We report an investigation of the invariant mass spectrum of the two jets with highest transverse momentum in \( pp \rightarrow W + 2\text{-jet} \) and \( W + 3\text{-jet} \) events to look for resonant enhancement. The data sample corresponds to an integrated luminosity of 5.0 fb\(^{-1}\) collected with the CMS detector at \( \sqrt{s} = 7 \) TeV. We find no evidence for the anomalous structure reported by the CDF Collaboration, and establish an upper limit of 5.0 pb at 95% confidence level on the production cross section for a generic Gaussian signal with mass near 150 GeV. Additionally, we exclude two theoretical models that predict a CDF-like dijet resonance near 150 GeV.

\[ \frac{d\sigma}{dp_T^2}(m_H \sim 150 \text{ GeV}) \ll \frac{d\sigma}{dp_T^2}(m_H \sim 125 \text{ GeV}) \]

Within the field volume is the silicon pixel and strip tracker extending up to \( |\eta| = 2.5 \), as well as a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadronic calorimeter (HCAL), both extending up to \( |\eta| = 3 \). Outside the field volume in the forward region \( (3 < |\eta| < 5) \) is an iron and quartz-fiber hadronic calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid, in the pseudorapidity range \( |\eta| < 2.4 \). The CMS coordinate system has its origin at the center of the detector, with the \( z \) axis pointing along the direction of the counterclockwise proton beam. The azimuthal angle is denoted as \( \phi \), the polar angle as \( \theta \), and the pseudorapidity is defined as \( \eta = - \ln(\tan(\theta/2)) \).

We employ selection criteria similar to those used at the Tevatron [1,2], but modified to adapt to the higher background rates and different experimental conditions at the LHC. We also place more stringent requirements on the jet kinematics, as suggested in Ref. [8], to enhance a signal compared to the irreducible \( W \) plus jets background.

Events are selected with one well-identified and isolated lepton (muon or electron), large missing transverse energy \( E_T \), and exactly two or exactly three high-\( p_T \) jets. The data were collected with a suite of single-lepton triggers, mostly with a \( p_T \) threshold of 24 GeV for muons and 25–32 GeV for electrons. The trigger efficiency for the selected muons (electrons) is about 94% (90%). We reconstruct muon candidates in the region \( |\eta| < 2.1 \) by combining information from the silicon tracker and the muon detectors by means of a global fit. We identify electron candidates within \( |\eta| < 1.44 \) and \( 1.57 < |\eta| < 2.5 \) as clustered energy deposits in the electromagnetic calorimeter that are matched to tracks. Muon and electron candidates need to fulfill quality criteria established for the measurement of the inclusive \( W \) and \( Z \) cross sections [9]. In addition, all leptons must be well-separated from hadronic activity in the event. Jets within a \( \eta-\phi \) cone of radius 0.3 around a lepton candidate are removed.
The muon (electron) transverse momentum must exceed 25 (35) GeV, and $p_T^\mu$ must be greater than 25 (30) GeV in the muon (electron) analysis. The transverse mass $M_T$ of each $W$ candidate must be greater than 50 GeV, where

$$M_T = \sqrt{2p_T^\ell E_T^\ell [1 - \cos(\phi_\ell - \phi_E^\ell)]}$$

and $\phi_\ell$ and $\phi_E^\ell$ are the azimuthal angles of the lepton and $E_T^\ell$, respectively. Events with more than one identified lepton are vetoed.

We reconstruct jets and $E_T^{\rm jet}$ [9,10] with the particle-flow algorithm [11], which combines information from several subdetectors. The jet finding uses the anti-$k_T$ clustering algorithm [12] with a distance parameter of 0.5. We require $|\eta_{\ jet}| < 2.4$ to ensure that they lie within the tracker acceptance, and a minimum jet $p_T$ of 30 GeV. Jets must satisfy identification criteria that eliminate jet candidates originating from noisy channels in the hadron calorimeter [13]. Jet-energy corrections are applied to account for the nonlinear response of the calorimeters to the particle energies and other instrumental effects. These corrections are based on in situ measurements using dijet, $\gamma +$ jet, and $Z +$ jet data samples [14]. Overlapping minimum-bias events from other pp collisions (pileup) and the underlying event can contribute additional energy to the reconstructed jets. The median energy density due to pileup is evaluated in each event and the corresponding energy is subtracted from each jet [15]. In addition, tracks that do not originate from the primary vertex are not considered for jet clustering [16]. We verify that the procedures successfully remove the dependence of jet response on the number of interactions in a single event. The jet $p_T$ resolution varies from 15% at $p_T = 40$ GeV to 6% at $p_T = 400$ GeV [14].

We evaluate the mass resolution $\sigma_{jj}$ for a selected jet pair using simulation and verify it using hadronic $W$ decays in data. We find $\sigma_{jj}$ to be 10% of $m_{jj}$ for masses around 150 GeV.

We require $\|\vec{p}_T^{j_1} + \vec{p}_T^{j_2}\| > 45$ GeV and $|\Delta \eta(j_1,j_2)| < 1.2$, where the jets are numbered in order of decreasing $p_T$. We retain events with exactly two or exactly three jets satisfying $p_T > 30$ GeV and with the leading jet having $p_T > 40$ GeV and pointing more than 0.4 rad in azimuth from the direction of the $E_T^{\rm jet}$. The selected jets and the lepton from the $W$ decay must originate from the same primary vertex. Additionally, we impose $0.3 < p_T^{j_1}/m_{jj} < 0.7$ to take advantage of the Jacobian nature of resonant dijet production as observed in simulation studies compared with nonresonant $W$ plus jets production.

$W$ production with two or more jets dominates the selected sample. Smaller contributions come from top-pair and single-top decays, Drell-Yan events with two or more jets, multijet production, and $WW$ and $WZ$ diboson production where one $W$ decays into leptons and the other $W$ or $Z$ decays into quarks.

The shapes of the $m_{jj}$ distributions for background processes are modeled using samples of simulated events. The MADGRAPH5 1.3.30 [17] event generator produces parton-level events with a $W$ boson and up to four partons on the basis of matrix-element (ME) calculations. (The Tevatron experiments used the ALPGEN generator [18].) The ME-parton shower matching scale $\mu$ is taken to be 20 GeV [19], and the factorization and renormalization scales are set to $\mu^2 = M_W^2 + p_T^2/2$. Samples of $t\bar{t}$ and Drell-Yan events are also generated with MADGRAPH. Single-top production is modeled with POWHEG 1.0 [20]. Multijet and diboson samples ($WW$, $WZ$, $ZZ$) are generated with PYTHIA 6.422 [21]. PYTHIA provides the parton shower simulation in all cases, with parameters of the underlying event set to the Z2 tune [22]. The set of parton distribution functions used is CTEQ6L1 [23]. A GEANT4-based simulation [24] of the CMS detector is used in the production of all Monte Carlo (MC) samples. Multiple proton-proton interactions within a bunch crossing are simulated, and the triggers are emulated. All simulated events are reconstructed and analyzed with the same software as data.

We generate signal samples for the $WH$ model using PYTHIA, with parameters corresponding a SM Higgs boson with $m_H = 150$ GeV. We use PYTHIA for technicolor generation as well. We generate leptophobic $Z'$ with MADGRAPH. The authors of Refs. [3,4] provided values for masses and other parameters of the technicolor and $Z'$ models that would best correspond to the signal observed by CDF.

We determine the contributions of the known SM processes to the observed $m_{jj}$ spectrum by means of an extended unbinned maximum-likelihood fit in the range between 40 GeV and 400 GeV. We fit separately in four event categories, $\{\mu, e\} \times \{2$-jet, 3-jet$,\}$, because the background compositions differ. The $m_{jj}$ signal region, 123 to 186 GeV, corresponding to $\pm 2\sigma_{jj}$, is excluded from this fit in order to arrive at an unbiased estimate of a possible resonant enhancement in this region.

Table I lists the SM processes included in the fit. The $W$ plus jets normalization is a free fit parameter because it is by far the dominant background. We allow the TABLE I. Treatment of background $m_{jj}$ shapes and normalizations in a fit to the data. The background normalizations are constrained within the fit to Gaussian distributions with the listed central values and widths.

<table>
<thead>
<tr>
<th>Process</th>
<th>Shape</th>
<th>Constraint on normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ plus jets</td>
<td>MC and data</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>Diboson</td>
<td>MC</td>
<td>$61.2,, pb,, \pm,, 10%,, (NLO)$ [25]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>MC</td>
<td>$163,, pb,, \pm,, 7%,, (NLO)$ [26]</td>
</tr>
<tr>
<td>Single-top</td>
<td>MC</td>
<td>$84.9,, pb,, \pm,, 5%,, (NNLL)$ [27–29]</td>
</tr>
<tr>
<td>Drell-Yan plus jets</td>
<td>MC</td>
<td>$3.05,, nb,, \pm,, 4.3%,, (NNLO)$ [30]</td>
</tr>
<tr>
<td>Multijet (QCD)</td>
<td>data</td>
<td>$E_T$ fit (described in text)</td>
</tr>
</tbody>
</table>
normalizations of the other background components to vary within Gaussian constraints around the central values also listed in Table I. The central values for all processes except multijet come from next-to-leading-order (NLO), next-to-next-to-leading-log (NNLL), or next-to-NLO (NNLO) calculations, and the constraints reflect the published uncertainties. We derive templates for the $m_{jj}$ distribution for each background from simulation except for the multijet events, which contribute when jets are misidentified as leptons. In a separate fit to events that fail the lepton isolation requirements, we determine the central value of the multijet normalization, the constraint on the normalization and the template for the $m_{jj}$ distribution [9]. The fit to data determines the correlations among the various fit parameters.

The default CMS MADGRAPH sample of the dominant $W$ plus jets background does not describe well the $m_{jj}$ spectrum in the $m_{jj}$ sidebands. Four alternative samples of $W$ events, with the scales $\mu$ and $q$ increased and reduced by a factor two with respect to those of the default, fail to provide significant improvement. Thus, we employ an empirically driven combination of three shapes to describe this component in the fit model,

$$F_{W+jets} = \alpha F_{W+jets}(\mu_0, q^2) + \beta F_{W+jets}(\mu^2, q_0^2) + (1 - \alpha - \beta) F_{W+jets}(\mu_0, q_0^2),$$

where $F_{W+jets}$ denotes the $m_{jj}$ shape from simulation. The parameters $\mu_0$ ($\mu'$) and $q_0$ ($q'$) correspond to the default (alternative) values of $\mu$ and $q$, respectively, while fractional contributions $\alpha$ and $\beta$ are free to vary between 0 and 1. We take $\mu' = 2 \mu_0$ or $0.5 \mu_0$ ($q' = 2 q_0$ or $0.5 q_0$), depending on which alternative sample provides a better fit to data. Furthermore, we verify, via pseudoexperiment simulations generated with an alternate shape, that the function in the above equation has sufficient freedom to describe the $W$ plus jets shape.

Figure 1(a) shows the observed $m_{jj}$ distribution for all four event categories combined, together with the fitted projections of the contributions of various SM processes. Figure 1(b) shows the same distribution after subtraction of all SM contributions from data except electroweak diboson WW/WZ events. No peak is visible in the spectrum except that near 80 GeV due to diboson events. Figure 1(c) shows the bin-by-bin pull. Table II presents the yields of the SM components obtained from the fit. The sum of all the contributions is compared to the number of observed events. All numbers except those in the last two rows are for the $m_{jj}$ range of 40 to 400 GeV. The last two rows compare the observed number of events and the number predicted by the fit in the $m_{jj}$ range of 123 to 186 GeV. The data agree with the SM expectations, and we find no significant excess in the signal region. We observe a sizable deficit in the muon 2-jet data with respect to the prediction from our model. We do not observe similar deviations in the other three categories, suggesting it is a fluctuation and not a systematic bias.

We validate the fit procedure by performing pseudoexperiments. In each experiment, we generate the $m_{jj}$ pseudodata of the SM processes, including the correlations taken from the fit to data, and then fit each pseudodata sample. The results indicate that the bias on the total yield is below 0.2% and that the fit underestimates the total yield uncertainty by about 30%. These effects are corrected for in the final result. Uncertainties in the jet energy are estimated using a sample of $W$ bosons decaying hadronically in a pure sample of semileptonic $t\bar{t}$ events. The mean and resolution of the reconstructed dijet mass distribution

---

**FIG. 1** (color online). (a) Distribution of the invariant mass spectrum of the leading two jets observed in data. Overlaid are the fit projections of the various components. The region between the vertical dashed lines is excluded from the fit. (b) The same distribution after subtraction of all SM components except the electroweak processes WW/WZ. Error bars correspond to the statistical uncertainties. The hatched band represents the uncertainty on the sum of the SM components including correlations from the fit. The dark blue histogram is a resonance consistent with detector resolution and normalized to the CDF cross section scaled as described in the text. (c) The bin-by-bin pull, (data fit)/(fit uncertainty). The bins in the figures are representative of the expected resolution for a given mass and the number of entries in each bin is scaled by its width.

251801-3
TABLE II. Event yields determined from maximum-likelihood fits to the data. The total fit yields are corrected for bias. The total fit uncertainties include the correlations among the various yields, as determined by the fit, and the corrections derived from the fit validation described in the text. The $\chi^2$ probability uses the residuals and the data and MC statistical errors.

<table>
<thead>
<tr>
<th>Process</th>
<th>2-jet</th>
<th>Muons</th>
<th>3-jet</th>
<th>2-jet</th>
<th>Electrons</th>
<th>3-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>W plus jets</td>
<td>58 919 ± 530</td>
<td>13 069 ± 366</td>
<td>29 787 ± 1153</td>
<td>8 397 ± 292</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibosons</td>
<td>1236 ± 114</td>
<td>333 ± 32</td>
<td>685 ± 65</td>
<td>184 ± 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>4570 ± 307</td>
<td>9049 ± 382</td>
<td>2556 ± 174</td>
<td>4265 ± 253</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-top</td>
<td>1765 ± 87</td>
<td>1001 ± 50</td>
<td>916 ± 46</td>
<td>521 ± 26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drell-Yan plus jets</td>
<td>1837 ± 79</td>
<td>561 ± 24</td>
<td>1061 ± 46</td>
<td>364 ± 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multijet (QCD)</td>
<td>29 ± 284</td>
<td>0 ± 90</td>
<td>3944 ± 1133</td>
<td>324 ± 160</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fit $\chi^2$ probability: 0.454 0.729 0.969 0.991

Total from fit:
- Total predicted: 41 511 ± 125
- Data: 41 050

In the signal region $123 < m_{jj} < 186$ GeV (excluded from the fit)
- Total predicted: 7 739 ± 95
- Data: 7 751

TABLE III. The PYTHIA cross sections at 7 TeV times branching fraction to jets ($\sigma \times B$) and overall efficiency times acceptance ($e.A$) for various signal models. The relative uncertainties in $e$ measurements are 1–2%. The uncertainty on $A$ is negligible.

<table>
<thead>
<tr>
<th>Signal model</th>
<th>$\sigma \times B$ (pb)</th>
<th>Muons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-jet</td>
<td>3-jet</td>
<td>2-jet</td>
</tr>
<tr>
<td>Technicolor  [3]</td>
<td>7.4</td>
<td>0.065</td>
<td>0.020</td>
</tr>
<tr>
<td>$Z'$ [4]</td>
<td>8.1</td>
<td>0.070</td>
<td>0.023</td>
</tr>
<tr>
<td>$WH$ [21]</td>
<td>0.059</td>
<td>0.060</td>
<td>0.019</td>
</tr>
</tbody>
</table>

In data agree within 0.6% with the expectation from simulation. A small difference in $E_T$ resolution [10] between data and simulation affects the signal acceptance for the new physics models under consideration at the 0.5% level. Further systematic uncertainties are due to the uncertainty of the trigger efficiency estimates (1%) and the estimate of lepton reconstruction and selection efficiency (2%) [9]. The uncertainty on the integrated luminosity is 2.2% [31].

We scrutinize the dijet mass spectrum near 150 GeV, searching for a technicolor, leptophobic $Z'$, or $WH$ resonant enhancement. We also use a generic signal model obtained by convolving a delta function centered at $m_{jj} = 150$ GeV with a Gaussian function having width equal to $\sigma_{jj}$. Figure 1(b) shows this generic signal shape. The expected number of signal events at the LHC for a given cross section at the Tevatron can be estimated by considering the ratio of the predicted cross sections for our reference process, $WH$ production with $M_H = 150$ GeV. This process is dominated by quark-antiquark ($q\bar{q}$) annihilation. As $q\bar{q}$ processes have the smallest increase in parton luminosity from the Tevatron to the LHC, this choice provides a conservative limit. We therefore assume

$$\sigma_{LHC}^{\text{dijet resonance}} = \frac{\sigma_{\text{dijet resonance}}^{LHC}}{\sigma_{\text{dijet resonance}}^{Tevatron}} \cdot \frac{\sigma_{WH}^{LHC}}{\sigma_{WH}^{Tevatron}},$$

where $\sigma_{LHC}^{WH} = 300.1$ fb [32] and $\sigma_{WH}^{Tevatron} = 71.8$ fb [33].

A generic Gaussian signal normalized to $\sigma_{WH}^{Tevatron} = 4$ pb corresponds to $\sigma_{LHC} = 16.7$ pb. Table III contains the values of $\sigma_{LHC}$ times the branching fraction to jets and of the overall efficiency times acceptance $e.A$ for the models considered.

Since we observe no resonant enhancement, we proceed to set exclusion limits using a modified frequentist CL$_S$ method [34,35] with profile likelihood as the test statistic. Inputs to the limit-setting procedure are the $m_{jj}$ distribution obtained by combining the SM components from the fit, the observed distribution in data, the expectation from the dijet resonance model under consideration, and the uncertainties associated with these quantities. Figure 2(a) shows the observed and expected CL$_S$ values versus cross section for a generic technicolor signal, after combining the results of all four event categories. We set a 95% C.L. upper limit of 5.0 pb and a 99.9% C.L. upper limit of 8.5 pb on the dijet production cross section for a generic resonance with $WH$-like $e.A$.

Figure 2(b) compares the 95% C.L. upper limits with the expected cross sections for technicolor, leptophobic $Z'$, and $WH$ ($M_H = 150$ GeV) signals. The technicolor and $Z'$ models are excluded. Because we have minimal sensitivity to $WH$, we compare the limit in Fig. 2(b) to 100 times the SM cross section as an illustration.

In summary, we have studied the invariant mass spectrum of the two jets with highest transverse momentum in
pp → W + 2-jet and W + 3-jet events, with the W decaying leptonically to a muon or electron. The analyzed data sample corresponds to an integrated luminosity of 5.0 fb⁻¹ at \( \sqrt{s} = 7 \text{ TeV} \). We find no evidence for a resonant enhancement near a dijet mass of 150 GeV, as reported by the CDF Collaboration, and set upper limits on the dijet production cross section of 5.0 pb at 95% C.L. and 8.5 pb at 99.9% C.L. Two theoretical models, lepto-phobic \( Z^0 \) and technicolor, which predict the presence of a resonant enhancement near 150 GeV, are excluded.

We thank Adam Martin and Matthew Buckley for help with simulation of technicolor and \( Z^0 \) models, respectively.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); 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); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS, and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).


(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der ÖAW, 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 Fisicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Instituto de Física Teórica, Universidade Estadual Paulista, Sao Paulo, Brazil
13Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14University of Sofia, Sofia, Bulgaria
15Institute of High Energy Physics, Beijing, China
16State Key Lab. of Nucl. Phys. and Tech., 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 de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
33Institute of High Energy 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 Physics “Demokritos”, Aghia Paraskevi, Greece
University of Athens, Athens, Greece
University of Ioannina, Ioannina, Greece
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
University of Debrecen, Debrecen, Hungary
Panjab University, Chandigarh, India
University of Delhi, Delhi, India
Saha Institute of Nuclear Physics, Kolkata, India
Bhabha Atomic Research Centre, Mumbai, India
Tata Institute of Fundamental Research-EHEP, Mumbai, India
Tata Institute of Fundamental Research-HECR, Mumbai, India
Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
INFN Sezione di Bari, Bari, Italy
Universita di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy
INFN Sezione di Bologna, Bologna, Italy
Universita di Bologna, Bologna, Italy
INFN Sezione di Catania, Catania, Italy
Universita di Catania, Catania, Italy
INFN Sezione di Firenze, Firenze, Italy
Universita di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
Universita di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
Universita di Milano-Bicocca, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Universita di Napoli “Federico II”, Napoli, Italy
INFN Sezione di Padova, Padova, Italy
Universita di Padova, Padova, Italy
INFN Sezione di Trento (Trento), Padova, Italy
Universita di Pavia, Pavia, Italy
INFN Sezione di Perugia, Perugia, Italy
Universita di Perugia, Perugia, Italy
INFN Sezione di Pisa, Pisa, Italy
Universita di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Universita di Roma “La Sapienza”, Roma, Italy
INFN Sezione di Torino, Torino, Italy
Universita di Torino, Torino, Italy
Universita del Piemonte Orientale (Novara), Torino, Italy
INFN Sezione di Trieste, Trieste, Italy
Universita 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
Benemérita Universidad Autónoma 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
University of Notre Dame, Notre Dame, Indiana USA

The Ohio State University, Columbus, Ohio USA

Princeton University, Princeton, New Jersey USA

University of Puerto Rico, Mayaguez, Puerto Rico USA

Purdue University, West Lafayette, Indiana USA

Purdue University Calumet, Hammond, Indiana USA

Rice University, Houston, Texas USA

University of Rochester, Rochester, New York USA

The Rockefeller University, New York, New York USA

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

University of Tennessee, Knoxville, Tennessee USA

Texas A&M University, College Station, Texas USA

Texas Tech University, Lubbock, Texas USA

Vanderbilt University, Nashville, Tennessee USA

University of Virginia, Charlottesville, Virginia USA

Wayne State University, Detroit, Michigan USA

University of Wisconsin, Madison, Wisconsin USA

a Deceased.
b Also at Vienna University of Technology, Vienna, Austria.
c Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
d Also at Universidade Federal do ABC, Santo Andre, Brazil.
e Also at California Institute of Technology, Pasadena, USA.

f Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
g Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
h Also at Suez Canal University, Suez, Egypt.
i Also at Zewail City of Science and Technology, Zewail, Egypt.

j Also at Cairo University, Cairo, Egypt.
k Also at Fayoum University, El-Fayoum, Egypt.
l Also at British University, Cairo, Egypt.
m Also at Ain Shams University, Cairo, Egypt.
n Also at National Centre for Nuclear Research, Swierk, Poland.
o Also at Université de Haute-Alsace, Mulhouse, France.
p Also at Joint Institute for Nuclear Research, Dubna, Russia.
q Also at Moscow State University, Moscow, Russia.
r Also at Brandenburg University of Technology, Cottbus, Germany.
s Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
t Also at Eötvös Loránd University, Budapest, Hungary.
u Also at Tata Institute of Fundamental Research—HECR, Mumbai, India.
v Also at University of Visva-Bharati, Santiniketan, India.
w Also at Sharif University of Technology, Tehran, Iran.
x Also at Isfahan University of Technology, Isfahan, Iran.
y Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
z Also at Facoltà Ingegneria Università di Roma, Roma, Italy.

aa Also at Università della Basilicata, Potenza, Italy.

bb Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

c One letter superscript. Also at Università degli studi di Siena, Siena, Italy.
d Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.

ee Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
ff Also at University of California, Los Angeles, Los Angeles, USA.

ff Also at University of Athens, Athens, Greece.

gh Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
k Also at The University of Kansas, Lawrence, USA.

ll Also at Paul Scherrer Institut, Villigen, Switzerland.

mm Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
Also at Gaziosmanpasa University, Tokat, Turkey.

Also at Adiyaman University, Adiyaman, Turkey.

Also at Izmir Institute of Technology, Izmir, Turkey.

Also at The University of Iowa, Iowa City, USA.

Also at Mersin University, Mersin, 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 School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.

Also at University of Sydney, Sydney, Australia.

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 KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

Also at Kyungpook National University, Daegu, Korea.