Search for Supersymmetry in pp Collisions at root s=7 TeV in Events with Two Photons and Missing Transverse Energy

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Search for Supersymmetry in pp Collisions at $\sqrt{s} = 7$ TeV in Events with Two Photons and Missing Transverse Energy

S. Chatrchyan *et al.*[*]
(CMS Collaboration)

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A search for supersymmetry in the context of general gauge-mediated breaking with the lightest neutralino as the next-to-lightest supersymmetric particle and the gravitino as the lightest is presented. The data sample corresponds to an integrated luminosity of 36 pb^{-1} recorded by the CMS experiment at the LHC. The search is performed by using events containing two or more isolated photons, at least one hadronic jet, and significant missing transverse energy. No excess of events at high missing transverse energy is observed. Upper limits on the signal cross section for general gauge-mediated supersymmetry between 0.3 and 1.1 pb at the 95% confidence level are determined for a range of squark, gluino, and neutralino masses, excluding supersymmetry parameter space that was inaccessible to previous experiments.

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Supersymmetry (SUSY), in particular the version based on gauge-mediated breaking [1–7], is of particular theoretical interest for physics beyond the standard model (SM). Supersymmetry stabilizes the mass of the SM Higgs boson, drives the grand unification of forces, and incorporates dark matter candidates within its framework. Previous searches for SUSY with gauge-mediated breaking [8–14] were performed by using a minimal model [15] as a benchmark. In that model, in order to reduce the number of free parameters, several assumptions, including gaugino mass unification, are made. These assumptions lead to a mass hierarchy in which strongly interacting SUSY partners are much heavier than the lightest chargino and neutralino. For example, the current best lower limit on the neutralino mass [9] of 175 GeV corresponds to gluino and squark mass limits of well above 1 TeV. In the more general case, the masses of strongly interacting SUSY partners can be much lighter, leading to large production cross sections at the LHC and allowing, even at low integrated luminosity, for the exploration of parameter space inaccessible at previous colliders.

In this Letter, we consider a general gauge-mediation (GGM) SUSY scenario [16,17], with the gravitino as the lightest SUSY particle and the lightest neutralino as the next-to-lightest (NLSP). In the following, it is assumed that the neutralino decays promptly to a gravitino and a photon. Cases with either a large neutralino lifetime or a large branching fraction into a Z and a gravitino are not considered in this Letter. The gravitino escapes detection, leading to missing transverse energy (E_T^{miss}). If R parity [18] is conserved, strongly interacting SUSY particles are pair-produced. Their decay chain includes one or several quarks or gluons and a neutralino, which in turn decays to a photon and a gravitino. The topology of interest for this search is, therefore, two or more isolated photons with large transverse energy (E_T), at least one hadronic jet, and large missing transverse energy E_T^{miss}.

A detailed description of the CMS detector can be found elsewhere [19]. The detector's central feature is a superconducting solenoid providing a 3.8 T axial magnetic field along the beam direction. Charged particle trajectories are measured by a silicon pixel and strip tracker system, covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity $\eta = -\ln \tan\theta/2$, and θ is the polar angle with respect to the counterclockwise beam direction. A lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracker volume. For the barrel calorimeter ($|\eta| < 1.479$), the modules are arranged in projective towers. Muons are measured in gas detectors embedded in the steel return yoke of the magnet. The detector is nearly hermetic, allowing for reliable measurement of E_T^{miss}. In the 2010 collision data, photons with energy greater than 20 GeV are measured within the barrel ECAL with a resolution of better than 1%, which is dominated by intercalibration precision.

The data used in this analysis, corresponding to an integrated luminosity of 36 pb^{-1}, were recorded during the 2010 run at a center-of-mass energy ($\sqrt{s}$) of 7 TeV at the Large Hadron Collider (LHC) at CERN. A two-level trigger system was used, based on the presence of at least one photon with a minimum transverse energy of 30 GeV. This data sample is used for the selection of both signal candidates and control samples used for background estimation. The efficiency for off-line

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

selected events to pass the trigger is estimated to be above 99%.

The photon candidates are reconstructed from clusters of energy in the ECAL. Candidates are required to have $E_T \geq 30$ GeV and $|\eta| \leq 1.4$. The ECAL cluster shape is required to be consistent with that expected from a photon, and the energy detected in the HCAL behind the photon shower is required not to exceed 5% of the ECAL energy. To suppress photons originating from quark or gluon hadronization, the photons are required to be isolated from other activity in the tracker, ECAL, and HCAL. The scalar sums of transverse energies of tracks and calorimeter deposits within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ of the candidate's direction are determined, after excluding the contribution from the candidate itself. These isolation sums are required to be $\leq 0.001 \times E_T + 2.0$ GeV, $0.006 \times E_T + 4.2$ GeV, and $0.0025 \times E_T + 2.2$ GeV, with E_T in GeV, for the tracker, ECAL, and HCAL, respectively.

Photons that fail either the shower shape or track isolation requirement are referred to as *fake photons*. Most of these fake photons are quarks or gluons that have hadronized predominantly to π^0's decaying into photons. They are used for the background estimation derived from the data.

The criteria above are efficient for selection of both electrons and photons. To separate them reliably, we search for hit patterns in the pixel detector consistent with a track from an electron (pixel match). The candidates with (without) pixel match are considered to be electrons (photons) [20]. Events in the signal sample (referred to below as the $\gamma\gamma$ sample) are required to have at least two photon candidates.

Jets are reconstructed from energy deposits in the calorimeters by using the anti-k_T clustering algorithm [21] with a size parameter of 0.5. The jet energy is corrected by using reconstructed tracks [22]. Selected jets must have $E_T \geq 30$ GeV and $|\eta| \leq 2.6$. In addition, to separate real jets from anomalous HCAL signals, the fraction of energy contributed to the jet shower by the highest energy HCAL channels must be $\leq 98\%$, the jet must have no single HCAL channel containing more than 90% of its total energy, and finally the ECAL energy fraction of the jet must be $\geq 1\%$. To be retained in the signal sample, events must contain at least one such jet isolated from both of the two highest-E_T photon candidates by $\Delta R \geq 0.9$.

The E_T^{miss} is determined by using calorimeter energy deposits. Corrections are applied by replacing calorimeter tower energies matched to charged hadrons and muons with their corresponding charged-track momenta [23].

Events are generated in the benchmark SUSY model [24] using PYTHIA 6.4 [25] in a three-dimensional grid of the NLSP, gluino, and squark masses. The soft masses of the squarks are taken to be degenerate. Sleptons and all other gauginos except the NLSP are assigned a mass of 1.5 TeV. The QCD production cross section at next-to-leading order is calculated for these points by using PROSPINO 2.1 [26] and is dominated by gluino-gluino, gluino-squark, and squark-squark production. The generated events are passed through the CMS detector simulation program, which is based on the GEANT4 [27] package, and reconstructed by using the same program as for the collision data to ensure that all features of the data, such as trigger and reconstruction, are applied to the Monte Carlo (MC) simulated SUSY signal sample.

The SUSY signal can be mimicked in several ways. Irreducible backgrounds from SM processes such as $Z(\to \nu\bar{\nu})\gamma\gamma$ and $W(\to \ell\nu)\gamma\gamma$ are negligible. The main backgrounds arise from SM processes with misidentified photons and/or mismeasured E_T^{miss}. The dominant contribution comes from mismeasurement of E_T^{miss} in QCD processes such as direct diphoton, photon plus jets, and multijet production, with jets mimicking photons in the latter two cases. This background is referred to as the *QCD background*. The strategy for determining this background is to use control samples that are kinematically similar to the candidate sample and that can be reasonably assumed to have no significant genuine E_T^{miss}. Two such samples are used. The first is a sample containing two fake photons, referred to as the ff sample below, comprising QCD multijet events. The second (ee) sample contains events with two electrons [28] with invariant mass between 70 and 110 GeV and is dominated by $Z \to ee$ decays.

The E_T resolution for electrons and fake photons is similar to the resolution for photons and is much better than the resolution for hadronic energy, so the E_T^{miss} resolution is dominated by the latter. The events in both control samples are reweighted to reproduce the diphoton transverse energy distribution in the candidate $\gamma\gamma$ sample and, therefore, the transverse energy of the hadronic recoil against the diphoton system; the reweighting factors range from 0.3 to 1.7. The shapes of the E_T^{miss} distributions obtained from both control samples are identical within the statistical and systematic uncertainties and are used to predict the E_T^{miss} background by normalizing to the number of events with $E_T^{\text{miss}} < 20$ GeV in the candidate sample.

The second background comes from events with real E_T^{miss}. It is dominated by events with a genuine or fake photon and a W that decays into a neutrino and an electron, with the latter misidentified as a photon. This background is referred to as the *electroweak background*. An electron is misidentified as a photon if it satisfies all the photon selection criteria but has no matching hit pattern in the pixel detector. To model this background, an $e\gamma$ candidate sample is defined, selected the same way as the $\gamma\gamma$ sample but requiring at least one electron and at least one photon instead of at least two photons. This sample is thus enriched with $W\gamma$ and W plus jets events (with real E_T^{miss}) similar to those in the candidate $\gamma\gamma$ sample. The probability $f_{e\to\gamma}$ to misidentify an electron as a photon is measured with $Z \to ee$ events to be $(1.4 \pm 0.4)\%$. The $e\gamma$ sample is

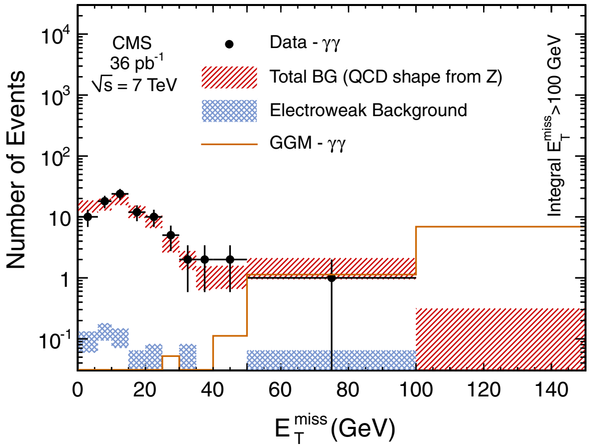

FIG. 1 (color online). E_T^{miss} distribution for $\gamma\gamma$ data, including the jet requirement, compared with backgrounds and a possible GGM SUSY signal. The solid circles with error bars represent the data. The double-hatched blue band represents the contribution of the electroweak background. The single-hatched red band shows the sum of the electroweak background with the QCD E_T^{miss} prediction obtained from the $Z \rightarrow ee$ sample. The widths of the bands correspond to the sum of the statistical and systematic uncertainties on the backgrounds. The prediction of the GGM SUSY sample point described in the text is shown in the plot as the solid line histogram.

then weighted by $f_{e\rightarrow\gamma}/(1 - f_{e\rightarrow\gamma})$ in order to estimate the contribution of this background to the signal sample.

Finally, high-energy muons from cosmic rays or beam halo can deposit a large amount of energy in the ECAL, leading to events with two photon candidates and E_T^{miss}. These events are suppressed to a negligible level by the jet requirement described above.

The E_T^{miss} distribution in the $\gamma\gamma$ sample is shown in Fig. 1, together with the estimates of the electroweak background and the total background using the QCD prediction from $Z \rightarrow ee$ and their uncertainties. Events with $E_T^{\mathrm{miss}} \leq 20$ GeV have negligible SUSY signal contribution (0.022 ± 0.009 event for the GGM SUSY sample point described below). The E_T^{miss} distributions for the ff and ee samples are then scaled so that their integrals below 20 GeV match that of the $\gamma\gamma$ sample minus the estimated electroweak contribution. Their integrals above 50 GeV give predictions of the QCD background.

Table I summarizes the number of $\gamma\gamma$ events observed and the numbers of background events expected with $E_T^{\mathrm{miss}} \geq 50$ GeV. The statistical and systematic uncertainties on the background predictions due to reweighting and normalization are shown separately. One event is observed, while the total background is expected to be 0.53 ± 0.37 (1.71 ± 0.64) events by using the ff (ee) samples and including the electroweak background. These two consistent estimates are averaged, by using log-normal distributions as probability density functions while taking into account the common component from the electroweak background and the correlated uncertainty due to the normalization, to obtain a prediction of 1.2 ± 0.4 background events. An additional conservative systematic uncertainty of 0.7 events is assigned by taking the largest difference between the average and the individual measurements, resulting in a total background uncertainty of 0.8 events.

The efficiency for SUSY events to satisfy the selection criteria is determined by applying correction factors derived from the data to the MC simulation of the signal. Since there exists no large clean sample of isolated photons in the data, we rely on similarities between the detector response to electrons and photons to extract the photon efficiency. The difference between the efficiencies for electrons and photons according to the MC simulation is 0.5%. The ratio of the electron efficiency from $Z \rightarrow ee$ events that pass all photon identification criteria (except for the pixel match) to the corresponding electron MC efficiencies gives an MC efficiency scale factor of 0.967 ± 0.015. This scale factor is applied to the efficiency to identify a photon from NLSP decay obtained with the MC simulation. The error on the scale factor also includes possible systematic effects from multiple interactions per bunch crossing (pileup), estimated to be less than 1%. The additional uncertainty on the efficiency of the requirement for no pixel match for a photon is estimated by varying the

TABLE I. The number of events with $E_T^{\mathrm{miss}} \geq 50$ GeV from the $\gamma\gamma$ event sample as well as the predicted number of background events with $E_T^{\mathrm{miss}} \geq 50$ GeV using either the fake-fake events or the $Z \rightarrow ee$ data.

Type	Number of events	Stat error	Reweight error	Normalization error
$\gamma\gamma$ events	1			
Electroweak background estimate	0.04 ± 0.03	± 0.02	± 0.0	± 0.01
QCD background estimate (ff)	0.49 ± 0.37	± 0.36	± 0.06	± 0.07
QCD background estimate (ee)	1.67 ± 0.64	± 0.46	± 0.38	± 0.23
Total background (using ff)	0.53 ± 0.37			
Total background (using ee)	1.71 ± 0.64			
Combined total background	1.2 ± 0.8			
Expected from GGM sample point	8.0 ± 1.7			

amount of tracker material in the detector simulation and is found to be equal to 0.5%. Other sources of systematic uncertainties in signal yield include the uncertainty on the integrated luminosity (11%) [29], parton distribution function uncertainty (10%–40%), and renormalization scale uncertainty (10%–20%), depending on the SUSY masses.

As a cross-check of the analysis method, in particular the determination of the QCD background contribution, the procedure is applied to a data sample selected in the same way as the $e\gamma$ sample described above, except that there is no requirement on the number of jets. The check consists of estimating the QCD background, events with no true $E_T^{\rm miss}$, in a sample populated with both QCD and events from the two dominant SM processes, $W\gamma$ and W plus jets, which have true $E_T^{\rm miss}$. An excess in the observed number of events with large $E_T^{\rm miss}$ over the estimated QCD background should be consistent with the yield from the W processes. The $E_T^{\rm miss}$ spectrum of the $e\gamma$ events is shown in Fig. 2 and exhibits a clear deviation from the predicted QCD background alone but agrees well with the sum of the QCD and W backgrounds.

This measurement and the estimated acceptance times efficiency are used to set upper limits on the gluino and squark production cross sections, employing a Bayesian method described in Ref. [30]. Both the log-normal and gamma priors are used to integrate over nuisance parameters in order to incorporate uncertainties on the total background rate, integrated luminosity, and total acceptance times efficiency. The observed 95% confidence level (C.L.) cross section limits, shown in Fig. 3, vary between 0.3 and 1.1 pb for a neutralino mass of 150 GeV as a function of squark and gluino masses. The variation in the limits is due to the dependence of the photon isolation efficiency on the number of jets in the event.

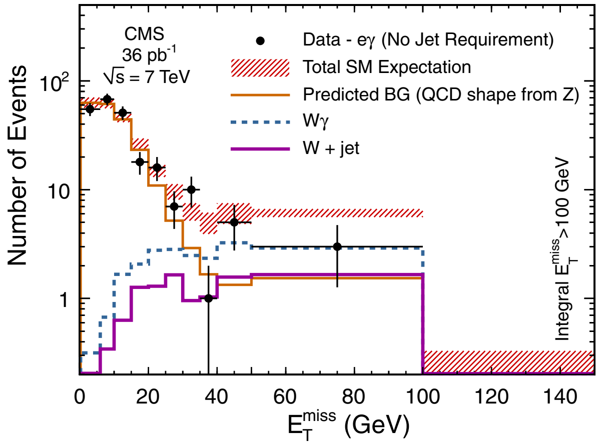

FIG. 2 (color online). The $E_T^{\rm miss}$ distribution of the $e\gamma$ candidates (solid circles with error bars) is compared to the QCD expectation for this spectrum from $Z \to ee$ events (solid histogram). The $W\gamma$ and W plus jet (with the jet misidentified as a photon) contributions are shown as dashed and dash-dotted histograms, respectively. The hatched red band represents the sum of all expected background components, and its width corresponds to the sum of the statistical and systematic uncertainties on the backgrounds.

To illustrate the limit-setting procedure, a particular signal point, with a squark mass of 720 GeV, gluino mass of 720 GeV, and neutralino mass of 150 GeV, is considered. The next-to-leading order signal cross section for this point is 1.04 pb, the efficiency times acceptance is $0.203 \pm 0.004({\rm stat}) \pm 0.008({\rm syst})$, and the parton distribution function and scale uncertainties are each 13%. The upper limit obtained from this measurement is 0.585 pb, while the expected cross section upper limit at the 95% C.L. is 0.628 pb. The expected number of events for this SUSY sample point for an integrated luminosity of 36 pb^{-1} is 8.0 ± 1.7 events. For comparison, the total next-to-leading order SUSY production cross section at the Tevatron for the same model point is 0.3 fb, leading to an expectation of less than half of an event for analysis [9].

The benchmark GGM model used in this Letter can be used to interpret these cross section limits as lower limits on squark and gluino masses. For each mass point we compare the predicted cross section with the measured upper limit and claim exclusion if the former is greater than the latter. The exclusion contours for three different choices of neutralino mass are shown in Fig. 4, together with the expected exclusion limit for a 150 GeV neutralino mass. The predicted cross section has uncertainties due to the choice of parton distribution function and scale. We varied the predicted cross section by 1 standard deviation of its uncertainty to ascertain the impact on the exclusion region. The results for 150 GeV neutralino mass are presented as a shaded band around the central value of the exclusion contour.

In summary, a search for evidence of GGM SUSY production in events that contain two or more high transverse energy isolated photons, one or more jets, and large

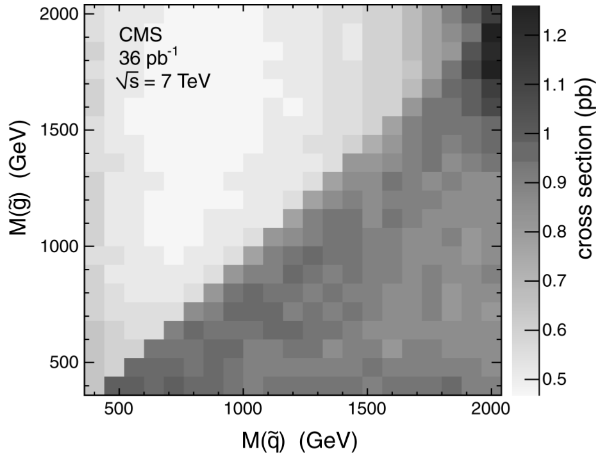

FIG. 3. 95% C.L. upper limits for GGM production cross section as a function of squark ($\tilde{q}$) and gluino ($\tilde{g}$) masses for a neutralino mass of 150 GeV.

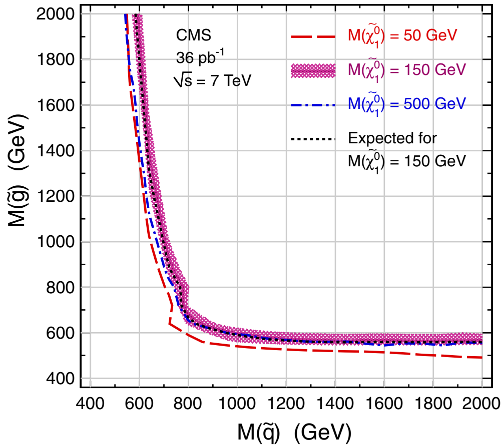

FIG. 4 (color online). Lower 95% C.L. exclusion limits on the squark ($\tilde{q}$) and gluino ($\tilde{g}$) masses in the GGM benchmark model for 50, 150, and 500 GeV neutralino ($\tilde{\chi}^0_1$) masses. The areas below and to the left of the lines are excluded. The expected exclusion limit for 150 GeV neutralino mass is shown by the dashed line. The shaded band represents ±1 standard deviation of theoretical uncertainty on the GGM cross section.

$E_T^{\rm miss}$ is presented. No such evidence is observed, leading to upper limits on the GGM SUSY cross section between 0.3 and 1.1 pb at the 95% C.L. across the parameter space of a benchmark model, setting the world's best direct lower limits on squark and gluino masses.

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S. Sumowidagdo,[116] R. Wilken,[116] S. Wimpenny,[116] W. Andrews,[117] J. G. Branson,[117] G. B. Cerati,[117] E. Dusinberre,[117] D. Evans,[117] F. Golf,[117] A. Holzner,[117] R. Kelley,[117] M. Lebourgeois,[117] J. Letts,[117] B. Mangano,[117] S. Padhi,[117] C. Palmer,[117] G. Petrucciani,[117] H. Pi,[117] M. Pieri,[117] R. Ranieri,[117] M. Sani,[117] V. Sharma,[117] S. Simon,[117] Y. Tu,[117] A. Vartak,[117] S. Wasserbaech,[117,ss] F. Würthwein,[117] A. Yagil,[117] J. Yoo,[117] D. Barge,[118] R. Bellan,[118] C. Campagnari,[118] M. D'Alfonso,[118] T. Danielson,[118] K. Flowers,[118] P. Geffert,[118] J. Incandela,[118] C. Justus,[118] P. Kalavase,[118] S. A. Koay,[118] D. Kovalskyi,[118] V. Krutelyov,[118] S. Lowette,[118] N. Mccoll,[118] V. Pavlunin,[118] F. Rebassoo,[118] J. Ribnik,[118] J. Richman,[118] R. Rossin,[118] D. Stuart,[118] W. To,[118] J. R. Vlimant,[118] A. Apresyan,[119] A. Bornheim,[119] J. Bunn,[119] Y. Chen,[119] M. Gataullin,[119] Y. Ma,[119] A. Mott,[119] H. B. Newman,[119] C. Rogan,[119] K. Shin,[119] V. Timciuc,[119] P. Traczyk,[119] J. Veverka,[119] R. Wilkinson,[119] Y. Yang,[119] R. Y. Zhu,[119] B. Akgun,[120] R. Carroll,[120] T. Ferguson,[120] Y. Iiyama,[120] D. W. Jang,[120] S. Y. Jun,[120] Y. F. Liu,[120] M. Paulini,[120] J. Russ,[120] H. Vogel,[120] I. Vorobiev,[120] J. P. Cumalat,[121] M. E. Dinardo,[121] B. R. Drell,[121] C. J. Edelmaier,[121] W. T. Ford,[121] A. Gaz,[121] B. Heyburn,[121] E. Luiggi Lopez,[121] U. Nauenberg,[121] J. G. Smith,[121] K. Stenson,[121] K. A. Ulmer,[121] S. R. Wagner,[121] S. L. Zang,[121] L. Agostino,[122] J. Alexander,[122] D. Cassel,[122] A. Chatterjee,[122] S. Das,[122] N. Eggert,[122] L. K. Gibbons,[122] B. Heltsley,[122] W. Hopkins,[122] A. Khukhunaishvili,[122] B. Kreis,[122] G. Nicolas Kaufman,[122] J. R. Patterson,[122] D. Puigh,[122] A. Ryd,[122] E. Salvati,[122] X. Shi,[122] W. Sun,[122] W. D. Teo,[122] J. Thom,[122] J. Thompson,[122] J. Vaughan,[122] Y. Weng,[122] L. Winstrom,[122] P. Wittich,[122] A. Biselli,[123] G. Cirino,[123] D. Winn,[123] S. Abdullin,[124] M. Albrow,[124] J. Anderson,[124] G. Apollinari,[124] M. Atac,[124] J. A. Bakken,[124] S. Banerjee,[124] L. A. T. Bauerdick,[124] A. Beretvas,[124] J. Berryhill,[124] P. C. Bhat,[124] I. Bloch,[124] F. Borcherding,[124] K. Burkett,[124] J. N. Butler,[124] V. Chetluru,[124] H. W. K. Cheung,[124] F. Chlebana,[124] S. Cihangir,[124] W. Cooper,[124] D. P. Eartly,[124] V. D. Elvira,[124] S. Esen,[124] I. Fisk,[124] J. Freeman,[124] Y. Gao,[124] E. Gottschalk,[124] D. Green,[124] K. Gunthoti,[124] O. Gutsche,[124] J. Hanlon,[124] R. M. Harris,[124] J. Hirschauer,[124] B. Hooberman,[124] H. Jensen,[124] M. Johnson,[124] U. Joshi,[124] R. Khatiwada,[124] B. Klima,[124] K. Kousouris,[124] S. Kunori,[124] S. Kwan,[124] C. Leonidopoulos,[124] P. Limon,[124] D. Lincoln,[124] R. Lipton,[124] J. Lykken,[124] K. Maeshima,[124] J. M. Marraffino,[124] D. Mason,[124] P. McBride,[124] T. Miao,[124] K. Mishra,[124] S. Mrenna,[124] Y. Musienko,[124,tt] C. Newman-Holmes,[124] V. O'Dell,[124] R. Pordes,[124] O. Prokofyev,[124] N. Saoulidou,[124] E. Sexton-Kennedy,[124] S. Sharma,[124] W. J. Spalding,[124] L. Spiegel,[124] P. Tan,[124] L. Taylor,[124] S. Tkaczyk,[124] L. Uplegger,[124] E. W. Vaandering,[124] R. Vidal,[124] J. Whitmore,[124] W. Wu,[124] F. Yang,[124] F. Yumiceva,[124] J. C. Yun,[124] D. Acosta,[125] P. Avery,[125] D. Bourilkov,[125] M. Chen,[125] M. De Gruttola,[125] G. P. Di Giovanni,[125] D. Dobur,[125] A. Drozdetskiy,[125] R. D. Field,[125] M. Fisher,[125] Y. Fu,[125] I. K. Furic,[125] J. Gartner,[125] B. Kim,[125] J. Konigsberg,[125] A. Korytov,[125] A. Kropivnitskaya,[125] T. Kypreos,[125] K. Matchev,[125] G. Mitselmakher,[125] L. Muniz,[125] C. Prescott,[125] R. Remington,[125] M. Schmitt,[125] B. Scurlock,[125] P. Sellers,[125] N. Skhirtladze,[125] M. Snowball,[125] D. Wang,[125] J. Yelton,[125] M. Zakaria,[125] C. Ceron,[126] V. Gaultney,[126] L. Kramer,[126] L. M. 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McCliment,[130] J.-P. Merlo,[130] H. Mermerkaya,[130,uu] A. Mestvirishvili,[130] A. Moeller,[130] J. Nachtman,[130] C. R. Newsom,[130] E. Norbeck,[130] J. Olson,[130] Y. Onel,[130] F. Ozok,[130] S. Sen,[130] J. Wetzel,[130] T. Yetkin,[130] K. Yi,[130] B. A. Barnett,[131] B. Blumenfeld,[131] A. Bonato,[131] C. Eskew,[131] D. Fehling,[131] G. Giurgiu,[131] A. V. Gritsan,[131] G. Hu,[131] P. Maksimovic,[131] S. Rappoccio,[131] M. Swartz,[131] N. V. Tran,[131] A. Whitbeck,[131] P. Baringer,[132] A. Bean,[132] G. Benelli,[132] O. Grachov,[132] R. P. Kenny Iii,[132] M. Murray,[132] D. Noonan,[132] S. Sanders,[132] J. S. Wood,[132] V. Zhukova,[132] A. f. Barfuss,[133] T. Bolton,[133] I. Chakaberia,[133] A. Ivanov,[133] S. Khalil,[133] M. Makouski,[133] Y. Maravin,[133] S. Shrestha,[133] I. Svintradze,[133] Z. Wan,[133] J. Gronberg,[134] D. Lange,[134] D. Wright,[134] A. Baden,[135] M. Boutemeur,[135] S. C. Eno,[135] D. Ferencek,[135] J. A. Gomez,[135] N. J. Hadley,[135] R. G. 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P. Harris,[136] Y. Kim,[136] M. Klute,[136] Y.-J. Lee,[136] W. Li,[136] C. Loizides,[136] P. D. Luckey,[136] T. Ma,[136] S. Nahn,[136] C. Paus,[136] D. Ralph,[136] C. Roland,[136] G. Roland,[136] M. Rudolph,[136] G. S. F. Stephans,[136] F. Stöckli,[136] K. Sumorok,[136] K. Sung,[136] E. A. Wenger,[136] S. Xie,[136] M. Yang,[136] Y. Yilmaz,[136] A. S. Yoon,[136] M. Zanetti,[136] S. I. Cooper,[137] P. Cushman,[137] B. Dahmes,[137] A. De Benedetti,[137] P. R. Dudero,[137] G. Franzoni,[137] J. Haupt,[137] K. Klapoetke,[137] Y. Kubota,[137] J. Mans,[137] V. Rekovic,[137] R. Rusack,[137] M. Sasseville,[137] A. Singovsky,[137] L. M. Cremaldi,[138] R. Godang,[138] R. Kroeger,[138] L. Perera,[138] R. Rahmat,[138] D. A. Sanders,[138] D. Summers,[138] K. Bloom,[139] S. Bose,[139] J. Butt,[139] D. R. Claes,[139] A. Dominguez,[139] M. Eads,[139] J. Keller,[139] T. Kelly,[139] I. Kravchenko,[139] J. Lazo-Flores,[139] H. Malbouisson,[139] S. Malik,[139] G. R. Snow,[139] U. Baur,[140] A. Godshalk,[140] I. Iashvili,[140] S. Jain,[140] A. Kharchilava,[140] A. Kumar,[140] S. P. Shipkowski,[140] K. Smith,[140] G. Alverson,[141] E. Barberis,[141] D. Baumgartel,[141] O. Boeriu,[141] M. Chasco,[141] S. Reucroft,[141] J. Swain,[141] D. Trocino,[141] D. Wood,[141] J. Zhang,[141] A. Anastassov,[142] A. Kubik,[142] N. Odell,[142] R. A. Ofierzynski,[142] B. Pollack,[142] A. Pozdnyakov,[142] M. Schmitt,[142] S. Stoynev,[142] M. Velasco,[142] S. Won,[142] L. Antonelli,[143] D. Berry,[143] M. Hildreth,[143] C. Jessop,[143] D. J. Karmgard,[143] J. Kolb,[143] T. Kolberg,[143] K. Lannon,[143] W. Luo,[143] S. Lynch,[143] N. Marinelli,[143] D. M. Morse,[143] T. Pearson,[143] R. Ruchti,[143] J. Slaunwhite,[143] N. Valls,[143] M. Wayne,[143] J. Ziegler,[143] B. Bylsma,[144] L. S. Durkin,[144] J. Gu,[144] C. Hill,[144] P. Killewald,[144] K. Kotov,[144] T. Y. Ling,[144] M. Rodenburg,[144] G. Williams,[144] N. Adam,[145] E. Berry,[145] P. Elmer,[145] D. Gerbaudo,[145] V. Halyo,[145] P. 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Hall-Wilton,[159] M. Herndon,[159] P. Klabbers,[159] J. Klukas,[159] A. Lanaro,[159] C. Lazaridis,[159] J. Leonard,[159] R. Loveless,[159] A. Mohapatra,[159] F. Palmonari,[159] D. Reeder,[159] I. Ross,[159] A. Savin,[159] W. H. Smith,[159] J. Swanson,[159] and M. Weinberg[159]

(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, Republic of 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]*Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[29]*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
[30]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[31]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
[32]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France*
[33]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[34]*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
[35]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[36]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[37]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[38]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[39]*University of Hamburg, Hamburg, Germany*
[40]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[41]*Institute of Nuclear Physics "Demokritos," Aghia Paraskevi, Greece*
[42]*University of Athens, Athens, Greece*
[43]*University of Ioánnina, Ioánnina, Greece*
[44]*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[45]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[46]*University of Debrecen, Debrecen, Hungary*
[47]*Panjab University, Chandigarh, India*
[48]*University of Delhi, Delhi, 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 and Fundamental Sciences (IPM), Tehran, Iran*
[53]*INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy*
[53a]*INFN Sezione di Bari, Bari, Italy*
[53b]*Università di Bari, Bari, Italy*
[53c]*Politecnico di Bari, Bari, Italy*
[54]*INFN Sezione di Bologna, Università di Bologna, Bologna, Italy*
[54a]*INFN Sezione di Bologna, Bologna, Italy*
[54b]*Università di Bologna, Bologna, Italy*
[55]*INFN Sezione di Catania, Università di Catania, Catania, Italy*
[55a]*INFN Sezione di Catania, Catania, Italy*
[55b]*Università di Catania, Catania, Italy*
[56]*INFN Sezione di Firenze, Università di Firenze, Firenze, Italy*
[56a]*INFN Sezione di Firenze, Firenze, Italy*
[56b]*Università di Firenze, Firenze, Italy*

[57a]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[58a]INFN Sezione di Genova, Genova, Italy
[59]INFN Sezione di Milano-Biccoca, Università di Milano-Bicocca, Milano, Italy
[59a]INFN Sezione di Milano-Biccoca, Milano, Italy
[59b]Università di Milano-Bicocca, Milano, Italy
[60]INFN Sezione di Napoli, Università di Napoli "Federico II," Napoli, Italy
[60a]INFN Sezione di Napoli, Napoli, Italy
[60b]Università di Napoli "Federico II," Napoli, Italy
[61]INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy
[61a]INFN Sezione di Padova, Padova, Italy
[61b]Università di Padova, Padova, Italy
[61c]Università di Trento (Trento), Padova, Italy
[62]INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[62a]INFN Sezione di Pavia, Pavia, Italy
[62b]Università di Pavia, Pavia, Italy
[63]INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
[63a]INFN Sezione di Perugia, Perugia, Italy
[63b]Università di Perugia, Perugia, Italy
[64]INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
[64a]INFN Sezione di Pisa, Pisa, Italy
[64b]Università di Pisa, Pisa, Italy
[64c]Scuola Normale Superiore di Pisa, Pisa, Italy
[65]INFN Sezione di Roma, Università di Roma "La Sapienza," Roma, Italy
[65a]INFN Sezione di Roma, Roma, Italy
[65b]Università di Roma "La Sapienza," Roma, Italy
[66]INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale (Novara), Torino, Italy
[66a]INFN Sezione di Torino, Torino, Italy
[66b]Università di Torino, Torino, Italy
[66c]Università del Piemonte Orientale (Novara), Torino, Italy
[67]INFN Sezione di Trieste, Università di Trieste, Trieste, 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 Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[76]Universidad Iberoamericana, Mexico City, Mexico
[77]Benemerita Universidad Autonoma 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]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[107]University of Bristol, Bristol, United Kingdom
[108]Rutherford Appleton Laboratory, Didcot, United Kingdom
[109]Imperial College, London, United Kingdom
[110]Brunel University, Uxbridge, United Kingdom
[111]Baylor University, Waco, Texas, USA
[112]Boston University, Boston, Massachusetts, USA
[113]Brown University, Providence, Rhode Island, USA
[114]University of California, Davis, Davis, California, USA
[115]University of California, Los Angeles, Los Angeles, California, USA
[116]University of California, Riverside, Riverside, California, USA
[117]University of California, San Diego, La Jolla, California, USA
[118]University of California, Santa Barbara, Santa Barbara, California, USA
[119]California Institute of Technology, Pasadena, California, USA
[120]Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
[121]University of Colorado at Boulder, Boulder, Colorado, USA
[122]Cornell University, Ithaca, New York, USA
[123]Fairfield University, Fairfield, Connecticut, USA
[124]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[125]University of Florida, Gainesville, Florida, USA
[126]Florida International University, Miami, Florida, USA
[127]Florida State University, Tallahassee, Florida, USA
[128]Florida Institute of Technology, Melbourne, Florida, USA
[129]University of Illinois at Chicago (UIC), Chicago, Illinois, USA
[130]The University of Iowa, Iowa City, Iowa, USA
[131]Johns Hopkins University, Baltimore, Maryland, USA
[132]The University of Kansas, Lawrence, Kansas, USA
[133]Kansas State University, Manhattan, Kansas, USA
[134]Lawrence Livermore National Laboratory, Livermore, California, USA
[135]University of Maryland, College Park, Maryland, USA
[136]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[137]University of Minnesota, Minneapolis, Minnesota, USA
[138]University of Mississippi, University, Mississippi, USA
[139]University of Nebraska–Lincoln, Lincoln, Nebraska, USA
[140]State University of New York at Buffalo, Buffalo, New York, USA
[141]Northeastern University, Boston, Massachusetts, USA
[142]Northwestern University, Evanston, Illinois, USA
[143]University of Notre Dame, Notre Dame, Indiana, USA
[144]The Ohio State University, Columbus, Ohio, USA
[145]Princeton University, Princeton, New Jersey, USA
[146]University of Puerto Rico, Mayaguez, Puerto Rico, USA
[147]Purdue University, West Lafayette, Indiana, USA
[148]Purdue University Calumet, Hammond, Indiana, USA
[149]Rice University, Houston, Texas, USA
[150]University of Rochester, Rochester, New York, USA
[151]The Rockefeller University, New York, New York, USA
[152]Rutgers, the State University of New Jersey, Piscataway, New Jersey, USA
[153]University of Tennessee, Knoxville, Tennessee, USA
[154]Texas A&M University, College Station, Texas, USA
[155]Texas Tech University, Lubbock, Texas, USA
[156]Vanderbilt University, Nashville, Tennessee, USA
[157]University of Virginia, Charlottesville, Virginia, USA

[158]*Wayne State University, Detroit, Michigan, USA*
[159]*University of Wisconsin, Madison, Wisconsin, USA*

[a] Deceased.
[b] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[c] Also at Universidade Federal do ABC, Santo Andre, Brazil.
[d] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[e] Also at Suez Canal University, Suez, Egypt.
[f] Also at British University, Cairo, Egypt.
[g] Also at Fayoum University, El-Fayoum, Egypt.
[h] Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
[i] Also at Massachusetts Institute of Technology, Cambridge, MA, USA.
[j] Also at Université de Haute-Alsace, Mulhouse, France.
[k] Also at Brandenburg University of Technology, Cottbus, Germany.
[l] Also at Moscow State University, Moscow, Russia.
[m] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[n] Also at Eötvös Loránd University, Budapest, Hungary.
[o] Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.
[p] Also at University of Visva-Bharati, Santiniketan, India.
[q] Also at Sharif University of Technology, Tehran, Iran.
[r] Also at Shiraz University, Shiraz, Iran.
[s] Also at Isfahan University of Technology, Isfahan, Iran.
[t] Also at Facoltà Ingegneria Università di Roma ‘‘La Sapienza,’’ Roma, Italy.
[u] Also at Università della Basilicata, Potenza, Italy.
[v] Also at Università degli studi di Siena, Siena, Italy.
[w] Also at California Institute of Technology, Pasadena, CA, USA.
[x] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[y] Also at University of California, Los Angeles, Los Angeles, CA, USA.
[z] Also at University of Florida, Gainesville, FL, USA.
[aa] Also at Université de Genève, Geneva, Switzerland.
[bb] Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.
[cc] Also at INFN Sezione di Roma, Università di Roma ‘‘La Sapienza,’’ Roma, Italy.
[dd] Also at University of Athens, Athens, Greece.
[ee] Also at The University of Kansas, Lawrence, KS, USA.
[ff] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[gg] Also at Paul Scherrer Institut, Villigen, Switzerland.
[hh] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[ii] Also at Gaziosmanpasa University, Tokat, Turkey.
[jj] Also at Adiyaman University, Adiyaman, Turkey.
[kk] Also at Mersin University, Mersin, Turkey.
[ll] Also at Izmir Institute of Technology, Izmir, Turkey.
[mm] Also at Kafkas University, Kars, Turkey.
[nn] Also at Suleyman Demirel University, Isparta, Turkey.
[oo] Also at Ege University, Izmir, Turkey.
[pp] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[qq] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[rr] Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
[ss] Also at Utah Valley University, Orem, UT, USA.
[tt] Also at Institute for Nuclear Research, Moscow, Russia.
[uu] Also at Erzincan University, Erzincan, Turkey.