

Search for New Physics in the Multijet and Missing Transverse Momentum Final State in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**

(CMS Collaboration)

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A search for physics beyond the standard model is performed in events with at least three jets and large missing transverse momentum produced in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. No significant excess of events above the expected backgrounds is observed in 4.98 fb^{-1} of data collected with the CMS detector at the Large Hadron Collider. The results are presented in the context of the constrained minimal supersymmetric extension of the standard model and more generically for simplified models. For the simplified models of gluino-gluino and squark-squark production, gluino masses below 1.0 TeV and squark masses below 0.76 TeV are excluded in case the lightest supersymmetric particle mass is below 200 GeV. These results significantly extend previous searches.

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Many extensions of the standard model (SM) of particle physics have been proposed to address the shortcomings of the SM, e.g., problems concerning the gauge hierarchy and identity of dark matter [1–3]. Supersymmetry (SUSY) is one such new physics model, which postulates a new symmetry that relates fermionic and bosonic degrees of freedom and introduces a superpartner for each SM particle. In R -parity conserving models [4], SUSY particles are produced in pairs, and the lightest SUSY particle (LSP) is stable. If the LSP is weakly interacting and neutral, it serves as a candidate for dark matter. At the Large Hadron Collider (LHC), squarks (\tilde{q}) and gluinos (\tilde{g}), the superpartners of the quarks and gluons, would be produced via the strong interaction and decay to SM particles and two LSPs. A typical signature is the all-hadronic final state, characterized by multiple jets arising from quarks and gluons, and large missing transverse momentum due to the unobserved LSPs.

Searches in this final state have been performed by experiments at the Fermilab Tevatron [5,6] and at the LHC [7–15]. This Letter presents a search in events with multiple jets and large missing transverse momentum produced in 7 TeV pp collisions using a data sample corresponding to an integrated luminosity of $4.98 \pm 0.11 \text{ fb}^{-1}$ [16] collected with the Compact Muon Solenoid (CMS) detector. The search strategy follows Ref. [7] but uses more than 100 times the amount of data. This search is not specifically optimized for a particular SUSY model but is sensitive to a variety of new physics models that lead to

the multijet final state with large missing transverse momentum. The results of this search are interpreted in the context of the constrained minimal supersymmetric extension of the SM (CMSSM) [17–19] and in a more general context for simplified models [20,21] of new particles decaying to one or two jets and a stable weakly interacting particle.

The central feature of the CMS detector [22] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. Charged particles are measured by the silicon tracker, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ [23]. The calorimeters surrounding the tracking volume cover $|\eta| < 3$. Outside the field, the quartz and steel forward hadron calorimeters extend the coverage to $|\eta| < 5$. Muons are identified in gas ionization detectors, covering $|\eta| < 2.4$, embedded in the steel return yoke of the magnet. A two-tier trigger system selects the pp collision events for use in this search.

The recorded events are reconstructed using the particle-flow algorithm [24], which reconstructs particles, namely, charged hadrons, photons, neutral hadrons, muons, and electrons, using the information from all subdetectors. These particles are then clustered into jets using the anti- k_T clustering algorithm with distance parameter 0.5 [25]. Corrections are applied to account for the dependence of the jet response on transverse momentum p_T and η [26] and for the effects of additional (pileup) pp collisions overlapping with the collision of interest [27,28].

The event sample for the search is selected by requiring at least three jets with $p_T > 50$ and $|\eta| < 2.5$. The further selection is based on two variables: H_T , defined as $H_T = \sum p_T$ where the sum is carried out over jets with $p_T > 50$ GeV and $|\eta| < 2.5$, and \vec{H}_T , defined as $\vec{H}_T = -\sum \vec{p}_T$

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

where the sum is over jets with $p_T > 30$ GeV and $|\eta| < 5$. Events are required to have $H_T > 500$ GeV and $\cancel{H}_T > 200$ GeV, where \cancel{H}_T is the magnitude of the $\vec{\cancel{H}}_T$. The \cancel{H}_T requirement rejects most of the QCD multijet background. Events with $\vec{\cancel{H}}_T$ aligned in azimuth with one of the two leading jets with $\Delta\phi < 0.5$ rad or along the third jet with $\Delta\phi < 0.3$ rad are removed to further reduce the QCD multijet background. Events containing isolated muons or electrons with $p_T > 10$ GeV are also vetoed in order to reject $t\bar{t}$ and $W/Z + \text{jets}$ backgrounds with leptons in the final state [7,29,30]. Events are also rejected if a jet with $p_T > 30$ GeV has an electromagnetic p_T fraction larger than 0.95 or a neutral hadron p_T fraction larger than 0.90. In addition, events affected by instrumental effects, particles from noncollision sources, and poor reconstruction quality are rejected (event cleaning) [7,31]. All these requirements constitute the baseline selection [32]. The event sample used in this search is collected by triggering on both H_T and \cancel{H}_T or only on H_T . The H_T threshold ranges from 160 to 350 GeV, and the \cancel{H}_T threshold ranges from 60 to 110 GeV. The trigger efficiency is measured to be consistent with 100% for the baseline event selection.

To increase the sensitivity of the search to the different kinematic regions of signal events, the sample of 1885 events passing the baseline selection is divided into 14 subsamples defined in terms of the H_T and \cancel{H}_T values (search selections), as listed in the first column of Table I.

The SM backgrounds mainly consist of $Z(\nu\bar{\nu}) + \text{jets}$ events and $W(\ell\nu) + \text{jets}$ events from W or $t\bar{t}$ production ($\ell = e, \mu, \text{ or } \tau$). The $W(\ell\nu) + \text{jets}$ events pass the search selection when the e/μ escapes detection or a τ decays hadronically. The QCD multijet events also contribute to the background when leptonic decays of heavy-flavor hadrons inside jets or jet energy mismeasurements lead to a

large \cancel{H}_T . The contributions from other SM processes are found to be negligible. In this search, all of the backgrounds are estimated from data [7].

Several Monte Carlo (MC) samples are used to model the signal as well as to develop and validate the background prediction methods. The $t\bar{t}$, $W/Z + \text{jets}$, and $\gamma + \text{jets}$ samples are produced using the MADGRAPH5 [33] generator, interfaced with the PYTHIA 6.4.24 [34] parton-shower model. The $t\bar{t}$ and $W/Z + \text{jets}$ samples are scaled up to the next-to-leading-order (NLO) or next-to-next-to-leading-order cross section predictions [35,36]. The QCD multijet and SUSY signal production is simulated with PYTHIA 6.4.24, the CTEQ6L [37] parton distribution functions (PDFs), and a CMS custom underlying event tuning [38]. The generated events are passed through a GEANT4-based [39] detector simulation and have the same distribution of pileup pp interactions as observed in the data.

The $Z(\nu\bar{\nu}) + \text{jets}$ background contribution is estimated using $\gamma + \text{jets}$ events by treating photons as $Z \rightarrow \nu\bar{\nu}$ decays. The Z boson and photon exhibit similar kinematic properties at high p_T , and the hadronic component of events is similar in the two cases [40–43]. A $\gamma + \text{jets}$ sample is collected by triggering on a γ candidate with or without an additional requirement on H_T , depending on the data-taking period. The photon candidates [44] are required to be isolated from other particles in the tracker and calorimeters and to have the shower shape consistent with that for a prompt photon. In order to predict the $Z(\nu\bar{\nu}) + \text{jets}$ background, the $\gamma + \text{jets}$ sample is corrected for the γ reconstruction efficiency and purity, both measured from data [7], and the $Z(\nu\bar{\nu}) + \text{jets}/\gamma + \text{jets}$ production ratio, obtained from the MADGRAPH simulation samples, which also takes into account the detector acceptance for photons. The total multiplicative correction factor to obtain the $Z(\nu\bar{\nu}) + \text{jets}$

TABLE I. Event yields for different backgrounds for the 14 search selections together with the total backgrounds, as determined from the collision data, and number of events observed in data. The quoted uncertainties are the combinations of the statistical and systematic uncertainties.

Selection H_T (GeV)	\cancel{H}_T (GeV)	$Z \rightarrow \nu\bar{\nu}$	$t\bar{t}/W \rightarrow e, \mu + X$	$t\bar{t}/W \rightarrow \tau_h + X$	QCD multijet	Total background	Data
500–800	200–350	359 ± 81	327 ± 47	349 ± 40	119 ± 77	1154 ± 128	1269
500–800	350–500	112 ± 26	48 ± 9	62.5 ± 8.7	2.2 ± 2.2	225 ± 29	236
500–800	500–600	17.6 ± 4.9	5.0 ± 2.2	8.7 ± 2.5	0.0 ± 0.1	31.3 ± 5.9	22
500–800	>600	5.5 ± 2.6	0.8 ± 0.8	2.0 ± 1.8	0.0 ± 0.0	8.3 ± 3.2	6
800–1000	200–350	48 ± 19	58 ± 15	56.3 ± 8.3	35 ± 24	197 ± 35	177
800–1000	350–500	16.0 ± 6.7	5.4 ± 2.3	7.2 ± 2.0	$1.2^{+1.3}_{-1.2}$	29.8 ± 7.5	24
800–1000	500–600	7.1 ± 3.7	2.4 ± 1.5	1.3 ± 0.6	$0.0^{+0.2}_{0.0}$	10.8 ± 4.0	6
800–1000	>600	3.3 ± 1.7	0.7 ± 0.7	1.0 ± 0.3	$0.0^{+0.1}_{0.0}$	5.0 ± 1.9	5
1000–1200	200–350	10.9 ± 5.1	13.7 ± 3.8	21.9 ± 4.6	19.7 ± 13.3	66 ± 15	71
1000–1200	350–500	5.5 ± 3.0	5.0 ± 4.4	2.9 ± 1.3	$0.4^{+0.7}_{-0.4}$	13.8 ± 5.5	12
1000–1200	>500	2.2 ± 1.7	1.6 ± 1.2	2.3 ± 1.0	$0.0^{+0.2}_{0.0}$	6.1 ± 2.3	4
1200–1400	200–350	3.1 ± 1.8	4.2 ± 2.1	6.2 ± 1.8	11.7 ± 8.3	25.2 ± 8.9	29
1200–1400	>350	2.3 ± 1.5	2.3 ± 1.4	$0.6^{+0.8}_{-0.6}$	$0.2^{+0.6}_{-0.2}$	5.4 ± 2.3	8
>1400	>200	3.2 ± 1.8	2.7 ± 1.6	1.1 ± 0.5	12.0 ± 9.1	19.0 ± 9.4	16

background prediction from the γ + jets event yield is 0.28 ± 0.06 for the baseline selection. The dominant systematic uncertainties on this background estimation originate from the theoretical uncertainty on the γ/Z cross section ratio (20–40%) [40,43], the detector acceptance (5–7%), and the γ reconstruction and isolation efficiency (1–10%), depending on the search regions.

As a cross check, the $Z(\nu\bar{\nu})$ + jets background is also estimated using $Z(\mu^+\mu^-)$ + jets events by treating muons as neutrinos and correcting for the acceptance and efficiencies of the $Z(\mu^+\mu^-)$ + jets event selection and the ratio of branching fractions $\mathcal{B}(\rightarrow \nu\bar{\nu})/\mathcal{B}(\rightarrow \mu^+\mu^-) = 5.95 \pm 0.02$ [45]. The $Z(\nu\bar{\nu})$ + jets background estimated with this method is found to be consistent with the one from the γ + jets events.

The $W(\ell\nu)$ + jets events ($\ell = e$ or μ) from W or top quark production constitute a background when an electron or muon is not identified or is nonisolated and therefore passes the lepton veto. This background is estimated from a μ + jets control sample, selected with the same criteria as those used for the search, except that we require exactly one rather than zero isolated μ . The transverse mass $m_T = \sqrt{2p_T^\mu \cancel{E}_T [1 - \cos(\Delta\phi)]}$ is required to be less than 100 GeV in order to select events containing a $W \rightarrow \mu\nu$ decay and to suppress possible new physics signal contamination, i.e., the signal events resulting in the μ + jets sample used for the background estimation. Here, \cancel{E}_T is the missing transverse energy [31], and $\Delta\phi$ is the azimuthal angle between the μ and the \cancel{E}_T . Events are weighted according to $(1/\epsilon_{\text{iso}}^\mu) [(1 - \epsilon_{\text{reco}}^{e,\mu})/\epsilon_{\text{reco}}^\mu]$ and $(\epsilon_{\text{reco}}^{e,\mu}/\epsilon_{\text{reco}}^\mu) [(1 - \epsilon_{\text{iso}}^{e,\mu})/\epsilon_{\text{iso}}^\mu]$ in order to predict events with unidentified leptons and nonisolated leptons, where $\epsilon_{\text{reco}}^{e,\mu}$ and $\epsilon_{\text{iso}}^{e,\mu}$ are the reconstruction and isolation efficiencies of the electrons and muons. The lepton reconstruction efficiencies are obtained from MC simulation, while the isolation efficiencies are extracted by applying a “tag-and-probe” method [46] on the $Z(\ell^+\ell^-)$ + jets events in data. The lepton reconstruction and identification efficiencies are parametrized in lepton p_T and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ relative to the closest jet, in order to account for the kinematic differences between $Z(\ell^+\ell^-)$ + jets events and the $t\bar{t}$ and W + jets events. Leptons that are out of acceptance and events lost due to the m_T requirement are accounted for using factors determined from simulation. This background estimation method based on the collision data is validated by applying it to a MC sample and comparing the predicted and the true detector-level background distributions.

The predicted background for each search region is listed in Table I. On this background estimation, low statistics in the μ + jets control sample are the dominant source of uncertainty in most of the search regions. The modeling of the lepton reconstruction and isolation efficiencies yields a 10% uncertainty. An additional uncertainty of 4–20% varying for different search regions is assigned based on

the statistical power of the validation of this background estimation method. A 3% uncertainty accounts for the effect of the presence of QCD, Z, or diboson events in the μ + jets sample, which are modeled by MC simulation.

The background from the hadronic decay of τ leptons (τ_h) is estimated from a sample of μ + jets events, selected from inclusive μ or $\mu + \geq 2$ -jet triggers by requiring exactly one μ with $p_T > 20$ GeV and $|\eta| < 2.1$. In this sample, the muon p_T is replaced with a jet p_T taken randomly from a simulated response function for a hadronically decaying τ lepton. The H_T and \cancel{H}_T of the event are recalculated including this τ jet, and the search selections are applied to predict the τ_h background. The τ -jet response function for $p_T^{\text{jet}}/p_T^\tau$ is obtained from simulated $t\bar{t}$ and $W(\tau\nu)$ + jets events by matching the reconstructed τ jet with the generated τ . Corrections are applied to account for the trigger efficiency, acceptance, and efficiency of the μ selection, and the ratio of branching fractions $\mathcal{B}(W \rightarrow \tau_h\nu)/\mathcal{B}(W \rightarrow \mu\nu) = 0.69 \pm 0.05$ [45]. This τ_h background estimation method is validated by applying it to the W and $t\bar{t}$ MC samples, and 6–13% uncertainties are assigned mainly to reflect the statistical power of this validation. The other main systematic uncertainties arise from the μ acceptance ($\leq 13\%$); the τ -jet response function ($\leq 20\%$); and the subtraction of residual QCD multijet, $Z(\mu^+\mu^-)$ + jets, and $(t\bar{t}/W) \rightarrow \tau\nu + X \rightarrow \mu\nu + X$ backgrounds ($\leq 2\%$), where the quoted uncertainties apply to all search regions.

The QCD background is estimated from collision data [7] recorded with a set of triggers having an H_T threshold ranging from 150 to 700 GeV. The data samples used include the electroweak contributions not removed by the lepton veto and any potential new physics events; however, their cross section is negligible compared to the QCD multijet cross section. First, the p_T values of the jets with $p_T > 15$ GeV in these events are adjusted within the jet p_T resolution, using a kinematic fit such that the events are balanced in the transverse plane. The jet p_T values in the rebalanced events are then smeared with the measured jet resolutions to predict the QCD multijet background. The jet p_T response functions are determined as a function of p_T and η using a QCD multijet MC sample that includes heavy-flavor quarks. The width and tail of the p_T response functions are subsequently adjusted to account for the differences in the resolutions measured in simulation and in data [26]. The width (σ) of the Gaussian part of the simulated response is 5 (30)% narrower than what is observed in the data for $|\eta| < 0.5$ ($2.3 < |\eta| < 5.0$). After correcting for this difference, the fraction of jets with response more than 2.5σ away from the mean value is consistent with that in the data within uncertainties. The main uncertainties in this QCD estimation method arise from the shape of the jet response functions, including the Gaussian width, the tails, the heavy-flavor contribution, and the effect of pileup on jets in an event. The method

has been validated in simulated QCD multijet events within the statistical uncertainties (30–50%), which are assigned as an additional uncertainty. The total uncertainty adds up to 60–70%.

The predicted yields of the SM background and the number of events observed in data are summarized in Table I for the 14 search regions. Figure 1 shows the H_T and \cancel{H}_T distributions predicted for the SM background, together with those observed in data. The data are consistent with the SM background estimates.

The 95% confidence level (C.L.) upper limits on the CMSSM signal cross section are set using a modified frequentist CL_s method, taking the profile likelihood as a test statistic [47–49]. The results from 14 exclusive search regions are combined into one test statistic considering the bin-to-bin correlations of the systematic uncertainties. The CMSSM model has five independent parameters: the universal scalar and gaugino masses at the grand unification scale, m_0 and $m_{1/2}$; the trilinear coupling, A_0 ; the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$; and the sign of the Higgsino mixing parameter, μ . The signal cross section is calculated at NLO and next-to-leading-log (NLL) accuracy [50–52]. The H_T and \cancel{H}_T distributions predicted for a low-mass CMSSM benchmark parameter set LM5, $m_0 = 230$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$, are shown in Fig. 1.

The acceptance times efficiency of the event selection for signal events is evaluated using the simulated CMSSM samples. The uncertainties on the background predictions, the luminosity determination (2.2%) [16], the signal acceptance and efficiency arising from the jet energy correction (8%), the jet energy resolution (2%), the PDF (6%), the trigger inefficiency (2%), and the event cleaning [31] (3%) are taken into account by the limit-setting procedure. The possible overprediction of the backgrounds due to the presence of the signal in the data samples used for the

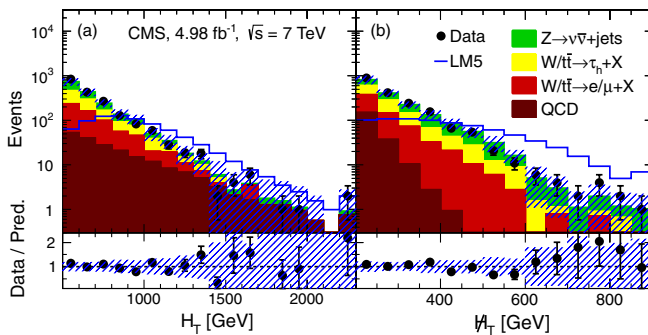


FIG. 1 (color online). The (a) H_T and (b) \cancel{H}_T distributions in the search data samples (circles) compared with histograms showing predictions of the SM background and SUSY signal (LM5, see the text) for events passing the baseline selection. The hatched region indicates the uncertainties on the background predictions. The last bin contains all events above the maximum values of H_T and \cancel{H}_T in the figures. The ratio of the observed data to the background predictions is also shown.

background prediction is estimated to be about 3–20%, depending on $(m_0, m_{1/2})$ values, and subtracted when testing for the signal + background hypothesis in the CL_s method.

The upper limits on the CMSSM signal cross section are mapped into lower limits in the $(m_0, m_{1/2})$ plane (exclusion contour), as shown in Fig. 2 [32,53]. The exclusion contours are also shown for the cases in which the signal cross section is varied by changing the renormalization and factorization scales by a factor of 2 and using the PDF4LHC recommendation [54] for the PDF uncertainty to illustrate the sensitivity of the exclusion to the signal cross section uncertainty. Conservatively, using the -1σ theory uncertainty values on the observed limit, squark masses below 1.2 TeV and gluino masses below 0.72 TeV are excluded for the chosen CMSSM parameter set.

The search results are also presented in a more general context of simplified models [20,21] of new particles (\tilde{q} or \tilde{g}) decaying to one or two jets and an undetectable weakly interacting particle ($\tilde{\chi}^0$). The model used here includes the production of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ pairs and their decays for a wide range of $(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ values, and other SUSY particles are decoupled by being given masses beyond the reach of the LHC. The signal acceptance times efficiency [32] and its uncertainty are evaluated in the same way as used for the CMSSM but using the simulated simplified model signal samples. The observed and expected 95% C.L. upper limits on the signal cross section of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production are shown in Fig. 3 in the

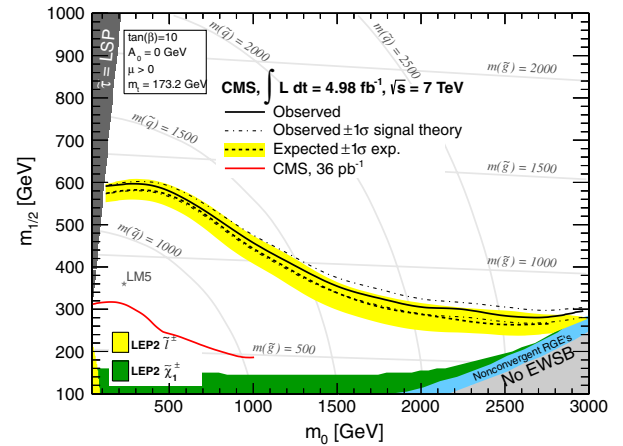


FIG. 2 (color online). The observed and expected 95% C.L. limits in the CMSSM $(m_0, m_{1/2})$ plane. The shaded region around the expected limit shows the $\pm 1\sigma$ variation in the expected limit, while the dot-dashed curves show the variation in the observed limit when the signal cross section is varied by its theoretical uncertainties. The remaining CMSSM parameters are $\tan\beta = 10$, $\mu > 0$, and $A_0 = 0$. The limits from an earlier CMS search [7] and from other experiments [55] are also shown. The limits from Ref. [7] are shown only up to 1000 GeV in m_0 , as done in [7]. The regions where the superpartner of the τ lepton ($\tilde{\tau}$) is the LSP, the renormalization group equations (RGEs) do not converge, or there is no electroweak symmetry breaking (EWSB) [53], are also indicated.

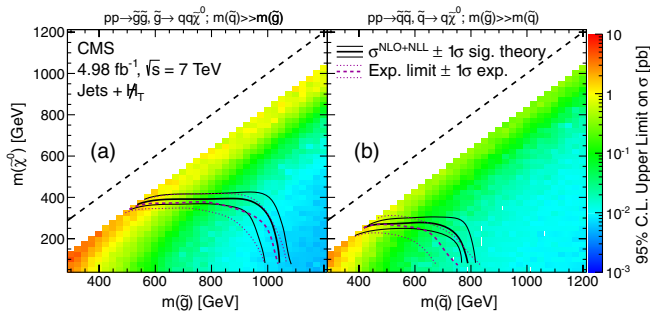


FIG. 3 (color online). The observed and expected 95% C.L. upper limits on the (a) $\tilde{g}\tilde{g}$ and (b) $\tilde{q}\tilde{q}$ cross sections in the $(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ planes obtained with the simplified model. Also shown are the $\pm 1\sigma$ variation in the expected limit and the variation in the observed limit when the signal cross section is varied by its theoretical uncertainties.

$(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ planes, together with contours where the signal cross sections from the NLO + NLL calculations [50–52] are excluded. The results are presented only in the region of $m(\tilde{g}, \tilde{q}) - m(\tilde{\chi}^0) > 150$ GeV, since the estimation of signal acceptance times efficiency becomes unreliable due to its strong dependence on the modeling of QCD radiation when the mass difference $m(\tilde{g}, \tilde{q}) - m(\tilde{\chi}^0)$ is smaller. In this model, the $m(\tilde{g})$ values below 1.0 TeV and $m(\tilde{q})$ values below 0.76 TeV are excluded for $m(\tilde{\chi}^0) < 200$ GeV.

In summary, a search for new physics has been performed in the final state with at least three jets and large \cancel{E}_T using a data sample corresponding to an integrated luminosity of 4.98 fb^{-1} collected in 7 TeV pp collisions with the CMS detector at the LHC. The observed numbers of events are consistent with the estimated SM background contributions, and 95% C.L. exclusion limits are set in the CMSSM parameter space which significantly extend the previous results. For the simplified models of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production, the $m(\tilde{g})$ values below 1.0 TeV and $m(\tilde{q})$ values below 0.76 TeV are excluded for $m(\tilde{\chi}^0) < 200$ GeV.

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R. Trayanov,¹³ M. Vutova,¹³ A. Dimitrov,¹⁴ R. Hadjiiska,¹⁴ V. Kozuharov,¹⁴ L. Litov,¹⁴ B. Pavlov,¹⁴ P. Petkov,¹⁴ J. G. Bian,¹⁵ G. M. Chen,¹⁵ H. S. Chen,¹⁵ C. H. Jiang,¹⁵ D. Liang,¹⁵ S. Liang,¹⁵ X. Meng,¹⁵ J. Tao,¹⁵ J. Wang,¹⁵ X. Wang,¹⁵ Z. Wang,¹⁵ H. Xiao,¹⁵ M. Xu,¹⁵ J. Zang,¹⁵ Z. Zhang,¹⁵ C. Asawatangtrakuldee,¹⁶ Y. Ban,¹⁶ S. Guo,¹⁶ Y. Guo,¹⁶ W. Li,¹⁶ S. Liu,¹⁶ Y. Mao,¹⁶ S. J. Qian,¹⁶ H. Teng,¹⁶ S. Wang,¹⁶ B. Zhu,¹⁶ W. Zou,¹⁶ C. Avila,¹⁷ J. P. Gomez,¹⁷ B. Gomez Moreno,¹⁷ A. F. Osorio Oliveros,¹⁷ J. C. Sanabria,¹⁷ N. Godinovic,¹⁸ D. Lelas,¹⁸ R. Plestina,^{18,g} D. Polic,¹⁸ I. Puljak,^{18,f} Z. Antunovic,¹⁹ M. Kovac,¹⁹ V. Brigljevic,²⁰ S. Duric,²⁰ K. Kadija,²⁰ J. Luetic,²⁰ S. Morovic,²⁰ A. Attikis,²¹ M. Galanti,²¹ G. Mavromanolakis,²¹ J. Mousa,²¹ C. Nicolaou,²¹ F. Ptochos,²¹ P. A. Razis,²¹ M. Finger,²² M. Finger, Jr.,²² Y. Assran,^{23,h} S. Elgammal,^{23,i} A. Ellithi Kamel,^{23,j} S. Khalil,^{23,i} M. A. Mahmoud,^{23,k} A. Radi,^{23,l,m} M. Kadastik,²⁴ M. Müntel,²⁴ M. Raidal,²⁴ L. 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Hackstein,³⁹ F. Hartmann,³⁹ T. Hauth,^{39,f} M. Heinrich,³⁹ H. Held,³⁹ K. H. Hoffmann,³⁹ S. Honc,³⁹ I. Katkov,^{39,p} J. R. Komaragiri,³⁹ P. Lobelle Pardo,³⁹ D. Martschei,³⁹ S. Mueller,³⁹ Th. Müller,³⁹ M. Niegel,³⁹ A. Nürnberg,³⁹ O. Oberst,³⁹ A. Oehler,³⁹ J. Ott,³⁹ G. Quast,³⁹ K. Rabbertz,³⁹ F. Ratnikov,³⁹ N. Ratnikova,³⁹ S. Röcker,³⁹ A. Scheurer,³⁹ F.-P. Schilling,³⁹ G. Schott,³⁹ H. J. Simonis,³⁹ F. M. Stober,³⁹ D. Troendle,³⁹ R. Ulrich,³⁹ J. Wagner-Kuhr,³⁹ S. Wayand,³⁹ T. Weiler,³⁹ M. Zeise,³⁹ G. Daskalakis,⁴⁰ T. Geralis,⁴⁰ S. Kesisoglou,⁴⁰ A. Kyriakis,⁴⁰ D. Loukas,⁴⁰ I. Manolakas,⁴⁰ A. Markou,⁴⁰ C. Markou,⁴⁰ C. Mavrommatis,⁴⁰ E. Ntomari,⁴⁰ L. Gouskos,⁴¹ T. J. Mertzimekis,⁴¹ A. Panagiotou,⁴¹ N. Saoulidou,⁴¹

I. Evangelou,⁴² C. Foudas,^{42,f} P. Kokkas,⁴² N. Manthos,⁴² I. Papadopoulos,⁴² V. Patras,⁴² G. Bencze,⁴³ C. Hajdu,^{43,f} P. Hidas,⁴³ D. Horvath,^{43,r} F. Sikler,⁴³ V. Veszpremi,⁴³ G. Vesztergombi,^{43,s} N. Beni,⁴⁴ S. Czellar,⁴⁴ J. Molnar,⁴⁴ J. Palinkas,⁴⁴ Z. Szillasi,⁴⁴ J. Karacsi,⁴⁵ P. Raics,⁴⁵ Z. L. Trocsanyi,⁴⁵ B. Ujvari,⁴⁵ S. B. Beri,⁴⁶ V. Bhatnagar,⁴⁶ N. Dhingra,⁴⁶ R. Gupta,⁴⁶ M. Jindal,⁴⁶ M. Kaur,⁴⁶ M. Z. Mehta,⁴⁶ N. Nishu,⁴⁶ L. K. Saini,⁴⁶ A. Sharma,⁴⁶ J. Singh,⁴⁶ Ashok Kumar,⁴⁷ Arun Kumar,⁴⁷ S. Ahuja,⁴⁷ A. Bhardwaj,⁴⁷ B. C. Choudhary,⁴⁷ S. Malhotra,⁴⁷ M. Naimuddin,⁴⁷ K. Ranjan,⁴⁷ V. Sharma,⁴⁷ R. K. Shivpuri,⁴⁷ S. Banerjee,⁴⁸ S. Bhattacharya,⁴⁸ S. Dutta,⁴⁸ B. Gomber,⁴⁸ Sa. Jain,⁴⁸ Sh. Jain,⁴⁸ R. Khurana,⁴⁸ S. Sarkar,⁴⁸ M. Sharan,⁴⁸ A. Abdulsalam,⁴⁹ R. K. Choudhury,⁴⁹ D. Dutta,⁴⁹ S. Kailas,⁴⁹ V. Kumar,⁴⁹ P. Mehta,⁴⁹ A. K. Mohanty,^{49,f} L. M. Pant,⁴⁹ P. Shukla,⁴⁹ T. Aziz,⁵⁰ S. Ganguly,⁵⁰ M. Guchait,^{50,t} M. Maity,^{50,u} G. Majumder,⁵⁰ K. Mazumdar,⁵⁰ G. B. Mohanty,⁵⁰ B. Parida,⁵⁰ K. Sudhakar,⁵⁰ N. Wickramage,⁵⁰ S. Banerjee,⁵¹ S. Dugad,⁵¹ H. Arfaei,⁵² H. Bakhshiansohi,^{52,v} S. M. Etesami,^{52,w} A. Fahim,^{52,v} M. Hashemi,⁵² H. Hesari,⁵² A. Jafari,^{52,v} M. Khakzad,⁵² M. Mohammadi Najafabadi,⁵² S. Paktinat Mehdiabadi,⁵² B. Safarzadeh,^{52,x} M. Zeinali,^{52,w} M. Abbrescia,^{53a,53b} L. Barbore,^{53a,53b} C. Calabria,^{53a,53b,f} S. S. Chhibra,^{53a,53b} A. Colaleo,^{53a} D. Creanza,^{53a,53c} N. De Filippis,^{53a,53c,f} M. De Palma,^{53a,53b} L. Fiore,^{53a} G. Iaselli,^{53a,53c} L. Lusito,^{53a,53b} G. Maggi,^{53a,53c} M. Maggi,^{53a} B. Marangelli,^{53a,53b} S. My,^{53a,53c} S. Nuzzo,^{53a,53b} N. Pacifico,^{53a,53b} A. Pompili,^{53a,53b} G. Pugliese,^{53a,53c} G. Selvaggi,^{53a,53b} L. Silvestris,^{53a} G. Singh,^{53a,53b} R. Venditti,^{53a} G. Zito,^{53a} G. Abbiendi,^{54a} A. C. Benvenuti,^{54a} D. Bonacorsi,^{54a,54b} S. Braibant-Giacomelli,^{54a,54b} L. Brigliadori,^{54a,54b} P. Capiluppi,^{54a,54b} A. Castro,^{54a,54b} F. R. Cavallo,^{54a} M. Cuffiani,^{54a,54b} G. M. Dallavalle,^{54a} F. Fabbri,^{54a} A. Fanfani,^{54a,54b} D. Fasanella,^{54a,54b,f} P. Giacomelli,^{54a} C. Grandi,^{54a} L. Guiducci,^{54a,54b} S. Marcellini,^{54a} G. Masetti,^{54a} M. Meneghelli,^{54a,54b,f} A. Montanari,^{54a} F. L. Navarria,^{54a,54b} F. Odorici,^{54a} A. Perrotta,^{54a} F. Primavera,^{54a,54b} A. M. Rossi,^{54a,54b} T. Rovelli,^{54a,54b} G. Siroli,^{54a,54b} R. Travaglini,^{54a,54b} S. Albergo,^{55a,55b} G. Cappello,^{55a,55b} M. Chiorboli,^{55a,55b} S. Costa,^{55a,55b} R. Potenza,^{55a,55b} A. Tricomi,^{55a,55b} C. Tuve,^{55a,55b} G. Barbagli,^{56a} V. Ciulli,^{56a,56b} C. Civinini,^{56a} R. D'Alessandro,^{56a,56b} E. Focardi,^{56a,56b} S. Frosali,^{56a,56b} E. Gallo,^{56a} S. Gonzi,^{56a,56b} M. Meschini,^{56a} S. Paoletti,^{56a} G. Sguazzoni,^{56a} A. Tropiano,^{56a,f} L. Benussi,⁵⁷ S. Bianco,⁵⁷ S. Colafranceschi,^{57,y} F. Fabbri,⁵⁷ D. Piccolo,⁵⁷ P. Fabbriatore,⁵⁸ R. Musenich,⁵⁸ A. Benaglia,^{59a,59b,f} F. 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 M. Vergili,¹⁰³ I. V. Akin,¹⁰⁴ T. Aliev,¹⁰⁴ B. Bilin,¹⁰⁴ S. Bilmis,¹⁰⁴ M. Deniz,¹⁰⁴ H. Gamsizkan,¹⁰⁴ A. M. Guler,¹⁰⁴
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 N. Valls,¹⁴⁵ M. Wayne,¹⁴⁵ M. Wolf,¹⁴⁵ B. Bylsma,¹⁴⁶ L. S. Durkin,¹⁴⁶ A. Hart,¹⁴⁶ C. Hill,¹⁴⁶ R. Hughes,¹⁴⁶
 K. Kotov,¹⁴⁶ T. Y. Ling,¹⁴⁶ D. Puigh,¹⁴⁶ M. Rodenburg,¹⁴⁶ C. Vuosalo,¹⁴⁶ G. Williams,¹⁴⁶ B. L. Winer,¹⁴⁶

N. Adam,¹⁴⁷ E. Berry,¹⁴⁷ P. Elmer,¹⁴⁷ D. Gerbaudo,¹⁴⁷ V. Halyo,¹⁴⁷ P. Hebda,¹⁴⁷ J. Hegeman,¹⁴⁷ A. Hunt,¹⁴⁷ P. Jindal,¹⁴⁷ D. Lopes Pegna,¹⁴⁷ P. Lujan,¹⁴⁷ D. Marlow,¹⁴⁷ T. Medvedeva,¹⁴⁷ M. Mooney,¹⁴⁷ J. Olsen,¹⁴⁷ P. Piroué,¹⁴⁷ X. Quan,¹⁴⁷ A. Raval,¹⁴⁷ B. Safdi,¹⁴⁷ H. Saka,¹⁴⁷ D. Stickland,¹⁴⁷ C. Tully,¹⁴⁷ J. S. Werner,¹⁴⁷ A. Zuranski,¹⁴⁷ J. G. Acosta,¹⁴⁸ E. Brownson,¹⁴⁸ X. T. Huang,¹⁴⁸ A. Lopez,¹⁴⁸ H. Mendez,¹⁴⁸ S. Oliveros,¹⁴⁸ J. E. Ramirez Vargas,¹⁴⁸ A. Zatserklyaniy,¹⁴⁸ E. Alagoz,¹⁴⁹ V. E. Barnes,¹⁴⁹ D. Benedetti,¹⁴⁹ G. Bolla,¹⁴⁹ D. Bortoletto,¹⁴⁹ M. De Mattia,¹⁴⁹ A. Everett,¹⁴⁹ Z. Hu,¹⁴⁹ M. Jones,¹⁴⁹ O. Koybasi,¹⁴⁹ M. Kress,¹⁴⁹ A. T. Laasanen,¹⁴⁹ N. Leonardo,¹⁴⁹ V. Maroussov,¹⁴⁹ P. Merkel,¹⁴⁹ D. H. Miller,¹⁴⁹ N. Neumeister,¹⁴⁹ I. Shipsey,¹⁴⁹ D. Silvers,¹⁴⁹ A. Svyatkovskiy,¹⁴⁹ M. Vidal Marono,¹⁴⁹ H. D. Yoo,¹⁴⁹ J. Zablocki,¹⁴⁹ Y. Zheng,¹⁴⁹ S. Guragain,¹⁵⁰ N. Parashar,¹⁵⁰ A. Adair,¹⁵¹ C. Boulahouache,¹⁵¹ K. M. Ecklund,¹⁵¹ F. J. M. Geurts,¹⁵¹ B. P. Padley,¹⁵¹ R. Redjimi,¹⁵¹ J. Roberts,¹⁵¹ J. Zabel,¹⁵¹ B. Betchart,¹⁵² A. Bodek,¹⁵² Y. S. Chung,¹⁵² R. Covarelli,¹⁵² P. de Barbaro,¹⁵² R. Demina,¹⁵² Y. Eshaq,¹⁵² A. Garcia-Bellido,¹⁵² P. Goldenzweig,¹⁵² J. Han,¹⁵² A. Harel,¹⁵² D. C. Miner,¹⁵² D. Vishnevskiy,¹⁵² M. Zielinski,¹⁵² A. Bhatti,¹⁵³ R. Ciesielski,¹⁵³ L. Demortier,¹⁵³ K. Goulianos,¹⁵³ G. Lungu,¹⁵³ S. Malik,¹⁵³ C. Mesropian,¹⁵³ S. Arora,¹⁵⁴ A. Barker,¹⁵⁴ J. P. Chou,¹⁵⁴ C. Contreras-Campana,¹⁵⁴ E. Contreras-Campana,¹⁵⁴ D. Duggan,¹⁵⁴ D. Ferencek,¹⁵⁴ Y. Gershtein,¹⁵⁴ R. Gray,¹⁵⁴ E. Halkiadakis,¹⁵⁴ D. Hidas,¹⁵⁴ A. Lath,¹⁵⁴ S. Panwalkar,¹⁵⁴ M. Park,¹⁵⁴ R. Patel,¹⁵⁴ V. Rekovic,¹⁵⁴ J. Robles,¹⁵⁴ K. Rose,¹⁵⁴ S. Salur,¹⁵⁴ S. Schnetzer,¹⁵⁴ C. Seitz,¹⁵⁴ S. Somalwar,¹⁵⁴ R. Stone,¹⁵⁴ S. Thomas,¹⁵⁴ G. Cerizza,¹⁵⁵ M. Hollingsworth,¹⁵⁵ S. Spanier,¹⁵⁵ Z. C. Yang,¹⁵⁵ A. York,¹⁵⁵ R. Eusebi,¹⁵⁶ W. Flanagan,¹⁵⁶ J. Gilmore,¹⁵⁶ T. Kamon,¹⁵⁶ V. Khotilovich,¹⁵⁶ R. Montalvo,¹⁵⁶ I. Osipenkov,¹⁵⁶ Y. Pakhotin,¹⁵⁶ A. Perloff,¹⁵⁶ J. Roe,¹⁵⁶ A. Safonov,¹⁵⁶ T. Sakuma,¹⁵⁶ S. Sengupta,¹⁵⁶ I. Suarez,¹⁵⁶ A. Tatarinov,¹⁵⁶ D. Toback,¹⁵⁶ N. Akchurin,¹⁵⁷ J. Damgov,¹⁵⁷ P. R. Duerdo,¹⁵⁷ C. Jeong,¹⁵⁷ K. Kovitanggoon,¹⁵⁷ S. W. Lee,¹⁵⁷ T. Libeiro,¹⁵⁷ Y. Roh,¹⁵⁷ I. Volobouev,¹⁵⁷ E. Appelt,¹⁵⁸ C. Florez,¹⁵⁸ S. Greene,¹⁵⁸ A. Gurrola,¹⁵⁸ W. Johns,¹⁵⁸ C. Johnston,¹⁵⁸ P. Kurt,¹⁵⁸ C. Maguire,¹⁵⁸ A. Melo,¹⁵⁸ P. Sheldon,¹⁵⁸ B. Snook,¹⁵⁸ S. Tuo,¹⁵⁸ J. Velkovska,¹⁵⁸ M. W. Arenton,¹⁵⁹ M. Balazs,¹⁵⁹ S. Boutle,¹⁵⁹ B. Cox,¹⁵⁹ B. Francis,¹⁵⁹ J. Goodell,¹⁵⁹ R. Hirsosky,¹⁵⁹ A. Ledovskoy,¹⁵⁹ C. Lin,¹⁵⁹ C. Neu,¹⁵⁹ J. Wood,¹⁵⁹ R. Yohay,¹⁵⁹ S. Gollapinni,¹⁶⁰ R. Harr,¹⁶⁰ P. E. Karchin,¹⁶⁰ C. Kottachchi Kankanamge Don,¹⁶⁰ P. Lamichhane,¹⁶⁰ A. Sakharov,¹⁶⁰ M. Anderson,¹⁶¹ M. Bachtis,¹⁶¹ D. Belknap,¹⁶¹ L. Borrello,¹⁶¹ D. Carlsmith,¹⁶¹ M. Cepeda,¹⁶¹ S. Dasu,¹⁶¹ L. Gray,¹⁶¹ K. S. Grogg,¹⁶¹ M. Grothe,¹⁶¹ R. Hall-Wilton,¹⁶¹ M. Herndon,¹⁶¹ A. Hervé,¹⁶¹ P. Klabbers,¹⁶¹ J. Klukas,¹⁶¹ A. Lanaro,¹⁶¹ C. Lazaridis,¹⁶¹ J. Leonard,¹⁶¹ R. Loveless,¹⁶¹ A. Mohapatra,¹⁶¹ I. Ojalvo,¹⁶¹ F. Palmonari,¹⁶¹ G. A. Pierro,¹⁶¹ I. Ross,¹⁶¹ A. Savin,¹⁶¹ W. H. Smith,¹⁶¹ and J. Swanson¹⁶¹

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*²*Institut für Hochenergiephysik der OeAW, Wien, Austria*³*National Centre for Particle and High Energy Physics, Minsk, Belarus*⁴*Universiteit Antwerpen, Antwerpen, Belgium*⁵*Vrije Universiteit Brussel, Brussel, Belgium*⁶*Université Libre de Bruxelles, Bruxelles, Belgium*⁷*Ghent University, Ghent, Belgium*⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*⁹*Université de Mons, Mons, Belgium*¹⁰*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*¹¹*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*¹²*Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil*¹³*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*¹⁴*University of Sofia, Sofia, Bulgaria*¹⁵*Institute of High Energy Physics, Beijing, China*¹⁶*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*¹⁷*Universidad de Los Andes, Bogota, Colombia*¹⁸*Technical University of Split, Split, Croatia*¹⁹*University of Split, Split, Croatia*²⁰*Institute Rudjer Boskovic, Zagreb, Croatia*²¹*University of Cyprus, Nicosia, Cyprus*²²*Charles University, Prague, Czech Republic*²³*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

- ²⁴*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ²⁵*Department of Physics, University of Helsinki, Helsinki, Finland*
- ²⁶*Helsinki Institute of Physics, Helsinki, Finland*
- ²⁷*Lappeenranta University of Technology, Lappeenranta, Finland*
- ²⁸*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
- ²⁹*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
- ³⁰*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
- ³¹*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- ³²*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
- ³³*E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia*
- ³⁴*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ³⁵*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- 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 Physics "Demokritos," Aghia Paraskevi, Greece*
- ⁴¹*University of Athens, Athens, Greece*
- ⁴²*University of Ioánnina, Ioánnina, Greece*
- ⁴³*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
- ⁴⁴*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁴⁵*University of Debrecen, Debrecen, Hungary*
- ⁴⁶*Panjab University, Chandigarh, India*
- ⁴⁷*University of Delhi, Delhi, India*
- ⁴⁸*Saha Institute of Nuclear Physics, Kolkata, India*
- ⁴⁹*Bhabha Atomic Research Centre, Mumbai, India*
- ⁵⁰*Tata Institute of Fundamental Research-EHEP, Mumbai, India*
- ⁵¹*Tata Institute of Fundamental Research-HECR, Mumbai, India*
- ⁵²*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ^{53a}*INFN Sezione di Bari, Bari, Italy*
- ^{53b}*Università di Bari, Bari, Italy*
- ^{53c}*Politecnico di Bari, Bari, Italy*
- ^{54a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{54b}*Università di Bologna, Bologna, Italy*
- ^{55a}*INFN Sezione di Catania, Catania, Italy*
- ^{55b}*Università di Catania, Catania, Italy*
- ^{56a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{56b}*Università di Firenze, Firenze, Italy*
- ⁵⁷*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵⁸*INFN Sezione di Genova, Genova, Italy*
- ^{59a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{59b}*Università di Milano-Bicocca, Milano, Italy*
- ^{60a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{60b}*Università di Napoli "Federico II," Napoli, Italy*
- ^{61a}*INFN Sezione di Padova, Padova, Italy*
- ^{61b}*Università di Padova, Padova, Italy*
- ^{61c}*Università di Trento (Trento), Padova, Italy*
- ^{62a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{62b}*Università di Pavia, Pavia, Italy*
- ^{63a}*INFN Sezione di Perugia, Perugia, Italy*
- ^{63b}*Università di Perugia, Perugia, Italy*
- ^{64a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{64b}*Università di Pisa, Pisa, Italy*
- ^{64c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{65a}*INFN Sezione di Roma, Roma, Italy*
- ^{65b}*Università di Roma "La Sapienza," Roma, Italy*
- ^{66a}*INFN Sezione di Torino, Torino, Italy*
- ^{66b}*Università di Torino, Torino, Italy*
- ^{66c}*Università del Piemonte Orientale (Novara), Torino, Italy*
- ^{67a}*INFN Sezione di Trieste, Trieste, Italy*

- ^{67b}*Università di Trieste, Trieste, Italy*
- ⁶⁸*Kangwon National University, Chunchon, Korea*
- ⁶⁹*Kyungpook National University, Daegu, Korea*
- ⁷⁰*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁷¹*Korea University, Seoul, Korea*
- ⁷²*University of Seoul, Seoul, Korea*
- ⁷³*Sungkyunkwan University, Suwon, Korea*
- ⁷⁴*Vilnius University, Vilnius, Lithuania*
- ⁷⁵*Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ⁷⁶*Universidad Iberoamericana, Mexico City, Mexico*
- ⁷⁷*Benemerita Universidad Autónoma de Puebla, Puebla, Mexico*
- ⁷⁸*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
- ⁷⁹*University of Auckland, Auckland, New Zealand*
- ⁸⁰*University of Canterbury, Christchurch, New Zealand*
- ⁸¹*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ⁸²*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ⁸³*Soltan Institute for Nuclear Studies, Warsaw, Poland*
- ⁸⁴*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ⁸⁵*Joint Institute for Nuclear Research, Dubna, Russia*
- ⁸⁶*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
- ⁸⁷*Institute for Nuclear Research, Moscow, Russia*
- ⁸⁸*Institute for Theoretical and Experimental Physics, Moscow, Russia*
- ⁸⁹*Moscow State University, Moscow, Russia*
- ⁹⁰*P.N. Lebedev Physical Institute, Moscow, Russia*
- ⁹¹*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
- ⁹²*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
- ⁹³*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ⁹⁴*Universidad Autónoma de Madrid, Madrid, Spain*
- ⁹⁵*Universidad de Oviedo, Oviedo, Spain*
- ⁹⁶*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ⁹⁷*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ⁹⁸*Paul Scherrer Institut, Villigen, Switzerland*
- ⁹⁹*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
- ¹⁰⁰*Universität Zürich, Zurich, Switzerland*
- ¹⁰¹*National Central University, Chung-Li, Taiwan*
- ¹⁰²*National Taiwan University (NTU), Taipei, Taiwan*
- ¹⁰³*Cukurova University, Adana, Turkey*
- ¹⁰⁴*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹⁰⁵*Bogazici University, Istanbul, Turkey*
- ¹⁰⁶*Istanbul Technical University, Istanbul, Turkey*
- ¹⁰⁷*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- ¹⁰⁸*University of Bristol, Bristol, United Kingdom*
- ¹⁰⁹*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹¹⁰*Imperial College, London, United Kingdom*
- ¹¹¹*Brunel University, Uxbridge, United Kingdom*
- ¹¹²*Baylor University, Waco, Texas, USA*
- ¹¹³*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹¹⁴*Boston University, Boston, Massachusetts, USA*
- ¹¹⁵*Brown University, Providence, Rhode Island, USA*
- ¹¹⁶*University of California, Davis, Davis, California, USA*
- ¹¹⁷*University of California, Los Angeles, Los Angeles, California, USA*
- ¹¹⁸*University of California, Riverside, Riverside, California, USA*
- ¹¹⁹*University of California, San Diego, La Jolla, California, USA*
- ¹²⁰*University of California, Santa Barbara, Santa Barbara, California, USA*
- ¹²¹*California Institute of Technology, Pasadena, California, USA*
- ¹²²*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹²³*University of Colorado at Boulder, Boulder, Colorado, USA*
- ¹²⁴*Cornell University, Ithaca, New York, USA*
- ¹²⁵*Fairfield University, Fairfield, Connecticut, USA*
- ¹²⁶*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹²⁷*University of Florida, Gainesville, Florida, USA*

- ¹²⁸Florida International University, Miami, Florida, USA
¹²⁹Florida State University, Tallahassee, Florida, USA
¹³⁰Florida Institute of Technology, Melbourne, Florida, USA
¹³¹University of Illinois at Chicago (UIC), Chicago, Illinois, USA
¹³²The University of Iowa, Iowa City, Iowa, USA
¹³³Johns Hopkins University, Baltimore, Maryland, USA
¹³⁴The University of Kansas, Lawrence, Kansas, USA
¹³⁵Kansas State University, Manhattan, Kansas, USA
¹³⁶Lawrence Livermore National Laboratory, Livermore, California, USA
¹³⁷University of Maryland, College Park, Maryland, USA
¹³⁸Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹³⁹University of Minnesota, Minneapolis, Minnesota, USA
¹⁴⁰University of Mississippi, University, Mississippi, USA
¹⁴¹University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁴²State University of New York at Buffalo, Buffalo, New York, USA
¹⁴³Northeastern University, Boston, Massachusetts, USA
¹⁴⁴Northwestern University, Evanston, Illinois, USA
¹⁴⁵University of Notre Dame, Notre Dame, Indiana, USA
¹⁴⁶The Ohio State University, Columbus, Ohio, USA
¹⁴⁷Princeton University, Princeton, New Jersey, USA
¹⁴⁸University of Puerto Rico, Mayaguez, USA
¹⁴⁹Purdue University, West Lafayette, Indiana, USA
¹⁵⁰Purdue University Calumet, Hammond, Indiana, USA
¹⁵¹Rice University, Houston, Texas, USA
¹⁵²University of Rochester, Rochester, New York, USA
¹⁵³The Rockefeller University, New York, New York, USA
¹⁵⁴Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA
¹⁵⁵University of Tennessee, Knoxville, Tennessee, USA
¹⁵⁶Texas A&M University, College Station, Texas, USA
¹⁵⁷Texas Tech University, Lubbock, Texas, USA
¹⁵⁸Vanderbilt University, Nashville, Tennessee, USA
¹⁵⁹University of Virginia, Charlottesville, Virginia, USA
¹⁶⁰Wayne State University, Detroit, Michigan, USA
¹⁶¹University of Wisconsin, Madison, Wisconsin, USA

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

^cAlso at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

^dAlso at Universidade Federal do ABC, Santo Andre, Brazil.

^eAlso at California Institute of Technology, Pasadena, CA, USA.

^fAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

^gAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

^hAlso at Suez Canal University, Suez, Egypt.

ⁱAlso at Zewail City of Science and Technology, Zewail, Egypt.

^jAlso at Cairo University, Cairo, Egypt.

^kAlso at Fayoum University, El-Fayoum, Egypt.

^lAlso at British University, Cairo, Egypt.

^mNow at Ain Shams University, Cairo, Egypt.

ⁿAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.

^oAlso at Université de Haute-Alsace, Mulhouse, France.

^pAlso at Moscow State University, Moscow, Russia.

^qAlso at Brandenburg University of Technology, Cottbus, Germany.

^rAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

^sAlso at Eötvös Loránd University, Budapest, Hungary.

^tAlso at Tata Institute of Fundamental Research-HECR, Mumbai, India.

^uAlso at University of Visva-Bharati, Santiniketan, India.

^vAlso at Sharif University of Technology, Tehran, Iran.

^wAlso at Isfahan University of Technology, Isfahan, Iran.

- ^xAlso at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
- ^yAlso at Facoltà Ingegneria Università di Roma, Roma, Italy.
- ^zAlso at Università della Basilicata, Potenza, Italy.
- ^{aa}Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ^{bb}Also at Università degli studi di Siena, Siena, Italy.
- ^{cc}Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
- ^{dd}Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
- ^{ee}Also at University of Florida, Gainesville, FL, USA.
- ^{ff}Also at University of California, Los Angeles, Los Angeles, CA, USA.
- ^{gg}Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.
- ^{hh}Also at INFN Sezione di Roma, Università di Roma "La Sapienza," Roma, Italy.
- ⁱⁱAlso at University of Athens, Athens, Greece.
- ^{jj}Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^{kk}Also at The University of Kansas, Lawrence, KS, USA.
- ^{ll}Also at Paul Scherrer Institut, Villigen, Switzerland.
- ^{mm}Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁿⁿAlso at Gaziosmanpasa University, Tokat, Turkey.
- ^{oo}Also at Adiyaman University, Adiyaman, Turkey.
- ^{pp}Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{qq}Also at The University of Iowa, Iowa City, IA, USA.
- ^{rr}Also at Mersin University, Mersin, Turkey.
- ^{ss}Also at Ozyegin University, Istanbul, Turkey.
- ^{tt}Also at Kafkas University, Kars, Turkey.
- ^{uu}Also at Suleyman Demirel University, Isparta, Turkey.
- ^{vv}Also at Ege University, Izmir, Turkey.
- ^{ww}Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{xx}Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
- ^{yy}Also at University of Sydney, Sydney, Australia.
- ^{zz}Also at Utah Valley University, Orem, UT, USA.
- ^{aaa}Also at Institute for Nuclear Research, Moscow, Russia.
- ^{bbb}Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{ccc}Also at Argonne National Laboratory, Argonne, IL, USA.
- ^{ddd}Also at Erzincan University, Erzincan, Turkey.
- ^{eee}Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ^{fff}Also at Kyungpook National University, Daegu, Korea.