Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

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

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.107.221804">http://dx.doi.org/10.1103/PhysRevLett.107.221804</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>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/69837">http://hdl.handle.net/1721.1/69837</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 Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

S. Chatrchyan et al.*
(CMS Collaboration)

A search for events with jets and missing transverse energy is performed in a data sample of $pp$ collisions collected at $\sqrt{s} = 7$ TeV by the CMS experiment at the LHC. The analyzed data sample corresponds to an integrated luminosity of 1.14 fb$^{-1}$. In this search, a kinematic variable $\alpha_T$ is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space of the constrained minimal supersymmetric extension of the standard model are set. In this model, squark masses below 1.1 TeV are excluded at 95% C.L.. Gluino masses below 1.1 TeV are also ruled out at 95% C.L. for values of the universal scalar mass parameter below 500 GeV.

DOI: 10.1103/PhysRevLett.107.221804

The standard model (SM) of particle physics is generally considered to be valid only at low energy scales and is expected to be superseded by a more complete theory at higher scales. Supersymmetric (SUSY) extensions to the SM [1–8] introduce a large number of new particles with the same quantum numbers as their SM partners, but differing by half a unit of spin. If $R$-parity conservation [9] is assumed, supersymmetric particles, such as squarks and gluinos, are produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of stable supersymmetric particles, such as squarks and gluinos, produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of stable supersymmetric particles, such as squarks and gluinos, produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of stable supersymmetric particles, such as squarks and gluinos, produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of stable supersymmetric particles, such as squarks and gluinos, produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of stable supersymmetric particles, such as squarks and gluinos, produced in pairs and decay to the lightest, stable supersymmetric particle (LSP).

*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 article’s title, journal citation, and DOI.

0031-9007/11/107(22)/221804(16) 221804-1 © 2011 CERN, for the CMS Collaboration
are required to have transverse energy $E_T > 50$ GeV. Events are vetoed if any additional jet satisfies $E_T > 50$ GeV and $|\eta| > 3$, or rare, spurious signals are identified in the calorimeters [34,35]. The highest-$E_T$ jet is required to be within the central tracker acceptance and the two highest-$E_T$ jets must each have $E_T > 100$ GeV. To suppress SM processes with genuine $E_T$ from neutrinos, events containing an isolated electron [36] or muon [37] with $p_T > 10$ GeV are vetoed. To select a pure multijet topology, events are vetoed in which an isolated photon [38] with $p_T > 25$ GeV is found.

The following two variables characterize the visible energy and missing momentum in the transverse plane: the scalar sum of the transverse energy $E_T$ of jets, defined as $H_T = \sum_{i=1}^{N_{\text{jett}}} E_T$, and the magnitude of the vector sum of the transverse momenta $\vec{p}_T$ of jets, defined as $H_T = \sum_{i=1}^{N_{\text{jett}}} |\vec{p}_T|$, where $N_{\text{jett}}$ is the number of jets with $E_T > 50$ GeV. Significant hadronic activity in the event is ensured by requiring $H_T > 275$ GeV. Following these selections, the background from multijet production, a manifestation of quantum chromodynamics (QCD), is still several orders of magnitude larger than the typical signal expected from SUSY. While the bulk of these multijet events do not exhibit significant $E_T$, large values can be observed due to stochastic fluctuations in the measurement of jet energies or mismeasurements caused by nonuniformities in the calibration of the calorimeters or detector inefficiencies.

The $\alpha_T$ kinematic variable, first introduced in Refs. [39–41], is used in the selection to efficiently reject events either without significant $E_T$ or with transverse energy mismeasurements, while retaining a large sensitivity to new physics with genuine $E_T$ signatures. For events with two jets, the variable is defined as $\alpha_T = E_T^{j_1}/M_T = E_T^{j_1}/\sqrt{H_T^2 - H_T^{j_1}^2}$, where $E_T^{j_1}$ is the transverse energy of the less-energetic jet, and $M_T$ is the transverse mass of the dijet system. For a perfectly measured dijet event with $E_T^{j_1} = E_T^{j_2}$ and jets back to back in $\phi$, and in the limit of large jet momenta compared to their masses, the value of $\alpha_T$ is 0.5. In the case of an imbalance in the measured transverse energies of back-to-back jets, $\alpha_T$ is smaller than 0.5. Values significantly greater than 0.5 are observed when $\alpha_T$ is 0.5. In the case of an imbalance in the measured transverse energies of back-to-back jets, $\alpha_T$ is smaller than 0.5. Values significantly greater than 0.5 are observed when $\alpha_T$ is 0.5.

Effective jet energy undermeasurements due to detector inefficiencies can lead to values of $\alpha_T$ slightly above 0.5. Such events are effectively rejected by requiring $\alpha_T > 0.55$ and by applying dedicated vetoes, described further in Ref. [23]. These final selections complete the definition of the hadronic signal sample. A disjoint hadronic control sample consisting predominantly of QCD multijet events is defined by requiring $\alpha_T < 0.55$.

As can be seen in Fig. 1, the only expected remaining backgrounds with $\alpha_T > 0.55$ stem from SM processes with genuine $E_T$ in the final state. In the dijet case, the largest backgrounds with genuine $E_T$ are the associated production of $W$ or $Z$ bosons with jets, followed by either the weak decays $Z \rightarrow \nu \bar{\nu}$ or $W \rightarrow \tau \nu$, where the $\tau$ decays hadronically and is identified as a jet, or by leptonic decays that are not rejected by the dedicated electron or muon vetoes. At higher jet multiplicities, top quark production, followed by semileptonic weak top quark decay, becomes important.

Events in the hadronic signal sample are recorded with a trigger condition that identifies candidate events with energetic jets and significant $E_T$. Events are selected if they have $H_T > 250$ GeV and $E_T$ above a threshold that evolves with instantaneous luminosity, from 60 to 90 GeV. In the region $275 < H_T < 325$ GeV, the efficiency with which events satisfying the full reconstruction and selection criteria are triggered is $0.99^{+0.01}_{-0.03}$. For events with $H_T > 325$ GeV, the efficiency is $1.00^{+0.03}_{-0.00}$. A set of pre-scaled $H_T$ trigger conditions are used to record events for the hadronic control sample.

FIG. 1 (color online). The distribution of $\alpha_T$, described in the text, for events in data with two or more jets (black dots with error bars representing the statistical uncertainties), after all event selection criteria except $\alpha_T$ are applied and $H_T > 375$ GeV. For illustrative purposes only, expected yields from simulation are also shown for QCD multijet events (dot-dashed line), associated production of top quarks, $W$, or $Z$ with jets (long-dashed line), the sum of all aforementioned SM processes (solid line) and the SUSY LM6 model (dotted line). The uncertainties for the SM expectation, due to the limited accuracy of the available simulation data sets and jet energy calibrations, are represented by the hatched area. The highest bin contains the overflows.
The analysis makes use of two additional data samples to estimate the backgrounds with genuine $\mathcal{E}_T$. First, a $\mu +$ jets sample is recorded with the hadronic trigger condition described above. The event selection, following closely the prescription described in Ref. [42], requires a single, isolated muon with $p_T > 10$ GeV in the final state and the transverse mass of the muon and $H_T$ system to be larger than 30 GeV to ensure a sample rich in $W$ bosons. The muon is required to be separated from the closest jet in the event by $\Delta \eta$ and $\Delta \phi$ such that the distance $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.5$. Second, a $\gamma +$ jets sample is selected using a dedicated photon trigger condition requiring a localized, large energy deposit in the ECAL with $p_T > 90$ GeV and that satisfies loose photon identification and isolation criteria [38]. The offline selection requires a single photon to be reconstructed with $p_T > 100$ GeV, $|\eta| < 1.45$, satisfying tight isolation criteria, and with a minimum distance to any jet of $\Delta R > 1.0$. For these selection criteria, the photon trigger condition is found to be fully efficient.

The hadronic signal region is divided into eight bins of $H_T$: two bins of width 50 GeV in the range $275 < H_T < 375$ GeV, five bins of width 100 GeV in the range $375 < H_T < 875$ GeV, and a final open bin, $H_T > 875$ GeV. As in Ref. [23], jet $E_T$ thresholds are scaled down from their nominal values in the lowest two $H_T$ bins to maintain jet multiplicities and thus comparable event kinematics, topologies, and background composition throughout the entire $H_T$ range. The background estimation methods described below are combined in the statistical interpretation of the observed data yields to provide a single prediction of the SM background in each $H_T$ bin of the hadronic signal region. With respect to Ref. [23], these refinements provide greater sensitivity across a broader SUSY parameter space and, in the context of CMSSM, up to higher-mass states.

The $\mu +$ jets data sample provides an estimate of the contributions from top quark and $W$ production (leading to $W +$ jets final states) still remaining in each $H_T$ bin of the hadronic signal region after all selection criteria are applied. Factors obtained from simulation [23] are then used to translate the yields in the $\mu +$ jets sample to estimates in each $H_T$ bin of the hadronic signal region. These factors are found to be only weakly dependent on $H_T$, ranging from 1.14 at low $H_T$ to 0.90 at high $H_T$. Conservative uncertainties on all the parameters entering these translation factors are assigned. The total systematic uncertainty is estimated to be $30\%$, dominated by the uncertainty on the efficiency for vetoing leptons. The remaining irreducible background of $Z \rightarrow \nu \bar{\nu} +$ jets events in the hadronic signal sample is estimated from $\gamma +$ jets events. These two processes have similar kinematic properties when the photon is ignored [43,44], while the latter has a larger production cross section. Translation factors that account for the ratio of cross sections for $\gamma +$ jets and $Z \rightarrow \nu \bar{\nu} +$ jets, and their relative acceptances, are obtained from simulation [23] and are used to estimate the number of $Z \rightarrow \nu \bar{\nu} +$ jets events in each $H_T$ bin of the hadronic signal region. As is the case of the $\mu +$ jets sample, these translation factors are only weakly dependent on $H_T$, ranging from 0.35 at low $H_T$ to 0.45 at high $H_T$. The main systematic uncertainties on these factors are associated with the ratio of cross sections between $\gamma +$ jets and $Z \rightarrow \nu \bar{\nu} +$ jets in the simulation ($30\%$), the efficiency for photon identification ($20\%$), and the purity of the photon selection ($20\%$), which add up in quadrature to $40\%$. These uncertainty estimates are verified by predicting the number of $\mu +$ two-jet events in each $H_T$ bin using the $\gamma +$ two-jet sample. The requirement of exactly two jets suppresses the top quark contribution in the muon sample, thus leaving a relatively pure $W +$ jets sample that is kinematically similar to the $Z \rightarrow \nu \bar{\nu} +$ jets sample. The predicted and observed event yields are consistent within the assigned systematic uncertainties.

Furthermore, the $H_T$ dependence of the ratio $R_{\alpha_T}$ is exploited to constrain the SM background estimate for each $H_T$ bin. This ratio is defined as the number of events with $\alpha_T$ above and below a threshold value of 0.55 for a given bin in $H_T$. The denominator of the ratio is always dominated by events from QCD multijet production and is measured in data with samples selected by the set of prescaled $H_T$ trigger conditions. The chosen $\alpha_T$ threshold ensures that, for a given bin in $H_T$, the numerator of the ratio is dominated by events from SM processes with genuine $\mathcal{E}_T$ from neutrinos, with no significant contribution from QCD multijet production. As observed in Ref. [23], this property leads to $R_{\alpha_T}$ being independent of $H_T$. The remaining backgrounds are those with genuine $\mathcal{E}_T$ from associated production of top quarks, $W$, or $Z$ with jets. By relaxing the $\alpha_T$ threshold to values lower than 0.55, the numerator is instead dominated by mismeasured QCD multijet events, and an exponential dependence of $R_{\alpha_T}$ on $H_T$ is observed [23]. The behaviors of $\alpha_T$ and $R_{\alpha_T}(H_T)$ are observed in data and simulation to be robust against the effects of multiple $p\bar{p}$ collisions per beam crossing (pileup). In the statistical interpretation of the analysis, $R_{\alpha_T}(H_T)$ is modeled as a superposition of a $H_T$-independent contribution from SM processes with genuine $\mathcal{E}_T$, and an exponentially falling contribution to accommodate any potential QCD contamination. The latter is considered even though no evidence of a significant QCD contamination is found in the hadronic signal region.

To obtain an accurate and consistent prediction of the SM background, a simultaneous binned likelihood fit using information from all three data samples is performed. The fit maximizes the likelihood $L_{\text{total}} = L_{\text{hadronic}} \times L_{\mu + \text{jets}} \times L_{\gamma + \text{jets}}$, where $L_{\text{hadronic}}$ characterizes $R_{\alpha_T}(H_T)$ in the hadronic sample with a single exponential function, $A e^{-kH_T}$, to accommodate any QCD contamination and a constant, $H_T$-independent contribution, $B$, to describe SM processes with genuine $\mathcal{E}_T$. The likelihoods $L_{\mu + \text{jets}}$ and $L_{\gamma + \text{jets}}$ describe the $H_T$-dependent yields in the $\mu +$ jets and
FIG. 2 (color online). The ratio $R_{\ell\ell}$ as a function of $H_T$, as measured in the hadronic data samples (black dots with error bars representing the statistical uncertainties). The ratios using the direct predictions from the $\mu +$ jets and $\gamma +$ jets samples are shown as open squares (offset for clarity, with error bars representing the statistical and systematic uncertainties). Also shown is the result of the simultaneous fit to the three data samples (solid line); the analogous result when assuming a $H_T$-independent prediction (dotted line); and, for illustrative purposes only, the expectation from the SUSY LM6 model when superimposed on the nominal fit result (long-dashed line).

For each $H_T$ bin, these yields are related to the numerator of $R_{\ell\ell}(H_T)$, measured in the hadronic signal sample, via the translation factors from the simulation.

With a fit probability ($p$ value) of 0.56, the hypothesis for the $R_{\ell\ell}$ dependence on $H_T$ reproduces the data well, as shown in Fig. 2. The only parameter with a significant nonzero value as determined by the fit is the constant term $B = (1.1 \pm 0.2) \times 10^{-3}$. The other two fit parameters, $A = (1.4 \pm 1.9) \times 10^{-5}$ and $k = (5.2 \pm 5.6) \times 10^{-3}$ GeV$^{-1}$, are compatible with zero, indicating that no significant QCD contamination has been observed in the signal region. Furthermore, as a cross check, the fit is repeated with the assumption that $R_{\ell\ell}$ is independent of $H_T$, which in turn implies that the numerator of the ratio is fully dominated by SM backgrounds with genuine $E_T$. The result of this fit, shown in Fig. 2, has a $p$ value of 0.41 and is in good agreement with the nominal fit.

To validate the background estimation of the simultaneous fit, the $\mu +$ jets and $\gamma +$ jets samples are used to predict directly the SM backgrounds with genuine $E_T$ in the different $H_T$ bins, independently of the fit. The prediction for each $H_T$ bin is taken as the numerator of the ratio $R_{\ell\ell}$, and the observed behavior in $H_T$ is shown in Fig. 2. This cross-check confirms, within the statistical and systematic uncertainties, the $H_T$ independence of $R_{\ell\ell}$, when the numerator is dominated by SM events with genuine $E_T$.

The fit results for all three data samples are listed in Table I, along with the observed yields in the data. Good agreement between the measured $H_T$ distribution and the fit is observed for all three data samples, indicating that the observed yields are compatible with the SM background expectation provided by the fit. The uncertainties listed with the SM predictions are obtained from an ensemble of pseudoexperiments. Figure 3 compares the result of the simultaneous fit to the observed yields in the hadronic signal sample.

Given the lack of an excess of events above the expected SM backgrounds, limits are set in the parameter space of the CMSSM. At each point of the parameter space, the SUSY particle spectrum is calculated with SOFTSUSY [45], and the signal events are generated at leading order with PYTHIA 6.4 [46]. Inclusive, process-dependent, next-to-leading-order (NLO) cross sections, obtained with the program PROSPINO [47], are used to calculate the observed and expected exclusion contours. The simulated signal events are reweighted so that the distribution of number of pileup events per beam crossing from the simulation matches that observed in data. Uncertainties on the SM background prediction, the luminosity measurement (4.5%) [48], the total acceptance times efficiency of the selection for the considered signal model (4.5%) [23,49], and NLO cross section and parton distribution functions (10%) are included in the limit. Although signal contributions to the total yield in each of the three considered data samples are allowed, the only relevant signal contribution originates from the hadronic data sample in the case of the CMSSM.

Figure 4 shows the observed and expected exclusion limits at 95% confidence level (C.L.) in the $(m_0, m_{1/2})$ plane for tan$\beta = 10$ and $A_0 = 0$ GeV, calculated with the CL$_S$ method [50]. For this choice of parameters in the CMSSM, squark masses below 1.1 TeV are excluded and gluino masses below the same value are ruled out for

<table>
<thead>
<tr>
<th>$H_T$ bin (GeV)</th>
<th>275–325</th>
<th>325–375</th>
<th>375–475</th>
<th>475–575</th>
<th>575–675</th>
<th>675–775</th>
<th>775–875</th>
<th>&gt;875</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM hadronic</td>
<td>787±32</td>
<td>310±8</td>
<td>202±9</td>
<td>60.4±4.2</td>
<td>20.3±1.8</td>
<td>7.7±0.8</td>
<td>3.2±0.4</td>
<td>2.8±0.4</td>
</tr>
<tr>
<td>Data hadronic</td>
<td>782</td>
<td>321</td>
<td>196</td>
<td>62</td>
<td>21</td>
<td>6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>SM $\mu +$ jets</td>
<td>367±15</td>
<td>182±8</td>
<td>113±5</td>
<td>36.5±3.8</td>
<td>13.4±2.2</td>
<td>4.0±1.4</td>
<td>0.8±0.9</td>
<td>0.7±0.9</td>
</tr>
<tr>
<td>Data $\mu +$ jets</td>
<td>389</td>
<td>156</td>
<td>113</td>
<td>39</td>
<td>17</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SM $\gamma +$ jets</td>
<td>834±28</td>
<td>325±17</td>
<td>210±12</td>
<td>64.7±6.9</td>
<td>21.1±3.9</td>
<td>10.5±2.5</td>
<td>6.1±0.9</td>
<td>5.5±0.9</td>
</tr>
<tr>
<td>Data $\gamma +$ jets</td>
<td>849</td>
<td>307</td>
<td>210</td>
<td>67</td>
<td>24</td>
<td>12</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

TABLE I. Comparison of the measured yields in the different $H_T$ bins for the hadronic, $\mu +$ jets and $\gamma +$ jets samples with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.
m_0 < 500 GeV. The exclusion limit changes at most by 20 GeV in the (m_0, m_{1/2}) plane for different parameter values (e.g., tan _\beta = 40 and A_0 = -500 GeV), indicating that the limit is only weakly dependent on these parameters.

In summary, the first search for supersymmetry from CMS based on an integrated luminosity in excess of 1 fb^{-1} has been reported. Final states with two or more jets and significant E_T, as expected from high-mass squark and gluino production and decays, have been analyzed. The search has been performed in eight bins of the scalar sum of the transverse energy of jets, H_T, considering events with H_T in excess of 275 GeV. The sum of standard model backgrounds per H_T bin has been estimated from a simultaneous binned likelihood fit to hadronic, mu + jets, and gamma + jets samples. The observed yields in the eight H_T bins have been found to be in agreement with the expected contributions from standard model processes. Limits on the CMSSM parameters have been derived and squark masses below 1.1 TeV are excluded at 95% C.L. in this model. Gluino masses in the same range are ruled out at 95% C.L. for m_0 < 500 GeV. This limit represents a tight constraint on the parameter space of SUSY models like the CMSSM.

We wish to 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); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, 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); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (U.K.); DOE and NSF (U.S.).

---

[34] S. Chatrchyan et al. (CMS), JINST 5, T03014 (2010).
D. Baumgartel,144 O. Boeriu,144 M. Chasco,144 S. Reucroft,144 J. Swain,144 D. Trocino,144 D. Wood,144 J. Zhang,144
M. Schmitt,145 S. Stoynev,145 M. Velasco,145 S. Won,145 L. Antonelli,146 D. Berry,146 A. Brinkerhoff,146
M. Hildreth,146 C. Jessop,146 D. J. Karmgard,146 J. Kolb,146 T. Kolberg,146 K. Lannon,146 W. Luo,146 S. Lynch,146
N. Marinelli,146 D. M. Morse,146 T. Pearson,146 R. Ruchti,146 J. Slaunwhite,146 N. Valls,146 M. Wayne,146
J. Ziegler,146 B. Bylsma,147 L. S. Durkin,147 C. Hill,147 P. Killewald,147 K. Kotov,147 T. Y. Ling,147 M. Rodenburg,147
C. Vuosalo,147 G. Williams,147 N. Adam,148 E. Berry,148 P. Elmer,148 D. Gerbaudo,148 V. Halyo,148 P. Hebda,148
X. T. Huang,149 A. Lopez,149 H. Mendez,149 S. Oliveros,149 J. E. Ramirez Vargas,149 A. Zatserklyaniy,149
E. Alagoz,150 V. E. Barnes,150 G. Bolla,150 M. Hildreth,150 C. Jessop,150 D. J. Karmgard,150 J. Kolb,150 T. Kolberg,150
K. Lannon,150 W. Luo,150 S. Lynch,150 N. Marinelli,150 D. M. Morse,150 T. Pearson,150 R. Ruchti,150 J. Slaunwhite,150
M. Rodenburg,151 H. D. Yoo,150 J. Zablocki,150 Y. Zheng,150 S. Guragain,151 N. Parashar,151 A. Adair,152
H. Flacher,153 A. Garcia-Bellido,153 P. Goldenzweig,153 Y. Gotra,153 J. Han,153 A. Harel,153 D. C. Miner,153
K. Goulianos,154 G. Lungu,154 S. Malik,154 C. Mesropian,154 S. Araora,155 O. Atramentov,155 A. Barker,155
C. Contreras-Campana,155 E. Contreras-Campana,155 D. Duggan,155 Y. Gershtein,155 R. Gray,155 E. Halkiadakis,155
D. Hidas,155 D. Hits,155 A. Lath,155 S. Panwalkar,155 M. Park,155 R. Patel,155 A. Richards,155 K. Rose,155
S. Schnetzer,155 S. Somalwar,155 R. Stone,155 S. Thomas,155 G. Cerizza,155 M. Hollingsworth,156 S. Spanier,156
J. Swanson,157 M. Weinberg157

(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der OeAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
11Instituto de Física Teórica, Universidade Estadual Paulista, Sao Paulo, Brazil
12Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
13University of Sofia, Sofia, Bulgaria
Institute of High Energy Physics, Beijing, China
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Universidad de Los Andes, Bogota, Colombia
Technical University of Split, Split, Croatia
University of Split, Split, Croatia
Institute Rudjer Boskovic, Zagreb, Croatia
University of Cyprus, Nicosia, Cyprus
Charles University, Prague, Czech Republic
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
Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse,
CNRS/IN2P3, Strasbourg, France
Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
Institute of High Energy Physics and Informatization, 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 Physics “Demokritos,” Aghia Paraskevi, Greece
University of Athens, Athens, Greece
University of Ioánnina, Ioánnina, Greece
FKI 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 and Fundamental Sciences (IPM), Tehran, Iran
INFN Sezione di Bari, Bari, Italy
Università di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy
INFN Sezione di Bologna, Bologna, Italy
Università di Bologna, Bologna, Italy
INFN Sezione di Catania, Catania, Italy
Università di Catania, Catania, Italy
INFN Sezione di Firenze, Firenze, Italy
Università di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
Università di Milano-Bicocca, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Università di Napoli “Federico II,” Napoli, Italy
INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
INFN Sezione di Pavia, Pavia, Italy
Università di Pavia, Pavia, Italy
University of California, Los Angeles, Los Angeles, California 90095, USA
University of California, Riverside, Riverside, California 92521, USA
University of California, San Diego, La Jolla, California 92093, USA
University of California, Santa Barbara, Santa Barbara, California 93106, USA
California Institute of Technology, Pasadena, California 91125, USA
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
University of Colorado at Boulder, Boulder, Colorado 80309, USA
Cornell University, Ithaca, New York 14853, USA
Fairfield University, Fairfield, Connecticut 06824, USA
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
University of Florida, Gainesville, Florida 32611, USA
Florida International University, Miami, Florida 33199, USA
Florida State University, Tallahassee, Florida 32306, USA
Florida Institute of Technology, Melbourne, Florida 32901, USA
University of Illinois at Chicago (UIC), Chicago, Illinois 60607, USA
The University of Iowa, Iowa City, Iowa 52242, USA
Johns Hopkins University, Baltimore, Maryland 21218, USA
The University of Kansas, Lawrence, Kansas 66045, USA
Kansas State University, Manhattan, Kansas 66506, USA
Lawrence Livermore National Laboratory, Livermore, California 94720, USA
University of Maryland, College Park, Maryland 20742, USA
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
University of Minnesota, Minneapolis, Minnesota 55455, USA
University of Mississippi, University, Mississippi 38677, USA
University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA
State University of New York at Buffalo, Buffalo, New York 14260, USA
Northeastern University, Boston, Massachusetts 02115, USA
Northwestern University, Evanston, Illinois 60208, USA
University of Notre Dame, Notre Dame, Indiana 46556, USA
The Ohio State University, Columbus, Ohio 43210, USA
Princeton University, Princeton, New Jersey 08544, USA
University of Puerto Rico, Mayaguez, Puerto Rico 00680
Purdue University, West Lafayette, Indiana 47907, USA
Purdue University Calumet, Hammond, Indiana 46323, USA
Rice University, Houston, Texas 77251, USA
The Rockefeller University, New York, New York 10021, USA
Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA
University of Tennessee, Knoxville, Tennessee 37996, USA
Texas A&M University, College Station, Texas 77843, USA
Texas Tech University, Lubbock, Texas 79409, USA
Vanderbilt University, Nashville, Tennessee 37235, USA
University of Virginia, Charlottesville, Virginia 22901, USA
Wayne State University, Detroit, Michigan 48202, USA
University of Wisconsin, Madison, Wisconsin 53706, USA

aDeceased.
bAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
cAlso at Universidade Federal do ABC, Santo Andre, Brazil.
dAlso at California Institute of Technology, Pasadena, CA,USA.
eAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
fAlso at Suez Canal University, Suez, Egypt.
gAlso at Cairo University, Cairo, Egypt.
hAlso at British University, Cairo, Egypt.
iAlso at Fayoum University, El-Fayoum, Egypt.
jAlso at Ain Shams University, Cairo, Egypt.
kAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.
lAlso at Universite de Haute-Alsace, Mulhouse, France.
mAlso at Moscow State University, Moscow, Russia.