Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a Pair of W and Z Bosons Using Pp Collisions at s=13TeV

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

<table>
<thead>
<tr>
<th>Citation</th>
<th>Sirunyan, A.M. et al. “Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a Pair of W and Z Bosons Using Pp Collisions at s=13TeV.” Physical Review Letters 119, 14 (October 2017): 141802 © 2017 CERN, for the CMS Collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.119.141802">http://dx.doi.org/10.1103/PhysRevLett.119.141802</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sun Jan 13 08:51:12 EST 2019</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/112206">http://hdl.handle.net/1721.1/112206</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>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.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a Pair of W and Z Bosons Using pp Collisions at $\sqrt{s} = 13$ TeV

A. M. Sirunyan et al.*
(CMS Collaboration)
(Received 8 May 2017; published 4 October 2017)

A search for charged Higgs bosons produced via vector boson fusion and decaying into W and Z bosons using proton-proton collisions at $\sqrt{s} = 13$ TeV is presented. The data sample corresponds to an integrated luminosity of 15.2 fb$^{-1}$ collected with the CMS detector in 2015 and 2016. The event selection requires three leptons (electrons or muons), two jets with large pseudorapidity separation and high dijet mass, and missing transverse momentum. The observation agrees with the standard model prediction. Limits on the vector boson fusion production cross section times branching fraction for new charged physical states are reported as a function of mass from 200 to 2000 GeV and interpreted in the context of Higgs triplet models.

DOI: 10.1103/PhysRevLett.119.141802

The discovery [1,2] of a Higgs boson [3–8] at the CERN LHC marks an important milestone in the exploration of the electroweak (EW) sector of the standard model (SM) [9–11]. Many aspects of EW interactions at the energy scale of 1 TeV, however, remain to be explored. At the LHC, the study of vector boson scattering (VBS) may reveal hints to extensions of the SM. In particular, extended Higgs sectors with additional SU(2) doublets [12–15] or triplets [16–23] introduce couplings of vector bosons to heavy neutral or charged Higgs bosons.

Searches for charged Higgs bosons ($H^\pm$) at the LHC currently focus on the production and the decay via couplings to fermions [24–32], well motivated by the minimal supersymmetric standard model [33]. In this model, the $H^\pm tb$ coupling is the dominant one irrespective of the mass of the charged Higgs boson $[m(H^\pm)]$ and tan$\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. Couplings to vector bosons are, however, largely suppressed in these models.

Higgs sectors extended by SU(2) triplets, however, give rise to charged Higgs bosons with couplings to W and Z bosons at the tree level. Higgs triplets appear in left-right symmetric [34–36], little Higgs [37–39], and supersymmetric models [40,41] and can generate neutrino masses via the seesaw mechanism [17–19,42,43]. A particularly prominent model is the Georgi-Machacek (GM) model [44], where two SU(2) triplets (one real and one complex) are added to the SM Higgs sector and preserve custodial symmetry for large vacuum expectation values of the SU(2) triplets. In such models, the charged Higgs bosons are produced via vector boson fusion (VBF), and the couplings depend on $m(H^\pm)$ and the parameter $\sin \theta_H$, or $s_H$, where $s_H^2$ denotes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplets. A representative Feynman diagram for the production by and decay into a W and Z boson pair is shown in Fig. 1.

In this Letter, we discuss the search for charged Higgs bosons that are produced via VBF and decay via couplings to W and Z bosons. The analysis is performed on a sample of proton-proton collisions collected at $\sqrt{s} = 13$ TeV center-of-mass energy by the CMS experiment at the LHC. The data sample corresponds to integrated luminosities of 2.3 and 12.9 fb$^{-1}$ recorded during the years 2015 and 2016, respectively. The search is performed using W and Z bosons decaying into electrons and muons. The event selection requires two jets with large pseudorapidity separation and a high dijet mass to select a VBF topology. The data are compared to the predictions of the GM model for a charged Higgs boson mass range of $200 < m(H^\pm) < 1000$ GeV. In addition, an exclusion limit on the VBF production cross section times branching

![FIG. 1. Example of a Feynman diagram showing the production of charged Higgs bosons via VBF.](image-url)
fraction ($\mathcal{B}$) for 200 < $m(H^\pm)$ < 2000 GeV is derived. A similar search was performed by the ATLAS Collaboration in proton-proton collisions at $\sqrt{s} = 8$ TeV in the semi-leptonic ($WZ \rightarrow q\ell\ell\ell$) final state [45]. Other experimental constraints on the GM model can be obtained from studies of $b$-meson decays [46] and $W^±W^±$ VBS processes [47,48].

The signal samples are produced with MADGRAPH5_aMC@NLO [49]. WZ production in association with two jets involving exclusively electroweak interactions at the tree level is generated at leading order (LO) using MADGRAPH5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production with both the strong and electroweak interaction vertices at next-to-leading order (NLO) using POWHEG and normalized to NLO with MADGRAPH5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production in association with two jets involving exclusively electroweak interactions at the tree level is generated at leading order (LO) using MADGRAPH5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production with both the strong and electroweak interaction vertices at the tree level is generated at leading order (LO) using MADGRAPH5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production in association with two jets involving exclusively electroweak interactions at the tree level is generated at leading order (LO) using MADGRAPH5_aMC@NLO and is referred to as an EW WZ background. Two-jet-associated WZ production with both the strong and electroweak interaction vertices at next-to-leading order (NLO) using POWHEG and normalized to the next-to-leading order (NNLO) cross-section prediction with a factor of 1.7 [55]. The PYTHIA 8 [57] package is used for parton showers, hadronization, and the underlying event simulation with parameters affecting the underlying event simulation set to the CUETP8M1 tune [58,59]. The NNPDF 3.0 [60] set is used as the default set of parton distribution functions (PDFs). For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [61], and event reconstruction is performed with the same algorithms as used for the data. The simulated samples include additional interactions per bunch crossing (pileup) matching the observed multiplicity in the data of about 11 and 20 interactions per bunch crossing in 2015 and 2016, respectively.

Details of the CMS detector, its performance, and the definition of the coordinate system can be found in Ref. [62]. The detector features a superconducting solenoid with a diameter of 6 m, providing a magnetic field of 3.8 T, and surrounding a silicon pixel and strip tracking detector, a lead tungstate electromagnetic calorimeter, and a brass scintillator hadronic calorimeter. Gas ionization detectors embedded into the steel-flux return yokes, the muon system, are installed around the solenoid. The subdetectors are composed into a barrel and two end cap sections. The hadron forward calorimeter provides calorimetry to pseudorapidities from $|\eta| > 3$ to $|\eta| < 5$. A particle-flow technique [63,64] is employed to identify and reconstruct the individual particles emerging from each collision.

Electrons are reconstructed within $|\eta| < 2.5$. The reconstruction combines the information from clusters of energy deposits in the electromagnetic calorimeter and the trajectory in the tracker [65]. The selection criteria depend on transverse momentum $p_T$ and $|\eta|$ and on a categorization based on observables sensitive to the amount of bremsstrahlung emitted. Muons are reconstructed within $|\eta| < 2.4$ [66]. The reconstruction combines the information from both the tracker and the muon spectrometer. Leptons are required to be isolated from other charged and neutral particles in the event. The lepton relative isolation is defined as the ratio of the $p_T$ sum of charged hadrons and neutral particles within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ (where $\phi$ is the azimuthal angle in radians) around the lepton and the lepton $p_T$. The relative isolation, corrected for pileup contributions, is required to be less than 6.5% (15%) for electrons (muons). Overall efficiencies of the reconstruction, identification, and isolation requirements for the prompt leptons are measured in the data in several bins of $p_T$ and $|\eta|$ using a “tag-and-probe” technique [67] applied to a sample of leptonically decaying Z boson events.

Jets are reconstructed using the anti-$k_T$ clustering algorithm [68] with a distance parameter $R = 0.4$, as implemented in the FASTJET package [69,70], and jet energy corrections are applied [71,72]. To suppress the top-quark background contribution in its decay to $b$ quarks, the combined secondary vertex $b$-tagging algorithm [73,74] requirement is used, corresponding to an efficiency of about 45% with a light flavor quark misidentification probability of 0.1%.

The missing transverse momentum vector $p_T^{miss}$ is defined as the negative vectorial sum of the momenta of all reconstructed particles in an event projected onto the plane perpendicular to the beams, corrected for pileup contributions [75]. Its magnitude is referred to as $p_T^{miss}$.

Events are selected by the trigger system requiring the presence of one or two high $p_T$ electrons or muons. The trigger efficiency is greater than 99% for events that pass all other selection criteria explained in the following. The selection of events aims to single out three-lepton events with the VBF topology. The event selection requires three lepton (electron or muon) candidates that meet the isolation and identification requirements. Two leptons are required to have $p_T > 20$ GeV, and the third lepton is required to have $p_T > 10$ GeV. Events with an additional fourth lepton with $p_T > 10$ GeV are rejected. Events are required to have at least two jets with $p_T > 30$ GeV, and $|\eta| < 4.7$. The VBF topology is exploited by requiring that the two jets of highest $p_T$ have a large dijet mass, $m_{jj} > 500$ GeV, and a large pseudorapidity separation, $|\Delta\eta_{jj}| > 2.5$. To reconstruct a Z boson candidate, a pair of same-flavor and opposite-charge leptons is required to have a dilepton invariant mass within 15 GeV of the nominal Z boson mass [76]. When there are two or more candidate pairs, the one with the mass closest to the nominal Z boson mass is chosen. The remaining lepton is associated with the W
boson decay, and it is required to have $p_T > 20$ GeV. The $p_T^{\text{miss}}$ in the event is required to be larger than 30 GeV to select $W$ boson decays. To reject the top-quark background, the event must not have jets passing the $b$-tagging selection. After these requirements, the signal efficiency is about 10%-15%, depending on $m(H^\pm)$. For extraction of the signal, the shape of the distribution of the transverse mass variable ($m_T$) obtained from the $WZ$ system is used:

$$m_T(WZ) = \sqrt{E_T(W) + E_T(Z)^2 - |\vec{p}_T(W) + \vec{p}_T(Z)|^2},$$  \hspace{1cm} (1)$$

where $\vec{p}_T(W)$ is reconstructed from the vectorial sum of $p_T^{\text{miss}}$ and the lepton $\vec{p}_T$ and $E_T(W)$ is calculated from the scalar sum of the lepton transverse energy and $p_T^{\text{miss}}$. Variables such as the invariant mass of the leptonically decaying $WZ$ system using constraints on the neutrino momentum from the $W$ boson mass [77] may be explored in future analyses.

A combination of methods using control samples in the data and detailed simulation studies is used to estimate background contributions. The following background categories are considered: $WZ$, $ZZ \rightarrow 4\ell$, $VVV$, $Z\ell$, and processes with nonprompt leptons.

The QCD and EW $WZ$ background constitutes about 80% of the total expected SM background yield. The normalization of the QCD $WZ$ background is obtained from a background-dominated sideband, outside of the search region and defined by the dijet variables, where the expected signal yield is negligible: 100 GeV $< m_{jj} < 500$ GeV and $|\Delta \eta_{jj}| < 2.5$. In this phase-space region, expected background contributions from EW $WZ$, $ZZ \rightarrow 4\ell$, $VVV$, $Z\ell$ production, and nonprompt leptons are estimated to contribute about 40% to the yield and are subtracted from the overall 266 events observed in data. The simulated sample of QCD $WZ$ processes is then normalized to match the observed number of events in this control region. The estimated normalization of events is consistent with the SM prediction obtained using the POWHEG NLO cross-section calculation. The EW $WZ$ background contributes about 30% to the overall $WZ$ background processes in the signal region.

The $ZZ \rightarrow 4\ell$, $VVV$, and $Z\ell$ contributions are estimated from simulated samples, with corrections to the lepton reconstruction, trigger and selection efficiencies, and momentum scale and resolution, estimated from data control samples. The overall expected contribution from these processes to the total background yield is about 10%, and the uncertainties in the estimates are dominated by the statistical component introduced by the number of simulated events passing the event selection requirements. The $ZZ \rightarrow 4\ell$ background is largely reduced by the $p_T^{\text{miss}}$ requirement and the veto on events containing an additional lepton.

The main contributions to nonprompt leptons are from $Z +$ jets and top-quark ($t\bar{t}$ and $tW$) events, where at least one of the jets or a jet constituent is misidentified as an isolated lepton. The dominant background at the final-selection level is $Z +$ jets. According to the simulation, fewer than 10% of the background events with at least one nonprompt lepton come from top-quark processes. Data control samples are used to estimate this background. Lepton candidates selected with loose identification requirements are defined in a sample of events dominated by dijet production. The efficiency for candidates to pass the full lepton selection criteria is measured and is parameterized as a function of $p_T$ and $\eta$. The calculated efficiencies are used as weights to extrapolate the yield of the sample of loose leptons to the sample of fully selected leptons. The background estimation method is validated on a nonprompt lepton $W +$ jets and $t\bar{t}$ enriched sample, selected by inverting the $Z$ boson mass or $b$-tagging criteria, where good agreement between the data and prediction is observed.

Uncertainties in the data-to-simulation scale factors applied to leptons in simulated samples result in an overall 4% normalization uncertainty for backgrounds estimated from the simulation. The experimental uncertainties in the lepton momentum scale and resolution, $p_T^{\text{miss}}$ modeling, and jet energy scale are applied in simulated events by smearing and scaling the relevant observables and propagating the effects to the kinematic variables used in the analysis, in particular, $m_T$. Uncertainties in the lepton momentum scale and resolution are smaller than 1% per lepton depending on the $p_T$ and $\eta$ of the lepton, and the effect on the yields at the analysis selection level is less than 1%. The uncertainties in the jet energy scale and resolution result in a 5% uncertainty in the signal yields. The uncertainty in the resolution of the $p_T^{\text{miss}}$ measurement is 10%. Randomly smearing the measured $p_T^{\text{miss}}$ by one standard deviation of the resolution gives rise to a 5% variation in the estimation of signal yields after the full selection. Uncertainties of 2.3% and 2.5% are assigned to the integrated luminosity measurements in the years 2015 and 2016, respectively [78,79]. The effect of higher-order corrections to the signal cross section in the GM model is taken from Ref. [80]. The theoretical uncertainty is dominated by missing higher-order EW corrections estimated to be 7%. Uncertainties in the signal acceptance due to PDF choice and renormalization and factorization scales are 2%-3% and less than 1%, respectively, estimated using the LO signal samples. Added in quadrature, the contributions result in an 8% uncertainty in the normalization of the signal samples.

The uncertainty in the estimation of the expected number of QCD $WZ$ events is 12%, which is estimated from the measured yields in the two-jet control region. An uncorrelated uncertainty of 30% is assigned on the normalization of $WZ$ events produced via EW processes, estimated from
the largest bin-by-bin differences after varying the renormalization and factorization scales. The total uncertainty in the prediction of the nonprompt background varies bin by bin in the \(m_T\) distribution between 30% and 80%, dominated by the low number of nonprompt leptons passing the sideband selection. A summary of the relative systematic uncertainties in the estimated signal and background yields is shown in Table I.

After applying the full selection, nine and 62 events are selected in the data collected in 2015 and 2016, respectively. The data yield together with the SM expectation for the different processes is given in Table II. The distribution of the \(m_T\) with bin boundaries given by \(m_T = [0, 100, 200, 400, 600, 800, 1000, 1200, 1500, \infty)\) GeV (the last bin is an overflow bin) is shown in Fig. 2. No event with \(m_T(WZ) > 800\) GeV is observed in the data, and overall agreement between the data and SM background prediction is observed.

A combined fit of the predicted signal and background yields in bins of \(m_T\) to the data is performed to derive expected and observed exclusion limits on \(\sigma_{VBF}(H^\pm)B(H^\pm \to WZ)\) at 95% confidence level using the CL_{sH} method [81–83]. The exclusion limits as a function of \(m(H^{\pm})\), assuming a small intrinsic width for \(H^{\pm}\), are shown in Fig. 3 (left). Values for \(\sigma_{VBF}(H^\pm)B(H^\pm \to WZ)\) ranging from 573 fb at \(m(H^\pm) = 200\) GeV to 36 fb at \(m(H^\pm) = 2000\) GeV are excluded by the data.

The model-independent exclusion limits are compared to the predicted cross sections at NNLO in the GM model [80] in the \(s_{H} - m(H^\pm)\) plane. For the probed parameter space and \(m_T\) distribution used for signal extraction, the varying width as a function of \(s_{H}\) is assumed to have negligible impact on the result. The value of the branching fraction

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal</th>
<th>WZ</th>
<th>VVV</th>
<th>(Z_{A})</th>
<th>ZZ</th>
<th>Nonprompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity 2015 (2016)</td>
<td>2.3 (2.5)</td>
<td>...</td>
<td>2.3 (2.5)</td>
<td>2.3 (2.5)</td>
<td>2.3 (2.5)</td>
<td>...</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>4.0</td>
<td>...</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>...</td>
</tr>
<tr>
<td>Lepton momentum scale</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>...</td>
</tr>
<tr>
<td>Jet momentum scale</td>
<td>5.0</td>
<td>10.0</td>
<td>6.0</td>
<td>30.0</td>
<td>13.0</td>
<td>...</td>
</tr>
<tr>
<td>(p_T^{\text{miss}}) resolution</td>
<td>5.0</td>
<td>1.7</td>
<td>1.0</td>
<td>...</td>
<td>7.0</td>
<td>...</td>
</tr>
<tr>
<td>(b) tagging</td>
<td>2.0</td>
<td>...</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>...</td>
</tr>
<tr>
<td>QCD (EW) WZ bkg. normalization</td>
<td>...</td>
<td>12 (30)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Nonprompt bkg. normalization</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>GM uncertainties</td>
<td>8</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The signal yields are shown for values of \(s_{H} = m(H^\pm)\) in the \(s_{H} - m(H^\pm)\) plane. For the probed parameter space and \(m_T\) distribution used for signal extraction, the varying width as a function of \(s_{H}\) is assumed to have negligible impact on the result. The value of the branching fraction

![Fig. 2. Transverse mass distributions after full selection, for data collected in 2015 (left) and 2016 (right). The background yield predictions correspond to the background-only hypothesis fit result. The signal distribution is shown for \(m(H^\pm) = 700\) GeV and the cross-section prediction in the GM model at \(s_{H} = 0.7\).](image-url)
B(H± → WZ) is assumed to be one. In Fig. 3 (right), the excluded σ_{VBF} values as a function of m(H±) are shown. The blue shaded region shows the parameter space for which the H± total width exceeds 10% of m(H±), where the model is not applicable due to perturbativity and vacuum stability requirements [80]. The observed limit excludes σ_{VBF} values greater than 0.45, 0.81, and 0.66 at m(H±) = 200, 400, and 1000 GeV, respectively.

In summary, we present a search for charged Higgs bosons produced via vector boson fusion and decaying into W and Z bosons in proton-proton collisions at √s = 13 TeV based on a sample corresponding to an integrated luminosity of 15.2 fb⁻¹. Events are required to have three leptons (electrons or muons), two jets with large pseudorapidity separation and high dijet mass, and missing transverse momentum. The number of events observed in the signal region agrees with the standard model prediction.

The first limits on σ_{VBF}(H±)B(H± → WZ) at √s = 13 TeV are obtained. The results are interpreted in the Georgi-Machacek model for which the most stringent limits to date are derived.

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, 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).

P. Fayet, A gauge theory of weak and electromagnetic

ATLAS Collaboration, Search for charged Higgs bosons

N. Craig and S. Thomas, Exclusive signals of an extended

T. D. Lee, A theory of spontaneous


A. Salam, in Elementary Particle Physics: Relativistic

G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M.

W. Konetschny and W. Kummer, Nonconservation of total

J. Schechter and J. W. F. Valle, Neutrino masses in

C. Englert, E. Re, and M. Spannowsky, Triplet Higgs boson

R. N. Mohapatra and J. C. Pati, A natural left-right

G. Senjanovic and R. N. Mohapatra, Exact left-right

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,

S. L. Glashow, Partial-symmetries of weak interactions,
Université Catholique de Louvain, Louvain-la-Neuve, Belgium
Université de Mons, Mons, Belgium
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
Universidade Estadual Paulista, São Paulo, Brazil
Universidade Federal do ABC, São Paulo, Brazil
Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
University of Sofia, Sofia, Bulgaria
Beihang University, Beijing, China
University of High Energy Physics, Beijing, China
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Universidad de Los Andes, Bogota, Colombia
University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
University of Split, Faculty of Science, Split, Croatia
Institute Rudjer Boskovic, Zagreb, Croatia
University of Cyprus, Nicosia, Cyprus
Charles University, Prague, Czech Republic
Universidad San Francisco de Quito, Quito, Ecuador
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
Department of Physics, University of Helsinki, Helsinki, Finland
Helsinki Institute of Physics, Helsinki, Finland
Lappeenranta University of Technology, Lappeenranta, Finland
IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
Georgian Technical University, Tbilisi, Georgia
Tbilisi State University, Tbilisi, Georgia
RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany
University of Hamburg, Hamburg, Germany
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
National and Kapodistrian University of Athens, Athens, Greece
National Technical University of Athens, Athens, Greece
University of Ioannina, Ioannina, Greece
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
Wigner Research Centre for Physics, Budapest, Hungary
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
Institute of Physics, University of Debrecen, Debrecen, Hungary
Indian Institute of Science (IISc), Bangalore, India
National Institute of Science Education and Research, Bhubaneswar, India
Panjab University, Chandigarh, India
University of Delhi, Delhi, India
Saha Institute of Nuclear Physics, Kolkata, India
Indian Institute of Technology Madras, Madras, India
Bhabha Atomic Research Centre, Mumbai, India
Tata Institute of Fundamental Research-A, Mumbai, India
Tata Institute of Fundamental Research-B, Mumbai, India
Indian Institute of Science Education and Research (IISER), Pune, India
Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
University College Dublin, Dublin, Ireland
INFN Sezione di Bari, Bari, Italy
Università di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy
PRL 119, 141802 (2017)  PHYSICAL REVIEW LETTERS  week ending 6 OCTOBER 2017

65a INFN Sezione di Bologna, Bologna, Italy 65b Università di Bologna, Bologna, Italy
66a INFN Sezione di Catania, Catania, Italy 66b Università di Catania, Catania, Italy
67a INFN Sezione di Firenze, Firenze, Italy 67b Università di Firenze, Firenze, Italy
68a INFN Laboratori Nazionali di Frascati, Frascati, Italy 68b INFN Sezione di Genova, Genova, Italy
69a Università di Genova, Genova, Italy 69b INFN Sezione di Milano-Bicocca, Milano, Italy
70a Università di Milano-Bicocca, Milano, Italy 70b INFN Sezione di Napoli, Roma, Italy
71a Università di Napoli ‘Federico II’, Roma, Italy 71b Università della Basilicata, Roma, Italy
71c Università G. Marconi, Roma, Italy 71d INFN Sezione di Padova, Padova, Italy
72a Università di Padova, Padova, Italy 72b Università di Trento, Trento, Italy
73a INFN Sezione di Pavia, Pavia, Italy 73b Università di Pavia, Pavia, Italy
74a INFN Sezione di Perugia, Perugia, Italy 74b Università di Perugia, Perugia, Italy
75a INFN Sezione di Pisa, Pisa, Italy 75b Università di Pisa, Pisa, Italy
76a Scuola Normale Superiore di Pisa, Pisa, Italy 76b INFN Sezione di Roma, Roma, Italy
76c Sapienza Università di Roma, Roma, Italy 76d INFN Sezione di Torino, Torino, Italy
77a Università di Torino, Torino, Italy 77b INFN Sezione di Trieste, Trieste, Italy
77c Università del Piemonte Orientale, Novara, Italy 77d Università di Trieste, Trieste, Italy
78a Kyungpook National University, Daegu, Korea 78b Chonbuk National University, Jeonju, Korea
79a Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
80a Hanyang University, Seoul, Korea 80b Korea University, Seoul, Korea
81a Seoul National University, Seoul, Korea 81b University of Seoul, Seoul, Korea
82a Sungkyunkwan University, Suwon, Korea 82b Vilnius University, Vilnius, Lithuania
83a National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
84a Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
85a Universidad Iberoamericana, Mexico City, Mexico
86a Universidad Autónoma de Puebla, Puebla, Mexico
87a Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
88a University of Auckland, Auckland, New Zealand
89a University of Canterbury, Christchurch, New Zealand
90a National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
91a National Centre for Nuclear Research, Swierk, Poland
92a Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
93a Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
94a Joint Institute for Nuclear Research, Dubna, Russia
95a Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
96a Institute for Theoretical and Experimental Physics, Moscow, Russia
97a Moscow Institute of Physics and Technology, Moscow, Russia
98a National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
99a P.N. Lebedev Physical Institute, Moscow, Russia
100a Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
107 Novosibirsk State University (NSU), Novosibirsk, Russia

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

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

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

111 Universidad Autónoma de Madrid, Madrid, Spain

112 Universidad de Oviedo, Oviedo, Spain

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

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

115 Paul Scherrer Institut, Villigen, Switzerland

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

117 Universität Zürich, Zurich, Switzerland

118 National Central University, Chung-Li, Taiwan

119 National Taiwan University (NTU), Taipei, Taiwan

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

121 Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

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

123 Bogazici University, Istanbul, Turkey

124 Istanbul Technical University, Istanbul, Turkey

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

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

127 University of Bristol, Bristol, United Kingdom

128 Rutherford Appleton Laboratory, Didcot, United Kingdom

129 Imperial College, London, United Kingdom

130 Brunel University, Uxbridge, United Kingdom

131 Baylor University, Waco, Texas, USA

132 Catholic University of America, Washington DC, USA

133 The University of Alabama, Tuscaloosa, Alabama, USA

134 Boston University, Boston, Massachusetts, USA

135 Brown University, Providence, Rhode Island, USA

136 University of California, Davis, Davis, California, USA

137 University of California, Los Angeles, California, USA

138 University of California, Riverside, Riverside, Riverside, USA

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

140 University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA

141 California Institute of Technology, Pasadena, California, USA

142 Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

143 University of Colorado Boulder, Boulder, Colorado, USA

144 Cornell University, Ithaca, New York, USA

145 Fairfield University, Fairfield, Connecticut, USA

146 Fermi National Accelerator Laboratory, Batavia, Illinois, USA

147 University of Florida, Gainesville, Florida, USA

148 Florida International University, Miami, Florida, USA

149 Florida State University, Tallahassee, Florida, USA

150 Florida Institute of Technology, Melbourne, Florida, USA

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

152 The University of Iowa, Iowa City, Iowa, USA

153 Johns Hopkins University, Baltimore, Maryland, USA

154 The University of Kansas, Lawrence, Kansas, USA

155 Kansas State University, Manhattan, Kansas, USA

156 Lawrence Livermore National Laboratory, Livermore, California, USA

157 University of Maryland, College Park, Maryland, USA

158 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

159 University of Minnesota, Minneapolis, Minnesota, USA

160 University of Mississippi, Oxford, Mississippi, USA

161 University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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

163 Northeastern University, Boston, Massachusetts, USA

164 Northwestern University, Evanston, Illinois, USA

165 University of Notre Dame, Notre Dame, Indiana, USA

166 The Ohio State University, Columbus, Ohio, USA