Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

V. Khachatryan et al.* (CMS Collaboration)

(Received 23 October 2014; revised manuscript received 11 December 2014; published 2 February 2015)

A study of vector boson scattering in $pp$ collisions at a center-of-mass energy of 8 TeV is presented. The data sample corresponds to an integrated luminosity of 19.4 fb$^{-1}$ collected with the CMS detector. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign $W$-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^\pm W^\pm$ and $WZ$ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

DOI: 10.1103/PhysRevLett.114.051801

PACS numbers: 14.70.Fm, 12.60.Cn, 13.38.-b, 13.85.Qk

Vector boson scattering (VBS) and quartic boson couplings are features of the standard model (SM) that remain largely unexplored by the LHC experiments. The observation of a Higgs boson [1–3], in accordance with a key prediction of the SM, motivates further study of the mechanism of electroweak symmetry breaking through measurements of VBS processes. In the absence of the SM Higgs boson, the amplitudes for these processes would increase as a function of center-of-mass energy and ultimately violate unitarity [4,5]. The Higgs boson actually observed by the LHC experiments may restore the unitarity, although some scenarios of physics beyond the SM predict enhancements for VBS through modifications to the Higgs sector or the presence of additional resonances [6,7].

This Letter presents a study of VBS in $pp$ collisions at $\sqrt{s} = 8$ TeV. The data sample corresponds to an integrated luminosity of 19.4 ± 0.5 fb$^{-1}$ collected with the CMS detector [8] at the LHC in 2012. The aim of the analysis is to find evidence for the electroweak production of same-sign $W$-boson pair events. The strong production cross section is reduced by the same-sign requirement, making the experimental signature of same-sign dilepton events an ideal topology for VBS studies. Candidate events have exactly two identified leptons of the same charge, two jets with large rapidity separation and dijet mass, and moderate missing transverse energy. The final states considered are $\mu^+\mu^-\nu_\mu\nu_\mu jj$, $e^+e^-\nu_e\nu_e jj$, $e^+\mu^-\nu_e\nu_\mu jj$, and their charge conjugates and $\tau$-lepton decays to electrons and muons. Figure 1 shows representative Feynman diagrams for the electroweak and QCD induced production.

The study of VBS presented here leads to measurements of the production cross sections for $W^\pm W^\pm$ and $WZ$ in a fiducial region. Evidence for electroweak production has been reported by the ATLAS Collaboration [9]. Various extensions of the SM alter the couplings of vector bosons. An excess of events could signal the presence of anomalous quartic gauge couplings (AQGCs) [10]. Doubly charged Higgs bosons are predicted in Higgs sectors beyond the SM where weak isotriplet scalars are included [11,12]; they can be produced via weak vector-boson fusion (VBF) and decay to pairs of same-sign $W$ bosons [13].

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.

FIG. 1. Representative Feynman diagrams for the electroweak and QCD induced same-sign $W$-boson pair production.
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 field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events within 3 μs, using information from the calorimeters and muon detectors. The high level trigger processor farm further reduces the event rate to a few hundred hertz before data storage. Details of the CMS detector and its performance can be found elsewhere [8].

Several Monte Carlo (MC) event generators are used to simulate the signal and background processes. The leading-order event generator MADGRAPH 5.2 [14] is used to produce event samples of diboson production via diagrams with two or fewer powers of αs and up to six electroweak vertices. This includes two categories of diagrams: those with exactly two powers of αs, which we refer to as quantum chromodynamic (QCD) production and those with no powers of αs, which we refer to as electroweak (EW) production. The EW category includes diagrams with WWW/W production, and diagrams where two or more W bosons scatter through the exchange of a Higgs boson, or a Z boson, or a photon. Double-parton scattering, triboson production, and doubly charged Higgs boson production diagrams are also generated using MADGRAPH 5.2. Top-quark background processes are generated with the next-to-leading-order event generator POWHEG 1.0 [15–18]. The set of parton distribution functions (PDFs) used is CTEQ6L1 [19] for MADGRAPH and CT10 [20] for POWHEG. All event generators are interfaced to PYTHIA 6.4 [21] for the showering of the partons and subsequent hadronization. The PYTHIA parameters for the underlying event were set according to the Z2∗ tune [22]. The detector response is simulated by the GEANT4 package [23] using a detailed description of the CMS detector. The average number of simultaneous proton-proton interactions per bunch crossing in the 8 TeV data is approximately 21; additional pp interactions overlapping with the event of interest are included in the simulated samples. Collision events are selected by the trigger system requiring the presence of one or two high transverse momentum (pT) muons or electrons. The trigger efficiency is greater than 99% for events that pass all other selection criteria explained below. A particle-flow algorithm [24,25] is used to reconstruct all observable particles in the event. It combines all the subdetector information to reconstruct individual particles and identify them as charged hadrons, neutral hadrons, photons, and leptons. The missing transverse energy Emiss_T is defined as the magnitude of the negative vector sum of the transverse momenta of all reconstructed particles (charged and neutral) in the event.

The selection of events aims to single out same-sign dilepton events with the VBS topology while reducing the top quark, Drell-Yan, and WZ background processes. All objects are selected following the methods described in Ref. [26]. To avoid bias, the number of events passing the selection was not evaluated until the analysis was complete.

Two same-sign lepton candidates, muons or electrons, with pT > 20 GeV and |η| < 2.4(2.5) for muons (electrons) are required to be isolated from other reconstructed particles in a cone of ΔR = 0.3, where ΔR = \sqrt{Δφ^2 + Δη^2}. Jets are reconstructed using the anti-k_T clustering algorithm [27] with a distance parameter R = 0.5, as implemented in the FASTJET package [28,29]. Events are required to have at least two selected jets with E_T > 30 GeV and |η| < 4.7. The VBS topology is targeted by requiring that the two jets with leading pT have large dijet mass, mjj > 500 GeV, and large pseudorapidity separation, |Δηjj| > 2.5.

To suppress top-quark backgrounds (t¯t and tW), a top-quark veto technique is used; it is based on the presence of a soft muon in the event from the semileptonic decay of the bottom quark and on bottom-quark jet tagging criteria based on the impact parameters of the constituent tracks [30]. A minimum dilepton mass, m_ℓℓ > 50 GeV, is required to reduce the W + jets and top-quark background processes. To reduce the background from WZ production, events with a third, loosely identified lepton with pT > 10 GeV are rejected. Drell-Yan events can be selected if the charge of one lepton is measured incorrectly. To reduce this background, |m_ℓℓ − m_Z| > 15 GeV is required for e±e± events. The charge confusion in dimuon events is negligible. The Drell-Yan background is further reduced by requiring Emiss_T > 40 GeV.

The nonprompt lepton background originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions, is suppressed by the identification and isolation requirements imposed on muons and electrons. The remaining contribution from the nonprompt lepton background is estimated directly from data. The efficiency for a predefined loose leptonlike object to pass the full lepton selection, typically called the “tight-to-loose ratio” (R_TL), is estimated in a control sample with one additional lepton candidate that passes the standard lepton selection criteria. To account for the dependence on kinematic observables, this ratio is parameterized as a function of pT and η. Systematic uncertainties are obtained by the application of R_TL to other control samples, accounting for the sample dependence in the estimation of R_TL. The WZ → 3ℓν process is normalized in a data control region by requiring a third fully identified lepton with pT > 10 GeV. The contribution of opposite-sign dilepton events to the signal region is estimated by applying data-to-simulation charge misidentification scale factors to simulated events with two opposite-sign leptons. The charge-misidentification fraction is estimated using Z boson events and is found to be between...
and selection efficiencies are measured using simulated processes. The normalization of the processes in the integrated luminosity \([31]\) is considered for all samples. In the statistical analysis, shape and normalization uncertainties are considered. The shape uncertainties are estimated by remaking the distribution of a given observable after considering the systematic variations for each sample composition and the method used to estimate it. The WZ normalization uncertainty is 35%, dominated by the small number of events in the trilepton control region. Theoretical uncertainties are estimated by varying the...
renormalization and factorization scales up and down by a factor of two from their nominal value in the event, and found to be 5% for the signal normalization and 50% for the triboson background normalization. A PDF uncertainty of 6%—8% in the normalization of the signal and WZ processes is included. The systematic uncertainties of the background normalizations are taken into account using log-normal distributions.

The cross section is extracted for a fiducial signal region. The fiducial region is defined by requiring two same-sign leptons with $p_T > 10$ GeV and $|\eta_\ell| < 2.5$, two jets with $p_T > 20$ GeV and $|\eta_j| < 5.0$, $m_{jj} > 300$ GeV, and $|\Delta\eta_{jj}| > 2.5$ and is less stringent than the event selection for our signal region. The measured cross section is corrected for the acceptance in this region using the MadGraph MC generator, which is also used to estimate the theoretical cross section. The acceptance ratio between the selected signal region and the fiducial region is 36% considering generator-level jet and lepton properties only. The overall acceptance times efficiency is 7.9%.

The MadGraph prediction of the same-sign $W$-boson pair cross section is corrected by a next-to-leading order to leading-order cross section ratio estimated using VBFNLO [32–34]. The fiducial cross section is found to be $\sigma_{\text{fid}}(W^+W^-jj) = 4.0^{+2.2}_{-1.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})$ fb with an expectation of $5.8 \pm 1.2$ fb.

In addition to the dilepton same-sign signal region, a $WZ \rightarrow 3\ell\nu$ control region is studied by requiring an additional lepton with $p_T > 10$ GeV. This control region allows the measurement of a fiducial cross section of the $WZjj$ process and is $\sigma_{\text{fid}}(WZjj) = 10.8 \pm 4.0(\text{stat}) \pm 1.3(\text{syst})$ fb with an expectation of $14.4 \pm 4.0$ fb. The fiducial region is defined in the same way as for the WW analysis, but requiring one more lepton with $p_T > 10$ GeV and $|\eta_\ell| < 2.5$. The acceptance ratio between the selected signal region and the fiducial region is 20% considering generator-level jet and lepton properties only. The overall acceptance times efficiency is 3.6%.

To compute the limits and significances, the CL$_S$ [35–37] construction is used. The observed (expected) significance for the $W^\pm W^\pm jj$ process is $2.0\sigma$ ($3.1\sigma$). Considering the QCD component of the $W^\pm W^\pm jj$ events as background and the EW component together with the EW-QCD interference as signal, the observed (expected) signal significance reduces to $1.9\sigma$ ($2.9\sigma$).

Various extensions to the SM alter the couplings between vector bosons. Reference [10] proposes nine independent C- and $P$-conserving dimension-eight effective operators to modify the quartic couplings between the weak gauge bosons. The variable $m_{\ell\ell}$ is more sensitive to AQGCs than $p_T^{\ell\ell}$, $m_{\ell\ell jj}$, and $m_{jj}$. Figure 3 (top) shows the expected $m_{\ell\ell}$ distribution for three values of $F_{T,0}/\Lambda^4$; $\Lambda$ is the scale of new physics and $F_{T,0}$ is the coefficient of one of the nine effective operators. The observed and expected upper and lower limits at 95% confidence level (C.L.) on the nine coefficients are shown in Table II, where all the results are obtained by varying the effective operators one by one. The effect of possible AQGCs on the WZ process in the signal region is negligible. Some operators for anomalous quartic gauge boson couplings may lead to tree-level unitarity violation. We also report the values of the operator coefficient for which unitarity is restored at the scale of 8 TeV, the unitarity limit. In addition to the limits on individual operator coefficients, the expected and observed two-dimensional 95% C.L. on $F_{S,0}/\Lambda^4$ and $F_{S,1}/\Lambda^4$ are presented in Fig. 3 (bottom): a linear combination of those operators leads to a scaling of the SM cross section.

Doubly charged Higgs bosons are predicted in models that contain a Higgs triplet field. Some of these scenarios

![Fig. 3](color online). The $m_{\ell\ell}$ distributions (top) after full selection with all SM backgrounds and $F_{T,0}/\Lambda^4 = -5.0, 0$ (SM), and $5.0$ TeV$^{-4}$; the last bin includes overflow events. Observed and expected two-dimensional 95% C.L. (bottom) for $F_{S,0}/\Lambda^4$ and $F_{S,1}/\Lambda^4$. 

---

**Table II**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{S,0}/\Lambda^4$</td>
<td>-5.0 TeV$^{-4}$</td>
<td>-5.0 TeV$^{-4}$</td>
</tr>
<tr>
<td>$F_{S,1}/\Lambda^4$</td>
<td>0 TeV$^{-4}$</td>
<td>0 TeV$^{-4}$</td>
</tr>
</tbody>
</table>

---

**Figure 3**

- **Top**: $m_{\ell\ell}$ distributions after full selection with all SM backgrounds and $F_{T,0}/\Lambda^4 = -5.0, 0$ (SM), and $5.0$ TeV$^{-4}$; the last bin includes overflow events. Observed and expected two-dimensional 95% C.L. (bottom) for $F_{S,0}/\Lambda^4$ and $F_{S,1}/\Lambda^4$.
- **Bottom**: Observed and expected two-dimensional 95% C.L. for $F_{S,0}/\Lambda^4$ and $F_{S,1}/\Lambda^4$.
TABLE II. Observed and expected upper and lower limits at 95% C.L. on the nine dimension-eight operators that affect quartic couplings between the weak gauge bosons. Limits from unitarity are reported. The units are TeV$^{-4}$.

<table>
<thead>
<tr>
<th>Operator coefficient</th>
<th>Exp. lower</th>
<th>Exp. upper</th>
<th>Obs. lower</th>
<th>Obs. upper</th>
<th>Unitarity limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{S,0}/A^4$</td>
<td>−42</td>
<td>43</td>
<td>−38</td>
<td>40</td>
<td>0.016</td>
</tr>
<tr>
<td>$F_{S,1}/A^4$</td>
<td>−129</td>
<td>131</td>
<td>−118</td>
<td>120</td>
<td>0.050</td>
</tr>
<tr>
<td>$F_{M,0}/A^4$</td>
<td>−35</td>
<td>35</td>
<td>−33</td>
<td>32</td>
<td>80</td>
</tr>
<tr>
<td>$F_{M,1}/A^4$</td>
<td>−49</td>
<td>51</td>
<td>−44</td>
<td>47</td>
<td>205</td>
</tr>
<tr>
<td>$F_{M,2}/A^4$</td>
<td>−70</td>
<td>69</td>
<td>−65</td>
<td>63</td>
<td>160</td>
</tr>
<tr>
<td>$F_{M,3}/A^4$</td>
<td>−76</td>
<td>73</td>
<td>−70</td>
<td>66</td>
<td>105</td>
</tr>
<tr>
<td>$F_{T,0}/A^4$</td>
<td>−4.6</td>
<td>4.9</td>
<td>−4.2</td>
<td>4.6</td>
<td>0.027</td>
</tr>
<tr>
<td>$F_{T,1}/A^4$</td>
<td>−2.1</td>
<td>2.4</td>
<td>−1.9</td>
<td>2.2</td>
<td>0.022</td>
</tr>
<tr>
<td>$F_{T,2}/A^4$</td>
<td>−5.9</td>
<td>7.0</td>
<td>−5.2</td>
<td>6.4</td>
<td>0.08</td>
</tr>
</tbody>
</table>

predict same-sign dilepton events from $W^± W^±$ decays with a VBF topology. The cross section for VBF production of $H^{±±}$ and decay to $W^± W^±$ is directly proportional to the vacuum expectation value of the triplet. The remaining five parameters in the model of the Higgs potential are adjusted to get the given $m_{H^{±±}}$ hypothesis while requiring one of the scalar singlets to have a mass of 125 GeV. The Georgi-Machacek model of Higgs triplets [38] is considered. For $m_{H^{±±}} = 200$ (800) GeV the following parameters are used: $λ_1 = 1$, $λ_2 = 1$, $λ_3 = 1$, $λ_4 = 2.37$ (4), and $λ_5 = 0.432$ (7.26). By using the $m_{jj}$ distribution, 95% C.L. upper limits on $σ_{H^{±±}} B(H^{±±} → W^± W^±)$ are derived as shown in Fig. 4. The experimental results are overlaid with theoretical cross sections for three values of the vacuum expectation value.

In summary, a study of vector boson scattering in $p p$ collisions at $\sqrt{s} = 8$ TeV has been presented based on a data sample corresponding to an integrated luminosity of 19.4 fb$^{-1}$. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign $W$-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^± W^±$ and $WZ$ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

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); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); MEST (Lithuania); INR (Italy); INFN (Italy); NRU and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

![FIG. 4 (color online). Expected and observed 95% C.L. upper limits on the cross section times branching fraction, $σ_{H^{±±}} B(H^{±±} → W^± W^±)$. Theoretical cross sections for three values of the vacuum expectation value (vev) are overlaid.](image-url)


R 36 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
   37 Deutsches Elektronen-Synchrotron, Hamburg, Germany
   38 University of Hamburg, Hamburg, Germany
   39 Institut für Experimentelle Kernphysik, Karlsruhe, Germany
   40 Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
   41 University of Athens, Athens, Greece
   42 University of Ioannina, Ioannina, Greece
   43 Wigner Research Centre for Physics, Budapest, Hungary
   44 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
   45 University of Debrecen, Debrecen, Hungary
   46 National Institute of Science Education and Research, Bhubaneswar, India
   47 Panjab University, Chandigarh, India
   48 University of Delhi, Delhi, India
   49 Saha Institute of Nuclear Physics, Kolkata, India
   50 Bhabha Atomic Research Centre, Mumbai, India
   51 Tata Institute of Fundamental Research, Mumbai, India
   52 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
   53 University College Dublin, Dublin, Ireland
   54a INFN Sezione di Bari, Bari, Italy
   54b Università di Bari, Bari, Italy
   54c Politecnico di Bari, Bari, Italy
   55a INFN Sezione di Bologna, Bologna, Italy
   55b Università di Bologna, Bologna, Italy
   56a INFN Sezione di Catania, Catania, Italy
   56b Università di Catania, Catania, Italy
   56c CSFNSM, Catania, Italy
   57a INFN Sezione di Firenze, Firenze, Italy
   57b Università di Firenze, Firenze, Italy
   58 INFN Laboratori Nazionali di Frascati, Frascati, Italy
   59a INFN Sezione di Genova, Genova, Italy
   59b Università di Genova, Genova, Italy
   60a INFN Sezione di Milano-Bicocca, Milano, Italy
   60b Università di Milano-Bicocca, Milano, Italy
   61a INFN Sezione di Napoli, Napoli, Italy
   61b Università di Napoli 'Federico II', Napoli, Italy
   61c Università della Basilicata (Potenza), Napoli, Italy
   61d Università Guglielmo Marconi (Roma), Napoli, Italy
   62a INFN Sezione di Padova, Padova, Italy
   62b Università di Padova, Padova, Italy
   62c Università di Trento (Trento), Padova, Italy
   63a INFN Sezione di Pavia, Pavia, Italy
   63b Università di Pavia, Pavia, Italy
   64a INFN Sezione di Perugia, Perugia, Italy
   64b Università di Perugia, Perugia, Italy
   65a INFN Sezione di Pisa, Pisa, Italy
   65b Università di Pisa, Pisa, Italy
   65c Scuola Normale Superiore di Pisa, Pisa, Italy
   66a INFN Sezione di Roma, Roma, Italy
   66b Università di Roma, Roma, Italy
   67a INFN Sezione di Torino, Torino, Italy
   67b Università di Torino, Torino, Italy
   67c Università del Piemonte Orientale (Novara), Torino, Italy
   68a INFN Sezione di Trieste, Trieste, Italy
   68b Università di Trieste, Trieste, Italy
   69 Kangwon National University, Chunchon, Korea
   70 Kyungpook National University, Daegu, Korea
   71 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
   72 University of Seoul, Seoul, Korea
   73 Korea University, Seoul, Korea
University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA

Purdue University, West Lafayette, USA

Purdue University Calumet, Hammond, USA

Rice University, Houston, USA

University of Rochester, Rochester, USA

The Rockefeller University, New York, USA

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

University of Tennessee, Knoxville, USA

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA

Wayne State University, Detroit, USA

University of Wisconsin, Madison, USA

\(^{a}\)Deceased.

\(^{b}\)Also at Vienna University of Technology, Vienna, Austria.

\(^{c}\)Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

\(^{d}\)Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

\(^{e}\)Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

\(^{f}\)Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

\(^{g}\)Also at Universidade Estadual de Campinas, Campinas, Brazil.

\(^{h}\)Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

\(^{i}\)Also at Joint Institute for Nuclear Research, Dubna, Russia.

\(^{j}\)Also at Suez University, Suez, Egypt.

\(^{k}\)Also at Cairo University, Cairo, Egypt.

\(^{l}\)Also at Fayoum University, El-Fayoum, Egypt.

\(^{m}\)Also at British University in Egypt, Cairo, Egypt.

\(^{n}\)Also at Sultan Qaboos University, Muscat, Oman.

\(^{o}\)Also at Université de Haute Alsace, Mulhouse, France.

\(^{p}\)Also at Brandenburg University of Technology, Cottbus, Germany.

\(^{q}\)Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

\(^{r}\)Also at Eötvös Loránd University, Budapest, Hungary.

\(^{s}\)Also at University of Debrecen, Debrecen, Hungary.

\(^{t}\)Also at University of Visva-Bharati, Santiniketan, India.

\(^{u}\)Also at King Abdulaziz University, Jeddah, Saudi Arabia.

\(^{v}\)Also at University of Ruhuna, Matara, Sri Lanka.

\(^{w}\)Also at Isfahan University of Technology, Isfahan, Iran.

\(^{x}\)Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

\(^{y}\)Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

\(^{z}\)Also at Università degli Studi di Siena, Siena, Italy.

\(^{aa}\)Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France.