV.

The use of recently developed jet substructure techniques in this analysis for identifying boosted top quarks and $W$ bosons enables us to probe cross sections of $T_{5/3}$ pair production that are between 10%–20% lower than would otherwise be possible for $T_{5/3}$ masses in the range 800–1000 GeV. The reconstruction of the $T_{5/3}$ mass benefits as well, and this can, in the event of a discovery in the future,
be used to distinguish a $T_{5/3}$ from other exotic particles which decay in a similar manner [52].

In summary, a search for an exotic top partner with charge $5/3$ in same-sign dileptonic events has been performed using 19.5 fb$^{-1}$ of data collected by the CMS experiment at $\sqrt{s} = 8$ TeV. No significant excess is observed in the data above the expected standard model background. An upper bound at the 95% confidence level is observed in the data above the expected standard model experiment at $m_{T}$ = 365 GeV. No significant excess is observed in the data above the expected standard model limits set by previous searches.

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: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COFUND (Europe); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); and DOE and NSF (U.S.A.).

PRL 112, 171801 (2014)  

D. Fasanella,\(^{56a,56b}\) P. Giacomelli,\(^{55a}\) C. Grandi,\(^{55a}\) L. Guidducci,\(^{56a,56b}\) S. Marcellini,\(^{56a}\) G. Masetti,\(^{56a}\) M. Meneghelli,\(^{56a,56b}\) A. Montanari,\(^{56a}\) F. L. Navarria,\(^{56a,56b}\) F. Odorici,\(^{55a}\) A. Perrotta,\(^{56a}\) F. Primavera,\(^{56a,56b}\) A. M. Rossi,\(^{56a,56b}\) T. Rovelli,\(^{56a,56b}\) G. P. Siroli,\(^{56a}\) N. Tosi,\(^{56a,56b}\) R. Travaglini,\(^{56a,56b}\) S. Albergo,\(^{57a,57b}\) G. Cappello,\(^{57a,57b}\) M. Chiorboli,\(^{57a,57b}\) S. Costa,\(^{57a,57b}\) F. Giordano,\(^{57a}\) R. Potenza,\(^{57a}\) A. Tricomi,\(^{57a}\) C. Tuve,\(^{57a,57b}\) G. Barbagli,\(^{58a,58b}\) V. Ciulli,\(^{58a,58b}\) C. Civinini,\(^{58a}\) R. D`Alessandro,\(^{58a}\) E. Focardi,\(^{58a,58b}\) E. Gallo,\(^{58a,58b}\) S. Goni,\(^{58a,58b}\) V. Gori,\(^{58a,58b}\) P. Lenzii,\(^{58a,58b}\) M. Meschini,\(^{58a}\) S. Paolotti,\(^{58a}\) G. Squazzoni,\(^{58a}\) A. Tropiano,\(^{58a}\) L. Benussi,\(^{59}\) S. Bianco,\(^{59}\) F. Fabbrini,\(^{59}\) D. Piccolo,\(^{59}\) P. Fabbricatore,\(^{60a}\) R. Ferretti,\(^{60a}\) F. Ferro,\(^{60a}\) M. Lo Vetere,\(^{60a,60b}\) R. Musenich,\(^{60a}\) E. Robutti,\(^{60a}\) S. Tosi,\(^{60a,60b}\) A. Benaglia,\(^{60a}\) M. E. Dinardo,\(^{61a,61b}\) S. Fiorenzi,\(^{61a,61b}\) S. Gennai,\(^{61a,61b}\) A. Ghezzi,\(^{61a,61b}\) G. Gavrilov,\(^{90}\) N. Lychkovskaya,\(^{90}\) V. Popov,\(^{90}\) G. Safronov,\(^{90}\) V. Konoplyanikov,\(^{87}\) G. Kozlov,\(^{87}\) A. Lanev,\(^{87}\) A. Malakhov,\(^{87}\) V. Matveev,\(^{87}\) P. Moisenz,\(^{87}\) V. Pichik,\(^{87}\) V. Perelygin,\(^{87}\) M. Savina,\(^{87}\) S. Shmatov,\(^{87}\) N. Skatchkov,\(^{87}\) A. Zarubin,\(^{87}\) V. Golovtsov,\(^{88}\) Y. Ivanov,\(^{88}\) V. Kim,\(^{88}\) P. Levchenko,\(^{88}\) V. Murzin,\(^{88}\) V. Oreshkin,\(^{88}\) I. Smirnov,\(^{88}\) V. Sulimov,\(^{88}\) L. Uvarov,\(^{88}\) S. Vavilov,\(^{88}\) A. Vorobyev,\(^{88}\) An. Vorobyev,\(^{88}\) Yu. Andreiv,\(^{88}\) A. Dermenev,\(^{88}\) S. G¨unenok,\(^{89}\) A. Golubev,\(^{89}\) K. Kirsanov,\(^{89}\) N. Krasnikov,\(^{89}\) A. Pashenkov,\(^{89}\) D. Tislov,\(^{89}\) A. Toropin,\(^{89}\) V. Epstein,\(^{90}\) V. Gavrilov,\(^{90}\) N. Lychkovskaya,\(^{90}\) V. Popov,\(^{90}\) G. Safronov,\(^{90}\) S. Semenov,\(^{90}\) A. Spiridonov,\(^{90}\) V. Stolin,\(^{90}\) E. Vlasov,\(^{88}\) A. Zhokin,\(^{90}\) V. Andreev,\(^{91}\) M. Azarkin,\(^{91}\) I. Dremin,\(^{91}\)
(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der OeAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Universidade Estadual Paulista, São Paulo, Brazil
13University of Split, Split, Croatia
14Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
15University of Sofia, Sofia, Bulgaria
16State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
17Universidad de Los Andes, Bogota, Colombia
18Technical University of Split, Split, Croatia
19University of Split, Split, Croatia
20Institute Rudjer Boskovic, Zagreb, Croatia
21University of Cyprus, Nicosia, Cyprus
22Charles University, Prague, Czech Republic
23Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
24National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
25Department of Physics, University of Helsinki, Helsinki, Finland
26Helsinki Institute of Physics, Helsinki, Finland
27Lappeenranta University of Technology, Lappeenranta, Finland
28DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
29Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
30Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
31Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
32Université Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
33Institute of Higher Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
34RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
35RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
36RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
37Deutsches Elektronen-Synchrotron, Hamburg, Germany
38University of Hamburg, Hamburg, Germany
39Institut für Experimentelle Kernphysik, Karlsruhe, Germany
40Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
41University of Athens, Athens, Greece
42University of Ioannina, Ioannina, Greece
43Wigner Research Centre for Physics, Budapest, Hungary
44Institute of Nuclear Research ATOMKI, Debrecen, Hungary
45University of Debrecen, Debrecen, Hungary
46National Institute of Science Education and Research, Bhubaneswar, India
47Panjab University, Chandigarh, India
48University of Delhi, Delhi, India
49Saha Institute of Nuclear Physics, Kolkata, India
50Rabha Atomic Research Centre, Mumbai, India
51Tata Institute of Fundamental Research - EHEP, Mumbai, India

171801-12
Tata Institute of Fundamental Research - HECR, Mumbai, India
Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
University College Dublin, Dublin, Ireland
INFN Sezione di Bari, Bari, Italy
Universitá di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy
INFN Sezione di Bologna, Bologna, Italy
Universitá di Bologna, Bologna, Italy
INFN Sezione di Catania, Catania, Italy
Universitá di Catania, Catania, Italy
CSFNSM, Catania, Italy
INFN Sezione di Firenze, Firenze, Italy
Universitá di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
Universitá di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
Universitá di Milano-Bicocca, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Universitá di Napoli `Federico II', Napoli, Italy
Universitá della Basilicata (Potenza), Napoli, Italy
Universitá G. Marconi (Roma), Napoli, Italy
INFN Sezione di Padova, Padova, Italy
Universitá di Padova, Padova, Italy
INFN Sezione di Pavia, Pavia, Italy
Universitá di Pavia, Pavia, Italy
INFN Sezione di Perugia, Perugia, Italy
Universitá di Perugia, Perugia, Italy
INFN Sezione di Pisa, Pisa, Italy
Universitá di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Universitá di Roma, Roma, Italy
INFN Sezione di Torino, Torino, Italy
Universitá di Torino, Torino, Italy
Universitá del Piemonte Orientale (Novara), Torino, Italy
INFN Sezione di Trieste, Trieste, Italy
Universitá di Trieste, Trieste, Italy
Kangwon National University, Chunchon, Korea
Kyungpook National University, Daegu, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Korea University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, Korea
Vilnius University, Vilnius, Lithuania
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
Benemerita Universidad Autonomia de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
aDeceased.
bAlso at Vienna University of Technology, Vienna, Austria.
cAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
dAlso at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
eAlso at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
fAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
gAlso at Universidade Estadual de Campinas, Campinas, Brazil.
hAlso at California Institute of Technology, Pasadena, USA.
iAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
jAlso at Zewail City of Science and Technology, Zewail, Egypt.
kAlso at Suez Canal University, Suez, Egypt.
lAlso at Cairo University, Cairo, Egypt.
mAlso at Fayoum University, El-Fayoum, Egypt.
nAlso at British University in Egypt, Cairo, Egypt.
oNow at Ain Shams University, Cairo, Egypt.
pAlso at Université de Haute Alsace, Mulhouse, France.
qAlso at Joint Institute for Nuclear Research, Dubna, Russia.
rAlso at Brandenburg University of Technology, Cottbus, Germany.
sAlso at The University of Kansas, Lawrence, USA.
tAlso at The University of Kansas, Lawrence, USA.
uAlso at Eötvös Loránd University, Budapest, Hungary.
vAlso at Tata Institute of Fundamental Research - EHEP, Mumbai, India.
wAlso at Tata Institute of Fundamental Research - HECR, Mumbai, India.
xNow at King Abdulaziz University, Jeddah, Saudi Arabia.
yAlso at University of Visva-Bharati, Santiniketan, India.
zAlso at University of Ruhuna, Matara, Sri Lanka.
aaAlso at Isfahan University of Technology, Isfahan, Iran.
abAlso at Sharif University of Technology, Tehran, Iran.
acAlso at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
ddAlso at Università degli Studi di Siena, Siena, Italy.
ecAlso at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France.
edAlso at Purdue University, West Lafayette, USA.
feAlso at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
ffAlso at National Centre for Nuclear Research, Swierk, Poland.
gAlso at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
hfAlso at Facoltà Ingegneria, Università di Roma, Roma, Italy.
iAlso at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
jAlso at University of Athens, Athens, Greece.
kmAlso at Paul Scherrer Institut, Villigen, Switzerland.
nAlso at Institute for Theoretical and Experimental Physics, Moscow, Russia.
oeAlso at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
pfAlso at Gaziosmanpasa University, Tokat, Turkey.
qgAlso at Adiyaman University, Adiyaman, Turkey.
rhAlso at Cag University, Mersin, Turkey.
Also at Mersin University, Mersin, Turkey.
Also at Izmir Institute of Technology, Izmir, Turkey.
Also at Ozyegin University, Istanbul, Turkey.
Also at Kafkas University, Kars, Turkey.
Also at Suleyman Demirel University, Isparta, Turkey.
Also at Ege University, Izmir, Turkey.
Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
Also at Kahramanmaras Sütçü Imam University, Kahramanmaras, Turkey.
Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
Also at Utah Valley University, Orem, USA.
Also at Institute for Nuclear Research, Moscow, Russia.
Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
Also at Argonne National Laboratory, Argonne, USA.
Also at Erzincan University, Erzincan, Turkey.
Also at Yildiz Technical University, Istanbul, Turkey.
Also at Texas A&M University at Qatar, Doha, Qatar.
Also at Kyungpook National University, Daegu, Korea.