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# Search for new physics in jet scaling patterns of multilepton events at $\sqrt{s} = 13$ TeV

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## Abstract

A first search for beyond the standard model physics in jet scaling patterns of multilepton events is presented, using a data sample corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$  of 13 TeV proton-proton collisions recorded by the CMS detector at the LHC. The search uses observed jet multiplicity distributions in one-, two-, and four-lepton events to explore possible enhancements in jet production rate in three-lepton events with and without bottom quarks. The data are found to be consistent with the standard model expectation. The results are interpreted in terms of supersymmetric production of electroweak chargino-neutralino superpartners with cascade decays terminating in prompt hadronic  $R$ -parity violating interactions.

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Following the discovery of the Higgs boson [1, 2], a number of critical questions remain open outside of the standard model (SM) of particle physics, such as physics underlying electroweak (EW) symmetry breaking and the Higgs boson mass [3–5], the origin of neutrino masses [6–9], the identity of dark matter, and the observed baryon asymmetry in the universe [10–13]. These make the search for new physics beyond the SM (BSM) an important mission of the CERN LHC. Despite the wide array of theoretical models put forth for BSM physics, the guidance they offer is not as specific as it was for the discovery of key pieces of the SM, and no direct signs of new physics have been found yet. Therefore, experimental efforts at the LHC must adopt a broad approach in searching for signs of BSM physics.

A compelling subset of BSM theories features events with multiple final-state leptons and enhanced production of hadronic jets in high energy proton-proton collisions [14–18]. The primary SM backgrounds for such signatures include production of massive vector bosons and top quarks in association with high jet multiplicity arising from initial- (ISR) and final-state radiation (FSR). The characterization of these SM background contributions faces major challenges as predictions of differential jet multiplicity distributions generally suffer from large theoretical uncertainties, including insufficient modeling of higher-order quantum chromodynamics (QCD) and EW effects. Significant discrepancies exist in state-of-the-art event and particle shower generators, as exemplified in recent studies of  $W$ ,  $Z$ ,  $t\bar{t}$ ,  $WZ$ ,  $ZZ$ , and  $t\bar{t}Z$  processes at the LHC [19–30].

These shortcomings impose serious limitations on experimental searches for BSM physics distinguished by such telltale hadronic enhancements. Indeed, analyses by the ATLAS and CMS Collaborations frequently rely on inclusive selection criteria and observables, instead of exploiting the exclusive multiplicity of jets [31–42]. Variables such as the transverse momentum ( $p_T$ ) imbalance due to invisible particles, transverse masses of invisible and visible particles, and scalar sum of transverse momenta of visible particles are less affected by these theoretical uncertainties, but they provide diminished sensitivity to jet production rates due to new physics. Furthermore, three-lepton events consistent with on-shell  $Z$  and  $W$  boson decays are often used as data control regions (CR) for determining corrections to production cross sections for simulations of  $WZ$  and  $t\bar{t}Z$  backgrounds. Thus, signatures that resemble such SM processes but with an enhancement in jet multiplicity constitute a blind spot in BSM search efforts.

This Letter presents the first direct search for BSM physics in exclusive jet multiplicity distributions of proton-proton collision events containing three leptons. The analysis targets events with on-shell leptonically decaying  $W$  and  $Z$  bosons and several additional soft jets. A precise prediction of the distribution of jets resulting from the SM  $WZ$  and  $t\bar{t}Z$  processes is thus crucial for detecting such new physics. Jet scaling pattern studies [43–50] have identified parametrization schemes, for example “staircase scaling”, to describe the production cross section ratios of successive jets in events containing an underlying hard process, such as lepton production. We employ a novel method that exploits the similarity of these patterns across different SM processes, where we use one-, two-, and four- lepton events in data to derive jet multiplicity corrections of event counts in neighboring bins, which are then applied to the three-lepton sample where enhanced jet production due to the BSM physics is posited. Application of these corrections derived from data greatly improves the estimation of hadronic activity that accompanies the three-lepton  $WZ$  and  $t\bar{t}Z$  SM background processes, and in turn allows for a sensitive search of the BSM physics targeted in this Letter.

The results are used to probe a previously unexplored class of supersymmetric (SUSY) [51–56] models that predict events with  $W$  and  $Z$  bosons along with an enhanced jet multiplicity. Electroweak production of a chargino-neutralino pair  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  (with masses  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ ) yields a

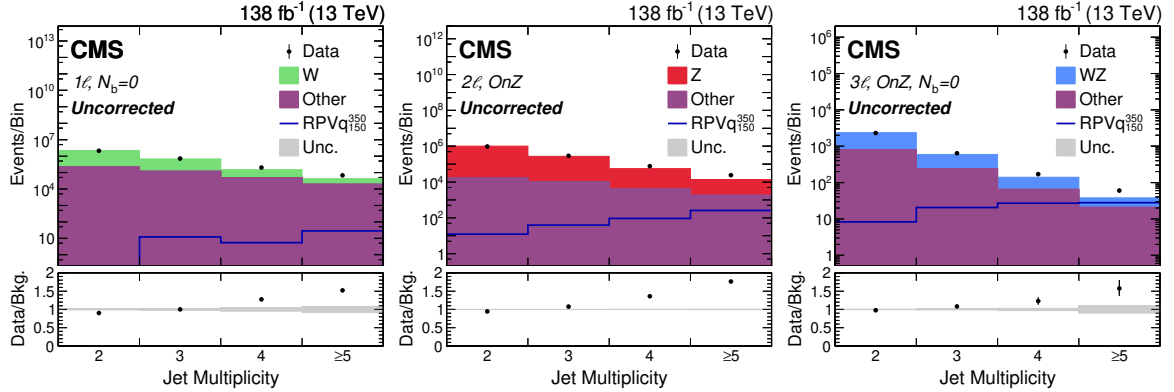


Figure 1: Distributions of jet multiplicity in a W-enriched selection of one-lepton events (left), a Z-enriched selection of two-lepton OnZ events (center), and a WZ-enriched selection of three-lepton OnZ events (right, search region) prior to corrections. The lower panels show the ratio of observed events (Data) to the total background prediction (Bkg.), with the gray bands representing the statistical uncertainty (Unc.) in the predictions. SM background predictions fall short of the observations in all cases for higher jet multiplicities. Expected RPVq ( $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = 350$  GeV,  $m_{\tilde{\chi}_1^0} = 150$  GeV) signal distributions are overlaid for comparison.

W and Z boson through cascade decays to a pair of the lightest SUSY particle (LSP) neutralino  $\tilde{\chi}_1^0$  (with mass  $m_{\tilde{\chi}_1^0}$ ),  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ . Each LSP subsequently decays promptly via hadronic R-parity violating (RPV) interactions [57–61]. The search targets on-shell leptonic decays of the massive vector bosons,  $W \rightarrow \ell \nu$  and  $Z \rightarrow \ell \ell$ , and we consider two scenarios for the three-quark decay of the LSP,  $\tilde{\chi}_1^0 \rightarrow uds$  or  $\tilde{\chi}_1^0 \rightarrow udb$ , referred to as RPVq and RPVb, respectively.

The analysis is based on a data sample of  $138 \text{ fb}^{-1}$  of 13 TeV pp collisions recorded by the CMS detector in 2016–2018 [62–64]. The CMS apparatus [65] is a nearly hermetic multipurpose detector, designed to trigger on [66, 67] and identify electrons, muons, photons, and hadrons [68–71]. A global “particle-flow” algorithm [72] is used to reconstruct all individual particles in an event. It combines information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build jets and missing transverse momentum ( $p_T^{\text{miss}}$ ) [73, 74].

Jets are clustered using the anti- $k_T$  algorithm with a radius parameter of 0.4, as implemented in the FASTJET package [75–77], and their energy is corrected on a jet-by-jet basis [78]. Jets originating from b quarks are identified with the DEEPIET algorithm operated at a medium working point having 70% average efficiency, with 10 and 1% efficiencies for misidentifying charm and light quarks, respectively [79–81]. The vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection onto the plane perpendicular to the beam axis of the negative vector-momenta sum of all reconstructed particle-flow objects in an event.

The data used in this search were recorded using a combination of isolated single-electron and -muon triggers with corresponding electron and muon  $p_T$  thresholds of 27 and 24 GeV in 2016, 32 and 27 GeV in 2017, and 32 and 24 GeV in 2018, respectively. We select events that contain 1–4 leptons (electrons or muons) and any number of jets. The leptons are required to be well-isolated with  $p_T > 10$  GeV and pseudorapidity  $|\eta| < 2.4$  [68, 69]. At least one of the leptons must satisfy tighter criteria with  $p_T > 30$  (35) GeV in 2016 (2017–2018) for an electron

or with  $p_T > 26$  (29) GeV in 2016 and 2018 (2017) for a muon. All jets are required to satisfy  $p_T > 30$  GeV and  $|\eta| < 2.5$ , as well as distance in  $\eta$ - $\phi$  space [65]  $\Delta R \equiv [(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2} > 0.4$  from a selected muon or electron, where  $\phi$  is the azimuthal angle in radians. In order to suppress contributions from low-mass quarkonium resonances, cascade decays of heavy-flavor hadrons, and low- $\Delta R$  FSR, events with two or more leptons are discarded if  $m_{\min} < 12$  GeV or  $\Delta R_{\min} < 0.2$ , where  $m_{\min}$  and  $\Delta R_{\min}$  are defined, respectively, as the minimum invariant mass and minimum  $\Delta R$  of all lepton pairs in the event, regardless of lepton charge and flavor.

Events satisfying the baseline selections are categorized using a set of invariant mass and multiplicity variables. The number of distinct opposite-sign same-flavor (OSSF) lepton pairs in an event is denoted as OSSF $n$ , where  $n$  is the number of such pairs, such that a  $\mu^+\mu^-\mu^-\mu^-$  event is labeled as OSSF1 and a  $\mu^+\mu^+\mu^-\mu^-$  event is labeled as OSSF2. Events with an OSSF lepton pair with an invariant mass between 76–106 GeV, consistent with leptonic decays of the Z boson, are labeled as OnZ. Otherwise, they are labeled as OffZ. The minimum lepton  $p_T$  requirement is raised to 20 GeV in all three-lepton OnZ events.

Figure 1 shows the jet multiplicity distributions across one-, two-, and three-lepton events enriched in W, Z, and WZ contributions, respectively. These demonstrate the impact, size, and similarity of the jet multiplicity mismodeling across different processes, and particularly that the shortcoming of the simulated WZ MC sample in modeling exclusive jet multiplicity bins in three-lepton events is consistent in shape and magnitude with that of a potential RPVq signal. This constitutes the primary motivation for the data-driven jet multiplicity correction and the choice of the signal model.

The search regions (SRs) comprise the three-lepton OnZ events with at least two jets. These are primarily classified based on their jet ( $N_j$ ) and b-tagged jet ( $N_b$ ) multiplicities. We define eight nonoverlapping SRs, namely with  $N_j = 2$ ,  $N_j = 3$ ,  $N_j = 4$ , and  $N_j \geq 5$ , further split according to  $N_b = 0$  or  $N_b \geq 1$ . The remaining one-, two-, three-, and four-lepton events are used as signal-depleted CRs to isolate, characterize, and quantify the major irreducible SM background processes, and to tailor the simulations to improve the description of SM processes. Although RPVq and RPVb signals can produce up to six jets, scenarios with low LSP mass or with Lorentz-boosted LSPs produce fewer jets in LSP decays because of the requirements on the reconstructed jet  $p_T$  and jet radius parameters, populating SRs with lower  $N_j$  and  $N_b$  values. In each  $N_j$  and  $N_b$  SR, a number of  $S_T$  bins are defined to probe for wide enhancements above SM expectations, where  $S_T$  is an event-based effective mass variable defined as  $p_T^{\text{miss}}$  plus the scalar  $p_T$  sum of electrons, muons, and jets. The  $S_T$  is proportional to the total mass of the BSM particles, and mitigates the model-specific combinatorial problem of building multibody resonances. The splitting of SRs along dimensions of jet multiplicity and  $S_T$  provides additional sensitivity against SM processes which may produce similar numbers of jets in the final state but with a different overall effective mass.

In all leptonic events, electrons and muons produced from the decays of W, Z, and Higgs bosons (either directly or via a leptonically decaying  $\tau$  lepton) are referred to as prompt leptons, and are often indistinguishable in momentum and isolation from those produced in signal events. Thus, the SM contributions consisting of only prompt leptons are referred to as the irreducible backgrounds. Reducible backgrounds are defined as those which include jets misidentified as leptons or where the leptons originate from heavy-quark decays, and background processes with such leptons are collectively labeled as “MisID” backgrounds.

Simulated samples are used in the estimation of the irreducible background as well as signal contributions. The WZ,  $t\bar{t}Z$ ,  $t\bar{t}W$ ,  $Z\gamma$ , and triboson backgrounds were generated using MADGRAPH5\_aMC@NLO 2.6.5 [82] at next-to-leading order (NLO) precision in perturbative QCD.

The background contribution from ZZ production via quark-antiquark annihilation was generated using POWHEG 2.0 [83–85] at NLO, while the contribution from gluon-gluon fusion production was generated at leading order (LO) using MCFM 7.0.1 [86]. Processes from Higgs boson production were generated using POWHEG, MADGRAPH5\_aMC@NLO, and JHUGEN 7.0.11 [87–90] at NLO. Contributions from other processes involving single or multiple top quarks or vector bosons were simulated using MADGRAPH5\_aMC@NLO at LO or NLO in QCD. Additionally, Z, W, and  $t\bar{t}$  processes primarily used for various studies in one- and two-lepton events were also generated at NLO with MADGRAPH5\_aMC@NLO and PYTHIA. All signal samples were generated with MADGRAPH5\_aMC@NLO at LO precision. A simplified model spectrum [91, 92] is assumed, consisting of degenerate wino-like chargino and neutralino that are superpartners of the  $SU(2)_L$  gauge fields with masses  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} \geq 125$  GeV, together with a bino-like neutralino LSP that is the superpartner of the  $U(1)_Y$  gauge field with mass  $m_{\tilde{\chi}_1^0} \leq m_{\tilde{\chi}_1^\pm} - 100$  GeV [93, 94]. All other SUSY particles are assumed to be sufficiently decoupled to be inaccessible at the LHC.

The NNPDF3.1 next-to-NLO parton distribution functions (PDFs) were used to generate all the background and signal samples [95]. To perform the parton showering, fragmentation, and hadronization of the matrix element level events in all samples, PYTHIA 8.240 [96] was used with the event tune CP5 [97]. The FxFx [98] or MLM [99] matching scheme is used in MADGRAPH samples to remove double-counted partons between the matrix element calculations and parton shower description, at NLO or LO precision, respectively. The response of the CMS detector was simulated using the GEANT4 toolkit [100]. Aside from the hard-scattering event, additional pp interactions from within the same or adjacent bunch crossing (pileup) are simulated and incorporated in the samples, and simulated events are reweighted according to the pileup distribution in the recorded data.

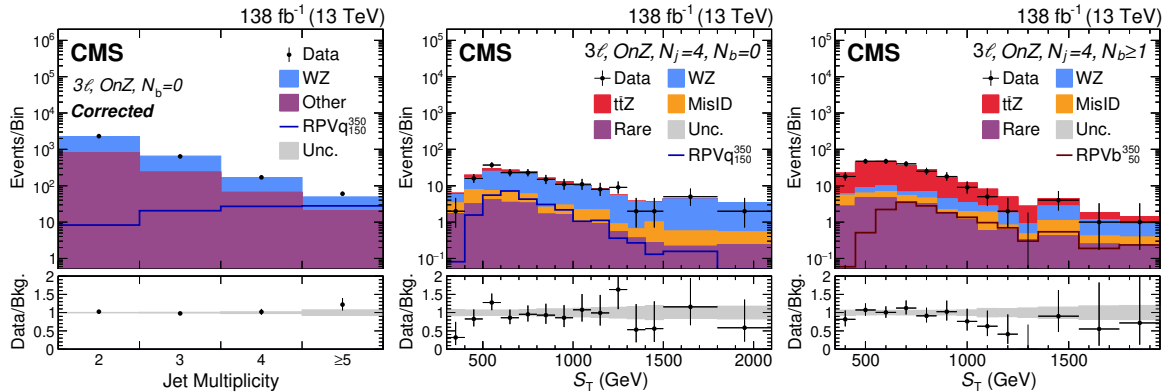


Figure 2: Example search region distributions of jet multiplicity with  $N_b = 0$  (left) as well as  $S_T$  in four-jet bins with  $N_b = 0$  (center) and  $N_b \geq 1$  (right). The lower panels show the ratio of observed events (Data) to the total background prediction (Bkg.), with the gray bands representing the sum of statistical (left), or statistical and systematic (center and right) uncertainties (Unc.) in the predictions. The expected background jet multiplicity distribution is obtained after applying the data driven corrections, whereas the  $S_T$  distributions and the uncertainties are obtained after also performing the binned maximum likelihood fit to the data under the background-only hypothesis. Expected RPVq and RPVb ( $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = 350$  GeV with  $m_{\tilde{\chi}_1^0} = 150$  and 50 GeV, respectively) signal distributions are overlaid for comparison.

The WZ and  $t\bar{t}Z$  processes are the dominant irreducible SM backgrounds in  $N_b = 0$  and  $N_b > 0$  SR events, respectively. Mismodeling of their differential jet multiplicity distributions in sim-

ulations constitutes the most significant source of uncertainty. Jet-multiplicity-dependent corrections are derived for the WZ and  $t\bar{t}Z$  backgrounds using CRs in data to mitigate such effects, while other characteristics of these events are obtained from simulations. Exclusive jet multiplicity distributions exhibit general scaling patterns dictated by the underlying SM hard-scattering process as well as the imposed selection criteria [47, 48]. Parametrizing ratios of successive exclusive jet cross sections offers a systematic method to correct and constrain jet multiplicity behavior for sufficiently similar processes, preferably from one with higher cross section to another with lower cross section. In particular, we use the similarities of the jet production mechanisms between the WZ background and the Z process as well as the  $t\bar{t}Z$  background and the  $t\bar{t}$  process to derive the jet scaling pattern information from data in signal-depleted event selections, and apply this pattern in SR events with two or more jets.

A two-lepton selection of Z-enriched events is used to derive corrections for the three-lepton WZ background process dominated by ISR jets. Although both Z and WZ production occur through EW processes, the kinematical variables of the recoiling ISR jets differ, primarily because of differences in the total invariant mass of the hard-scattering system. These are compensated by an additional selection of  $p_T > 100$  GeV applied to the lepton pair (reconstructed Z boson candidate) in the Z-enriched two-lepton events, as studied in simulated samples. This method is validated in the  $N_j$  distributions of a selection of one-lepton CR events enriched in W boson contributions using the same corrections derived in two-lepton Z boson events, where the observed discrepancies between the data and expected background are reduced to less than 10% for  $N_j \geq 2$  after applying the corrections. The jet scaling behavior compatibility of the W, Z, and WZ processes in similarly produced simulated samples are shown in Fig. 1, with comparisons against one- (left), two- (center) and three-lepton (right, SR) data events, respectively. Figure 2 (left) illustrates the jet multiplicity distribution of the WZ-dominated three-lepton SR events after the corrections, such that the prediction of an example RPVq signal that has been previously shown to be comparable in shape and magnitude to the potential mismodeling in the simulated WZ sample can no longer be accommodated. Similarly, a one-lepton selection of  $t\bar{t}$ -enriched events is used to measure the jet scaling corrections for the three-lepton  $t\bar{t}Z$  background process, as both processes include contributions from ISR and FSR jets as well as decays of the hard-scattering system ( $t \rightarrow Wb \rightarrow qq\bar{b}$ ); moreover, the two hard-scattering systems have comparable total invariant masses. Indeed, the compatibility of the  $t\bar{t}$  and  $t\bar{t}Z$  processes in their jet scaling behavior is validated in simulated samples, where no significant differences have been observed.

The Z-enriched two-lepton events are also used to check the modeling performance of the  $S_T$  variable in exclusive jet multiplicity bins in simulation, which is observed to be consistent with data up to individual normalization factors. A set of three- and four-lepton CRs are further defined to verify the modeling of  $S_T$  and other relevant kinematic variables, as well as to obtain cross section normalization factors for the irreducible backgrounds. For the WZ contributions, a selection of three-lepton OnZ events with 0 or 1 jet is used, whereas a  $t\bar{t}Z$ -enriched CR is created by selecting four-lepton events with only one OnZ pair, at least one b-tagged jet, and  $S_T > 350$  GeV. Other contributions mostly come from  $Z\gamma$  and ZZ processes, where the former contributes via ISR or FSR photons that convert asymmetrically such that only one of the resultant leptons is reconstructed in the detector, and the latter contributes via events where one of the leptons originating from the Z boson decays is not reconstructed or identified as an electron or muon. A dedicated OffZ three-lepton selection is defined for the  $Z\gamma$  process, where the total mass of the three-lepton system is required to be within the Z boson mass window of  $91 \pm 15$  GeV. Four-lepton OSSF2 events with either two OnZ pairs and any number of b-tagged jets, or one OnZ pair and no b-tagged jets, are used to normalize and study ZZ

simulations. Additionally, dedicated jet-multiplicity-dependent corrections are derived for the ZZ background simulation in three-lepton events using the signal-depleted four-lepton events. Other SM processes without a dedicated CR, including triboson, Higgs boson, and other rare SM contributions, are collectively referred to as “Rare” backgrounds and are normalized to their NLO or LO theoretical cross sections. The final cross section normalizations of all major irreducible backgrounds and signal are ultimately simultaneously obtained by a binned maximum likelihood fit to all SRs and three- and four-lepton CRs, where the normalized cross sections from the CRs are solely used as initial values.

The MisID background contributions are estimated using a “matrix method” [101, 102] from a set of sideband regions defined in data for each SR. The sideband regions consist of events with leptons passing less stringent selection criteria, where at least one lepton fails the isolation requirements used in the analysis. The method used in this analysis follows the implementation detailed in Refs. [41, 103], and is validated in OnZ three-lepton simulated events as well as signal-depleted OSSF0 and OSSF1 OffZ three-lepton data events.

A number of systematic uncertainties arise from the corrections applied to the background and signal simulations. These include corrections for the efficiencies of the electron and muon triggers, lepton reconstruction, identification, and isolation, as well as the lepton energy scale and resolution modeling, and for jets and  $p_T^{\text{miss}}$ , b tagging efficiency, pileup modeling, and energy scale and resolution corrections. Each of these uncertainty sources is considered for the main irreducible WZ and  $t\bar{t}Z$  backgrounds and the signal samples, where they are evaluated by varying the corresponding correction factor up and down by one standard deviation of its associated uncertainty. The resulting variations in the  $N_j$ ,  $N_b$ , and  $S_T$  spectra of the main irreducible backgrounds are used to define associated systematic uncertainties, which are typically less than 10%. The uncertainties in the integrated luminosity vary in the range of 1.2–2.5% among the data-taking years [62–64]. The uncertainties due to the NNPDF3.1 PDF set [95] used in WZ and  $t\bar{t}Z$  samples are also evaluated, and found to be negligible in the phase space probed by the analysis but are nonetheless considered.

The MisID background estimate from control samples in data has an uncertainty in the range of 20–30%. It has a minor impact on the results since the MisID background is not a major contributor in the SRs. Additionally, all background and signal estimates have uncertainties due to a limited number of events in simulated samples or data sidebands. These statistical uncertainties are typically subdominant, but are nonetheless propagated to the results.

The dominant systematic uncertainties arise from the normalization of the WZ and  $t\bar{t}Z$  backgrounds in the  $N_j \geq 2$  phase space as well as the uncertainties applied to the WZ and  $t\bar{t}Z$  jet multiplicity corrections. The normalization factors for these backgrounds are included as free parameters in the maximum likelihood fit together with the targeted signal process. The jet multiplicity corrections affect the  $N_j$  shapes of the WZ and  $t\bar{t}Z$  contributions, and are implemented as independent constraints on the ratios of event counts in neighboring jet multiplicity bins. A relative uncertainty of 30% is assigned to each of these ratio constraints as induced by various systematic effects, where the primary contributors are the residual nonclosure effects in the modeling of WZ and  $t\bar{t}Z$  processes by Z and  $t\bar{t}$  processes as studied in simulated samples (up to 20%) and the stability of correction factors as functions of data-taking period and detector conditions (up to 10%). In the one-lepton  $t\bar{t}$  and two-lepton Z-enriched data events where the jet multiplicity corrections are measured, the contributions of other processes are estimated and subtracted using simulated samples. Thus, we also evaluate the impact of various simulation-based uncertainties on the corrections. Among these, jet energy scale and b tagging efficiency correction uncertainties as well as normalization uncertainties are the most



relevant, but their total impact on the jet multiplicity corrections is measured to be less than 5%. In contrast, the statistical uncertainties are found to be negligible throughout.

The following results have been determined using the CMS statistical analysis tool, COMBINE [104]. A simultaneous, binned maximum likelihood fit is performed across all events in SRs and the three- and four-lepton CRs, where sources of systematic uncertainties, including those of statistical origin, are incorporated in the likelihood as nuisance parameters. No statistically significant deviation from the SM background is observed. Representative  $S_T$  background spectra in four-jet SRs are provided in Fig. 2 with  $N_b = 0$  (center), and  $N_b \geq 1$  (right).

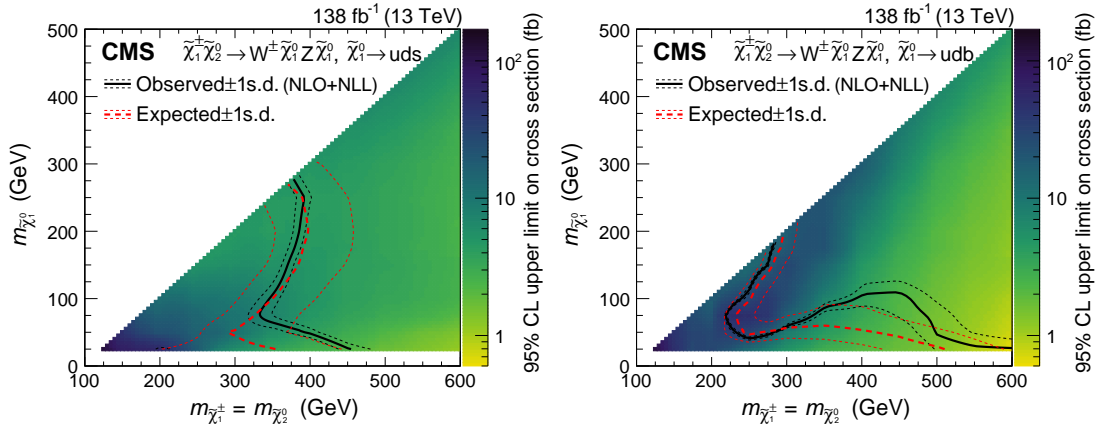


Figure 3: The 95% confidence level upper limits on the RPVq (left) and RPVb (right) signal production cross sections as a function of  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$  and  $m_{\tilde{\chi}_1^0}$ . Contour lines indicate the observed (bold solid) and median expected (bold dashed) boundaries with 1 standard deviation (s.d.) as well as the 68% expected bands (thin dashed), where the latter on the observed contour line is due to the theoretical uncertainty on the signal production cross section.

Using the modified frequentist approach with the  $CL_s$  criterion [105, 106] in the asymptotic approximation [107], the results are interpreted as upper limits at 95% confidence level on the production cross section of chargino-neutralino pairs in the class of SUSY models explored here, separately considering the RPVq and RPVb signal scenarios. The signal production cross sections are computed at NLO plus next-to-leading logarithmic (NLL) precision under the simplified model assumption [108, 109]. Figure 3 shows the observed and expected upper limits on the excluded  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production cross sections. In the range of probed chargino-neutralino masses, the RPVq (RPVb) model is excluded for an LSP mass of up to 275 (180) GeV. Tabulated results are provided in the associated HEPData record [110].

Previously, the ATLAS and CMS Collaborations have set constraints on  $R$ -parity conserving or RPV scenarios with chargino-neutralino pair production in signatures involving low hadronic activity or significant  $p_T$  imbalance due to undetected stable neutralino LSPs [111, 112], or in signatures with three or more charged leptons [36, 113], as well as constraints on long-lived RPV decays of metastable neutralino LSPs [114–117] and hadronic RPV decays of superpartners involving top quarks [118, 119]. In comparison, these are the first dedicated constraints targeting EW superpartner pair production with prompt decays of the LSPs via hadronic RPV interactions in final states with jets and three leptons.

In summary, the first search for beyond the standard model physics in jet multiplicity distributions of multilepton events has been performed using proton-proton collision data collected with the CMS detector at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . No deviations from standard model expectations have been observed and the first

direct bounds are set on a class of supersymmetric models populating final states with jets and three leptons.

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














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








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



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



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









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






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













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
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










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










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






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





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















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










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





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
































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




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



































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


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












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









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H. Bakhshiansohi<sup>41</sup> , A. Jafari<sup>42</sup> , M. Zeinali<sup>43</sup> 































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























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






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
P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> 

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



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L. Benussi , S. Bianco , S. Meola<sup>49</sup> , D. Piccolo 










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F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 




























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A. Benaglia<sup>a</sup> , F. Brivio<sup>a</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , R. Gerosa<sup>a,b</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a</sup> , M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , S. Palluotto<sup>a,b</sup> , D. Pedrini<sup>a</sup> , A. Perego<sup>a,b</sup> , B.S. Pinolini<sup>a</sup> , G. Pizzati<sup>a,b</sup> , S. Ragazzi<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> 










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S. Buontempo<sup>a</sup> , A. Cagnotta<sup>a,b</sup> , F. Carnevali<sup>a,b</sup> , N. Cavallo<sup>a,c</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,50</sup> , P. Paolucci<sup>a,29</sup> , B. Rossi<sup>a</sup> 















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

























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








#### INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy








S. Ajmal<sup>a,b</sup> , M.E. Ascioti<sup>a,b</sup> , G.M. Bilei<sup>a</sup> , C. Carrivale<sup>a,b</sup> , D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,53</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 

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





































C. Aimè<sup>a</sup> , C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , R. Bhattacharya<sup>a</sup> , L. Bianchini<sup>a,b</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , M. Cipriani<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a</sup> , D. Matos Figueiredo<sup>a</sup> , A. Messineo<sup>a,b</sup> , S. Mishra<sup>a</sup> , M. Musich<sup>a,b</sup> , F. Palla<sup>a</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , F. Vaselli<sup>a,c</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> 

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F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> ,  
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R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , C. Borca<sup>a,b</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> ,  
R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> ,  
F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</sup> , L. Markovic<sup>a,b</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , L. Menzio<sup>a,b</sup> ,  
P. Meridiani<sup>a</sup> , E. Migliore<sup>a,b</sup> , M. Monteno<sup>a</sup> , R. Mulargia<sup>a</sup> , M.M. Obertino<sup>a,b</sup> ,  
G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> ,  
F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , A. Staiano<sup>a</sup> , C. Tarricone<sup>a,b</sup> , D. Trocino<sup>a</sup> ,  
G. Umoret<sup>a,b</sup> , R. White<sup>a,b</sup> 

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G. Della Ricca<sup>a,b</sup> 





**Kyungpook National University, Daegu, Korea**

S. Dogra , J. Hong , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon , Y.D. Oh ,  
M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

**Department of Mathematics and Physics - GWNU, Gangneung, Korea**

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G. Bak , P. Gwak , H. Kim , D.H. Moon 

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


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


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


























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

















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







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






























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










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

















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


















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




























**University of Bristol, Bristol, United Kingdom**

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw, V.J. Smith , K. Walkingshaw Pass




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A.H. Ball, K.W. Bell , A. Belyaev<sup>78</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 













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I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, C.A. Carrillo Montoya , G.S. Chahal<sup>79</sup> , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , A. Howard, G. Iles , C.R. Knight , P. Krueper, J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios, M. Mieskolainen , J. Nash<sup>80</sup> , M. Pesaresi , P.B. Pradeep, B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee<sup>29</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 




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











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R. Bartek , A. Dominguez , A.E. Simsek 


















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B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson, C.U. Perez , P. Rumerio<sup>81</sup> , E. Usai , R. Yi 

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A. Akpinar , C. Cosby , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 



















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G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan<sup>82</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell, S. Sagir<sup>83</sup> , X. Shen , F. Simpson , M. Stamenkovic , N. Venkatasubramanian,














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S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo , F. Zhang 

























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K. Adamidis, M. Bachtis , D. Campos, R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo, E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

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A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 
















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A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang















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S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















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J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 






































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





























J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 

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

















J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

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













M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma 

B. Klima , K.H.M. Kwok , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>84</sup> , F. Ravera , A. Reinsvold Hall<sup>85</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 








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C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field , C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 





























#### Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez , H. Prosper , P.R. Prova , M. Wulansatiti , R. Yohay , J. Zhang 















#### Florida Institute of Technology, Melbourne, Florida, USA

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










#### University of Illinois Chicago, Chicago, Illinois, USA

M.R. Adams , A. Baty , C. Bennett , R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth , A. Hingrajiya , D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti , T. Roy , S. Rudrabhatla , N. Singh , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























#### The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , D. Blend , K. Dilsiz<sup>86</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili<sup>87</sup> , O. Neogi , H. Ogul<sup>88</sup> , Y. Onel , A. Penzo , C. Snyder , E. Tiras<sup>89</sup> 









#### Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 





















#### The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu<sup>90</sup> , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 

























#### Kansas State University, Manhattan, Kansas, USA

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 



#### University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , J. Bistany-riebman , Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe , E. Popova<sup>91</sup> , A. Shevelev , L. Wang 













**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn , A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 












**University of Minnesota, Minneapolis, Minnesota, USA**

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering , R. Rusack , R. Saradhy , N. Strobbe 




















**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia , I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 



























**Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , J. Li , M. Lu , G. Madigan , R. McCarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









**Northwestern University, Evanston, Illinois, USA**

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , M. McGinnis , Y. Miao , D.G. Monk , M.H. Schmitt , A. Talierecio , M. Velasco

















**University of Notre Dame, Notre Dame, Indiana, USA**

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>15</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalia 

**The Ohio State University, Columbus, Ohio, USA**

A. Basnet , M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 




















**Princeton University, Princeton, New Jersey, USA**














































































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