THE EUROPEAN
PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

# Search for new phenomena with multiple charged leptons in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$

**CMS Collaboration**[*]

CERN, 1211 Geneva 23, Switzerland

**Abstract** Results are reported from a search for physics beyond the standard model in final states with at least three charged leptons, in any combination of electrons or muons. The data sample corresponds to an integrated luminosity of 2.3 fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$, recorded by the CMS experiment at the LHC in 2015. Two jets are required in each event, providing good sensitivity to strong production of gluinos and squarks. The search regions, sensitive to a range of different new physics scenarios, are defined using the number of jets tagged as originating from bottom quarks, the sum of the magnitudes of the transverse momenta of the jets, the imbalance in the overall transverse momentum in the event, and the invariant mass of opposite-sign, same-flavor lepton pairs. The event yields observed in data are consistent with the expected background contributions from standard model processes. These results are used to derive limits in terms of $R$-parity conserving simplified models of supersymmetry that describe strong production of gluinos and squarks. Model-independent limits are presented to facilitate the reinterpretation of the results in a broad range of scenarios for physics beyond the standard model.

## 1 Introduction

Many types of beyond-the-standard-model (BSM) theories can produce multilepton events (three or more leptons) with a wide array of unique signatures [1–5], including a number of supersymmetric (SUSY) models [6–15]. In these models, multilepton final states can arise from the decay of multiple vector bosons, e.g., in $t\bar{t}$ production with $t \to cH$ followed by $H \to WW^*$ or $H \to ZZ^*$, or in strong production of pairs of squarks or gluinos, which often initiate complex decay chains that can result in multiple W and/or Z bosons. The standard model (SM) processes that produce this final state are also characterized by multiple bosons and are well-understood both theoretically [16–30] and experimentally [31–35].

This paper describes a search for new physics in final states with three or more leptons, electrons or muons, produced at the CERN LHC, in proton–proton (pp) collisions at a center-of-mass energy of 13 TeV, with the CMS detector. The data correspond to an integrated luminosity of 2.3 fb$^{-1}$ collected in 2015. The expected irreducible backgrounds come from diboson production (WZ and ZZ) or other SM processes, including $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$. These backgrounds are modeled using Monte Carlo (MC) simulations that have appropriate corrections applied to match the behavior of reconstructed objects in data. Reducible backgrounds are processes that produce one or more misidentified or nonprompt leptons, i.e., those that arise from jets or meson decays, that pass all reconstruction, identification, and isolation criteria. Estimates of the probabilities of observing misidentified or nonprompt leptons based on control samples in data are used.

As an example of the type of BSM models for which this search has sensitivity, we interpret the results of this analysis in the context of SUSY models that feature strong production of pairs of squarks ($\tilde{q}$) or gluinos ($\tilde{g}$). In addition to multiple leptons, these models predict that events can contain multiple jets, b-tagged jets, and missing transverse momentum. Searches probing similar models have been carried out by the ATLAS and CMS Collaborations using pp collisions at 8 TeV [36–44], and at 13 TeV [45–52]. Previous searches exclude models with gluino mass less than approximately 1500 GeV, for a neutralino mass of 50 GeV, and models with bottom squark mass less than 830 GeV.

The result of the search, which is consistent with SM expectation, can also be used to constrain other BSM models not explicitly considered in this paper. To this end, we also provide upper limits on possible BSM contributions in the kinematic tail of the search variables in terms of the product of cross section, detector acceptance, and selection efficiency.

## 2 The CMS detector

The CMS detector features a superconducting solenoid of 6 m internal diameter that creates a magnetic field of 3.8 T. Inside

* e-mail: cms-publication-committee-chair@cern.ch

Springer

the magnet volume are a silicon pixel and strip tracker, an electromagnetic calorimeter (ECAL) made of lead tungstate crystals, and a hadron calorimeter (HCAL) made of brass and scintillator, each composed of a barrel and two endcap sections. Forward calorimeters provide additional pseudorapidity ($\eta$) coverage for the HCAL. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The first level of the CMS trigger system, composed of specialized hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from approximately 100 kHz to less than 1 kHz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [53].

## 3 Event selection and Monte Carlo simulation

Events used in this analysis are selected by the triggers that collect dilepton and multilepton events for later study, using variables constructed by the HLT. One set of triggers requires two leptons satisfying loose isolation criteria and transverse momentum $p_T > 17$ GeV for the leading lepton and $p_T > 12$ (8) GeV for the subleading lepton in the case of electrons (muons). The second set of triggers places no requirements on the isolation, has a lower $p_T$ threshold for the two leptons, $p_T > 8$ GeV, and also requires that the scalar sum of jets with $p_T > 40$ GeV reconstructed in the HLT be greater than 300 GeV.

Electron candidates are reconstructed using tracking and electromagnetic calorimeter information by combining Gaussian sum filter tracks and ECAL energy deposits [54]. The electron identification is performed using a multivariate discriminant built with shower shape, track cluster matching, and track quality variables. The working point for the selection is chosen to maintain approximately 90% efficiency for accepting electrons produced in the decays of W and Z bosons and also to efficiently reject candidates originating from jets. To reject electrons originating from photon conversions, electrons are required to have hits in all possible inner layers of the tracker and to be incompatible with any secondary vertices containing only another electron. The selected electron candidates must have $|\eta| < 2.5$.

Muon candidates are reconstructed in a global fit to the combined information from both the silicon tracker and the muon spectrometer [55]. An identification is performed using the quality of the geometrical matching between measurements in the tracker and the muon system. To ensure the candidates are within the fiducial volume of the detector, we require that the candidate pseudorapidities satisfy $|\eta| < 2.4$.

The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects are the objects returned by a jet finding algorithm [56,57] applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum. Both electron and muon candidates are required to have a transverse (longitudinal) impact parameter of less than 0.5 (1.0) mm from the primary vertex. In addition, a requirement on the three-dimensional impact parameter significance is applied. This variable is the value of the impact parameter divided by its uncertainty and is required to be less than 4 for both electrons and muons. The rejection of nonprompt leptons is more efficient using the impact parameter significance than the value of impact parameter for similar prompt-lepton acceptance.

Lepton isolation is constructed using three different variables. The mini isolation, $I_{\mathrm{mini}}$, is the ratio of the amount of measured energy in a cone to the transverse momentum of the lepton. The radius is $p_T$-dependent: $R_{\mathrm{iso}} = 10\,\mathrm{GeV}/\min(\max(p_T(\ell), 50\,\mathrm{GeV}), 200\,\mathrm{GeV})$, resulting in radii between 0.05 and 0.2. Requiring $I_{\mathrm{mini}}$ to be below a given threshold ensures that the lepton is locally isolated, even in Lorentz-boosted topologies.

The second variable is the ratio of the lepton $p_T$ and the $p_T$ of the jet matched to the lepton: $p_T^{\mathrm{ratio}} = p_T(\ell)/p_T(\mathrm{jet})$. This jet must be separated by no more than 0.4 in $\Delta R$ from the lepton it is matched to, where $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. In most cases, this is the jet containing the lepton. If no jet is found within $\Delta R < 0.4$, then $p_T^{\mathrm{ratio}} = 1$. The use of $p_T^{\mathrm{ratio}}$ is a simple way to identify nonprompt low-$p_T$ leptons originating from low-$p_T$ b-quarks that decay with larger opening angles than the one used in the mini isolation.

The last variable is $p_T^{\mathrm{rel}}$, which is calculated by subtracting the lepton momentum from the momentum vector of the geometrically matched jet described above and then finding the component of the lepton momentum that is transverse to this new vector. If there is no matched jet, $p_T^{\mathrm{rel}} = 0$. This variable allows us to recover leptons from accidental overlap with jets in events where some of the final state particles are close together in Lorentz-boosted topologies.

Using the three variables above, a lepton is considered isolated if $I_{\mathrm{mini}} < I_1$ and that either $p_T^{\mathrm{ratio}} > I_2$ or $p_T^{\mathrm{rel}} > I_3$. The $I_i$ values depend on the flavor of the lepton. The probability to misidentify a jet is higher for electrons, so tighter isolation values are used. The logic behind this isolation is that a lepton should be locally isolated ($I_{\mathrm{mini}}$) and should carry the major part of the energy of the corresponding jet ($p_T^{\mathrm{ratio}}$) unless its overlap with the jet is accidental ($p_T^{\mathrm{rel}}$). For electrons (muons), the tight selection requirements are $I_1 = 0.12$ (0.16), $I_2 = 0.76$ (0.69), and $I_3 = 7.2$ (6.0) GeV. The loose lepton isolation is relaxed to $I_{\mathrm{mini}} < 0.4$, and the other requirements are dropped. The loose leptons are used

for background estimates. These selection requirements were optimized using MC simulations.

The offline selection requires at least three well-identified leptons in the event and any pair of opposite sign and same flavor (OSSF) leptons having an invariant mass greater than 12 GeV to reject low mass Drell–Yan and quarkonium processes. The leptons must pass offline $p_T$ thresholds of 20, 15, and 10 GeV for the first, second, and third lepton, respectively, when $p_T$-ordered. For this offline selection, the trigger efficiency is above 99%.

Jets are reconstructed from particle-flow candidates [58] clustered using the anti-$k_T$ algorithm [56] with a distance parameter of 0.4 as implemented in the FASTJET package [57]. Only jets with $p_T > 30$ GeV and within the tracker acceptance $|\eta| < 2.4$ are considered. Additional criteria are applied to reject events containing noise and mismeasured jets [59–61]. To avoid double counting, the closest matching jets to leptons are not considered if they are separated from the lepton by less than 0.4 in $\Delta R$. From those selected jets, the quantity $H_T$ is defined by $H_T = \sum_{\text{jets}} |\mathbf{p_T}|$, for all jets that satisfy the above-mentioned criteria. Jet energies are corrected for a shift in the energy scale, contributions from additional, simultaneous pp collisions (pileup), and residual nonuniformity and nonlinearity differences between data and simulation [60].

The combined secondary vertex algorithm [62,63] is used to assess the likelihood that a jet originates from a bottom quark (b jet). Jets in this analysis are considered to be b tagged if they pass the algorithm's medium working point, which has a tagging efficiency of approximately 70% and a mistag rate of approximately 1% for light quarks and gluons.

The missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ is defined as the negative vector sum of transverse momenta of all particle-flow candidates reconstructed in the event. Its magnitude is referred to as $p_T^{\text{miss}}$. Jet energy corrections are propagated to the $p_T^{\text{miss}}$ following the procedure described in Ref. [64].

To estimate the contribution of SM processes to the signal regions (described in Sect. 4) and to calculate the efficiency for new physics models, MC simulations are used. All the SM samples are generated using the MADGRAPH5_aMC@NLO 2.2.2 [65–67] program at leading order (LO) or next-to-leading order (NLO) in perturbative QCD, with the exception of the diboson production samples (WZ and ZZ) that are generated using POWHEG v2 [68–72] at NLO precision. The NNPDF3.0 [73] LO (NLO) parton distribution function (PDF) set is used in MC simulations generated at LO (NLO). Parton showering and hadronization are simulated using PYTHIA 8.205 [74] with the underlying event tune CUETP8M1 [75]. The CMS detector response is determined using a GEANT4-based model [76].

Events corresponding to the production of SUSY processes are generated with MADGRAPH5_aMC@NLO at LO precision, allowing up to two additional partons in the matrix element calculations. The SUSY particle decays, parton showering, and hadronization are simulated with PYTHIA. The detector response for signal events is simulated using a CMS fast-simulation package [77] that is validated against the GEANT4-based model. Cross sections for SUSY signal processes, calculated at NLO with next-to-leading-log (NLL) gluon resummation, are taken from the LHC SUSY Cross Section Working Group [78–83]. All simulated events are processed with the same reconstruction procedure as data. They include the effects of additional interactions, which can occur in the same or adjacent beam crossings (pileup). The distribution of additional interactions is matched to that observed in data. The pileup interactions are simulated by overlaying the primary interaction with additional minimum bias events, which are generated with the same PYTHIA configuration as described above.

## 4 Search strategy

The goal of this analysis is to search for possible excesses over the expected yields from SM processes in different categories of events with three or more leptons. With the 2.3 fb$^{-1}$ data sample at $\sqrt{s} = 13$ TeV, the search is focused on strongly produced SUSY particles, which benefit most from the increase of the production cross section with respect to 8 TeV. A few examples of diagrams of simplified models of SUSY processes [84,85] that can give rise to multilepton final states are shown in Fig. 1. In these models, SUSY particles that are not directly included in the diagrams are assumed to be too heavy to be accessible at the LHC. Therefore, the free parameters in these models are usually the mass of the produced particles: gluinos and squarks, as well as the mass of the lightest supersymmetric particle (LSP).

Typical SUSY processes relevant for this work include T1tttt, which corresponds to gluino pair production where each gluino decays to a $t\bar{t}$ pair and the LSP (Fig. 1—top). Another model, referred to as T5qqqqWZ, involves gluino pair production, where each gluino decays to a pair of light quarks (u, d, s, and c) and a neutralino ($\widetilde{\chi}_2^0$) or chargino ($\widetilde{\chi}_1^{\pm}$), followed by decay of the neutralino or the chargino to a W or Z boson, respectively, and the LSP (Fig. 1—middle). The probability for the decay to proceed via $\widetilde{\chi}_1^+$, $\widetilde{\chi}_1^-$, or $\widetilde{\chi}_2^0$ is 1/3 for each case, leading to the probabilities of having WW, ZZ or WZ bosons in the final state to be about 44.5, 11.1, and 44.5%, respectively. Only the final state with WZ bosons contributes significantly to the acceptance of this search. Final states with WW bosons do not contribute, and the contribution from ZZ final states decaying to four leptons is negligibly small. In this scenario the neutralino and chargino are assumed to be mass-degenerate. A model called T6ttWW, features bottom squark pair production with their subsequent cascade decays via top quarks and W bosons
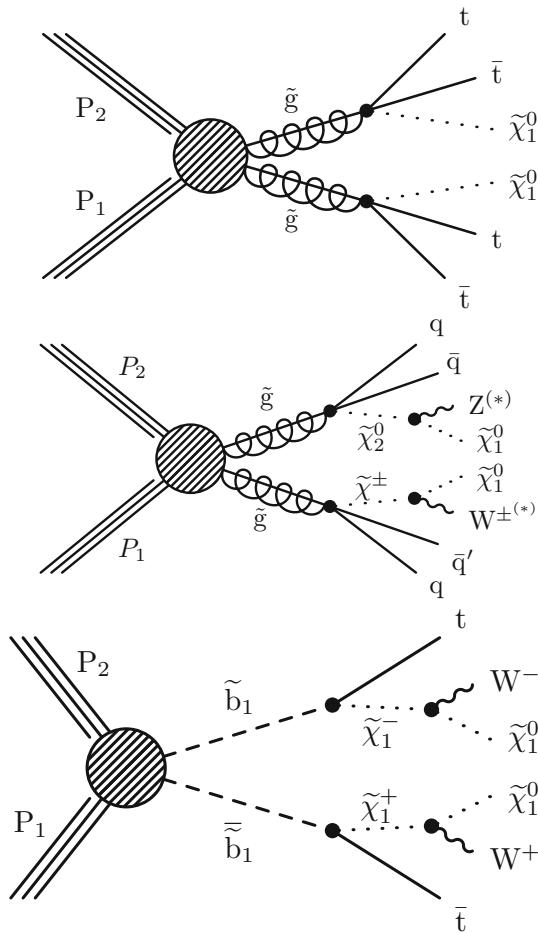
**Fig. 1** Diagrams for gluino and bottom squark pair production leading to multilepton events for simplified models of supersymmetry: (top) T1tttt, (middle) T5qqqqWZ, and (bottom) T6ttWW

(Fig. 1—bottom). The LSP is a neutralino in all of these models.

For the definition of the signal regions (SRs) we use several event variables: the number of b-tagged jets ($N_b$), $H_T$, $p_T^{miss}$, and a classification depending on whether the event contains any OSSF dilepton pairs with an invariant mass between 76 and 106 GeV, i.e. consistent with the Z boson (called "on-Z" if so and "off-Z" otherwise in the following). Events that do not contain any OSSF pairs are included in the off-Z sample.

The separation in b-tagged jet multiplicities maximizes signal-to-background ratios for different signal models. For example, the T1tttt model features several b jets, which would be categorized into SRs which are almost free of WZ background owing to the b-tagged jet requirement. Including the zero b-tagged SRs keeps the analysis sensitive to signatures such as the T5qqqqWZ model. Additionally, a categorization in $H_T$ and $p_T^{miss}$ is useful to distinguish between compressed and noncompressed SUSY spectra, i.e. models with small

or large mass differences between the SUSY particles in the decay chain.

A baseline selection is applied to the data set to select events of interest: three or more electrons or muons satisfying the requirements $p_T \geq 20$, 15, and 10 GeV; $m_{\ell\ell} \geq 12$ GeV; at least two jets; $H_T \geq 60$ GeV; and $p_T^{miss} \geq 50$ GeV. Events containing additional leptons with $p_T > 10$ GeV are included in the event selection. Table 1 shows the definition of the subdivision of the baseline selection into two sets of SRs for events that contain on-Z and off-Z dilepton pairs. There are 15 SRs for each of the two groups, hence in total 30 SRs. A set of four SRs with low or medium $H_T$ and low or medium $p_T^{miss}$ are defined for each of the b-tagged jet multiplicities 0, 1, and 2. Motivated by the low expected yield of events with $N_b \geq 3$, SR 13 is defined for high b-tagged jet multiplicities and also has $p_T^{miss} < 300$ GeV and $H_T < 600$ GeV. Two additional SRs with large $H_T$ (SR 14) and large $p_T^{miss}$ (SR 15), respectively, have been defined as nearly background-free SRs, since noncompressed SUSY models can yield events with very large values of $p_T^{miss}$ or $H_T$. Both of these SRs are inclusive in the number of b-tagged jets, and every selected event with $p_T^{miss} \geq 300$ GeV is categorized in SR 15, while SR 14 is populated with events with $p_T^{miss} < 300$ GeV and $H_T \geq 600$ GeV.

## 5 Background estimation

Backgrounds in the multilepton final states can be divided in three categories:

1. Nonprompt or misidentified leptons are those arising from heavy-flavor decays, misidentified hadrons, electrons from unidentified photon conversions, or muons from light-meson decays in flight. For this analysis, $t\bar{t}$ events can enter the SRs if nonprompt leptons are present in addition to the prompt leptons from the W boson decays. These nonprompt leptons typically originate from semileptonic decays of hadrons containing a b quark, which, in this case, is not reconstructed as a jet. Therefore, $t\bar{t}$ events typically have low $H_T$ and $p_T^{miss}$ and predominately populate SR 1 and SR 5, with 0 and 1 b-tagged jets, respectively.

   In addition to $t\bar{t}$, Drell–Yan events can enter the baseline selection, although they are largely suppressed by the $p_T^{miss} > 50$ GeV requirement. Processes that yield only one prompt lepton, e.g. W+jets and single top quark production, are effectively suppressed by the three-lepton requirement because of the low probability that the two nonprompt leptons pass the tight identification and isolation requirements.

**Table 1** Definition of multilepton signal regions. These regions are the same for the on-Z and off-Z regions

| $N_j$ | $N_b$ | $p_T^{miss}$ (GeV) | $60 \leq H_T < 400\,\text{GeV}$ | $400 \leq H_T < 600\,\text{GeV}$ | $H_T \geq 600\,\text{GeV}$ |
|---|---|---|---|---|---|
| $\geq 2$ | 0 | 50–150 | SR 1 | SR 3 | |
| | | 150–300 | SR 2 | SR 4 | |
| | 1 | 50–150 | SR 5 | SR 7 | SR 14 |
| | | 150–300 | SR 6 | SR 8 | |
| | 2 | 50–150 | SR 9 | SR 11 | |
| | | 150–300 | SR 10 | SR 12 | |
| | $\geq 3$ | 50–300 | SR 13 | | |
| | $\geq 0$ | $\geq 300$ | SR 15 | | |

2. Diboson production could yield multilepton final states with up to three prompt leptons in WZ production and up to four prompt leptons in ZZ production. Especially in signal regions without b-tagged jets, WZ production has a sizable contribution. The normalization of this background is obtained from a dedicated control region enriched in WZ events.

3. Other SM processes that can yield three or more leptons are $t\bar{t}W$, $t\bar{t}Z$, and triboson production VVV where V stands for a W or Z boson. We also include the contribution from the SM Higgs boson produced in association with a vector boson or a pair of top quarks in this category of backgrounds. Processes that produce additional leptons from internal conversions, which are events that contain a virtual photon that decays to leptons, are also included here as $X + \gamma$, where X is predominantly $t\bar{t}$ or Z. Those backgrounds are obtained from simulation and appropriate systematic uncertainties are assigned.

The background contribution from nonprompt and misidentified leptons is estimated using the "tight-to-loose ratio" method [52]. The tight-to-loose ratio $f$ is the probability for a nonprompt lepton that satisfies the loose requirements to also satisfy the full set of requirements. The nonprompt background contribution is obtained from the number of events in an application region containing events with at least one of the leptons failing the full set of tight identification and isolation requirements, but passing the loose requirements, weighted by $f/(1 - f)$. This ratio is measured in a control sample of QCD multijet events that is enriched in nonprompt leptons (measurement region), by requiring exactly one lepton passing the loose object selection and one recoiling jet with $\Delta R(\text{jet}, \ell) > 1.0$. To suppress events with leptons from W and Z boson decays, $p_T^{miss} < 20\,\text{GeV}$ and $M_T < 20\,\text{GeV}$ are also required, where $M_T = \sqrt{2 p_T^{miss} p_T(\ell)(1 - \cos \Delta\phi)}$ and $\Delta\phi$ is the difference in azimuthal angle between the lepton and $\mathbf{p}_T^{miss}$. The remaining contribution from these electroweak processes within the measurement region is subtracted using estimates from MC simulations.

The dependence of the tight-to-loose ratio on the flavor of the jet from which the nonprompt lepton originates is reduced by parameterizing the ratio as a function of a variable that is more strongly correlated with the parent parton $p_T$ than with lepton $p_T$. This variable is calculated by correcting the lepton $p_T$ as a function of the energy in the isolation cone around it. This definition leaves the $p_T$ of the leptons passing the isolation requirement unchanged and modifies the $p_T$ of those failing the requirement, so that it is a better proxy for the parent parton $p_T$ and results in a flatter tight-to-loose ratio as a function of the parent parton $p_T$. The cone correction significantly improves the results of the method when applying it in simulation. The flavor dependence, which is much more important for the case of electrons, is also reduced by adjusting the loose object selection to obtain similar ratios for nonprompt electrons that originate from both light- and heavy-flavor jets. To avoid experimental biases, the tight-to-loose ratio is also measured as a function of $\eta$.

The tight-to-loose ratio method of estimating the nonprompt background is validated in a control region exclusive to our baseline selection with minimal signal contamination. This region is defined by having three tight leptons, one or two jets, $20 < p_T^{miss} < 50\,\text{GeV}$, and an off-Z dilepton pair. We find agreement of the order of 20% between the predicted and observed yields in this control region in data, which validates the predictions and uncertainties of this method.

The WZ process is one of the main backgrounds in the regions with zero b-tagged jets. The relative contribution of this process in various SRs is estimated from the MC simulation at NLO, but the normalization is taken from a control region that is highly enriched for this process: three leptons pass nominal identification and isolation requirements, two leptons form an OSSF pair with $|m_{\ell\ell} - m_Z| < 15\,\text{GeV}$, the number of jets is zero or one, the number of b-tagged jets is zero, $30 < p_T^{miss} < 100\,\text{GeV}$, and the $M_T$ of the third lepton (not in the pair forming the Z) is required to be at least 50 GeV to suppress contamination from Drell–Yan processes. The expected WZ purity in the selected sample is 84%. Using this control region, we find that the WZ background predictions from simulation are consistent with data. The ratio

between the prediction and data obtained with $2.3\,\mathrm{fb}^{-1}$ of data is $1.13 \pm 0.17$. The uncertainty on the normalization of the WZ background includes the statistical uncertainty related to the event yield in the CR and a systematic component related to a small contamination of the CR due to other processes.

## 6 Systematic uncertainties

Systematic uncertainties are characterized as either experimental, theoretical, or arising from the limited size of simulated event samples. These sources of uncertainties and their magnitudes are described below, and are summarized in Table 2. The table also provides the effect of varying the uncertainties by $\pm 1$ standard deviation (s.d.) on the signal and background yields. The jet energy scale uncertainty and the uncertainty in the b tagging efficiency are the only ones that can cause simulated events to migrate between signal regions.

The major experimental source of uncertainty is the knowledge of the jet energy scale (JES), which accounts for differences between kinematical variables from data and simulation and affects signal and background events that are taken from simulation samples [60,61]. For the data set used in this analysis, the uncertainties on the JES vary from 2 to 8%, depending on the $p_T$ and $\eta$ of the jet. The impact of these uncertainties is assessed by shifting the jet energy correction

factors for each jet up and down by $\pm 1$ s.d. and recalculating all of the kinematic quantities. The JES uncertainties are propagated to the missing transverse momentum and all variables derived from jets (numbers of jets and b-tagged jets, and $H_T$) used in this analysis; this propagation results in 1–20% variation in the MC background estimation in the regions with higher data yields.

A similar approach is used for the uncertainties associated with the corrections for the b tagging efficiencies for light-, charm-, and bottom-flavour jets, which are parametrized as a function of $p_T$ and $\eta$ [62,63]. The variation of the scale factor correcting for the differences between data and simulation is at maximum 5–10%, and leads to an effect of 1–20% on the yields, depending on the SR and on the topology of the events under study. If one considers only highly populated SRs to get an overview of the main effects on the background yields, the bulk of the $t\bar{t}W$ yield varies by $\sim$10% and the WZ yield by $\sim$13%.

Lepton identification scale factors have been measured by comparing efficiencies in data and simulation using the "tag-and-probe" method [54,55] and are applied as a function of lepton $p_T$ and $\eta$. The corresponding uncertainties on the scale factors have been evaluated and are approximately 2% for both electrons and muons. Trigger efficiency scale factors have been found to be very close to unity. An uncertainty of 3% in the scale factors has, however, been assigned to cover the difference between trigger efficiencies measured in simulation over a large number of samples.

**Table 2** Summary of the sources of uncertainties and their magnitudes. The third column provides the changes in yields of signal and background induced by one s.d. changes in the magnitude of uncertainties

| Source | Magnitude (%) | Effect on yield (%) |
|---|---|---|
| Integrated luminosity [88] | 2.7 | 2.7[a] |
| Limited MC sample sizes | 1–100 | 1–100[a] |
| Jet energy scale | 2–8 | 1–20[a] |
| b tagging efficiency | 5–10 | 1–20[a] |
| Pileup | 5 | 3[a] |
| Renormalization and factorization scales | −50 / +100 | 11–13 (cross-section) / 3–18 (acceptance) ($t\bar{t}W,t\bar{t}Z,t\bar{t}H$) |
| PDF | — | 2–3 ($t\bar{t}W,t\bar{t}Z,t\bar{t}H$) |
| Other backgrounds | 50 | 50 (rare processes, tribosons, etc.) |
| Lepton efficiencies | 2 | 6[a] |
| Trigger efficiencies | 3 | 3[a] |
| FastSim lepton efficiencies | 3–10 | 3–10 FastSim signals |
| FastSim trigger efficiencies | 5 | 5 FastSim signals |
| Tight-to-loose ratio control region statistical uncertainty | 1–100 | 1–100 (nonprompt bkg. only) |
| Tight-to-loose ratio systematic uncertainty | 30 | 30 (nonprompt bkg. only) |
| EW subtraction in tight-to-loose ratio | 100 (ewk. SF) | 1–5 (nonprompt bkg. only) |
| WZ control region normalization | 15 | 15 (WZ only) |
| WZ extrapolation | 10–30 | 2–30 (WZ only) |

[a] Applied to both signal and background simulation samples

All these uncertainties related to corrections of the simulation (JES corrections, b tagging efficiency scale factors, lepton identification and trigger scale factors) have been estimated also for the fast simulation used for the signal samples. We propagate them to the expected signal yields following the same procedure.

The uncertainties in the renormalization ($\mu_R$) and factorization scales ($\mu_F$) and the PDF are considered for some of the rare processes, namely $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$. Both the changes in the acceptance and cross sections due to those effects are taken into account.

For the study of the renormalization and factorization scale uncertainties, variations up and down by a factor of two with respect to the nominal values of $\mu_R$ and $\mu_F$ are considered. The maximum difference in the yields with respect to the nominal case is observed when both scales are varied simultaneously up and down. The effect on the overall cross section is found to be about 13% for $t\bar{t}W$ and about 11% for $t\bar{t}Z$. An additional uncertainty in the acceptance corresponding to different signal regions is included. This is found to be between 3 and 18% depending on the SR and process.

The uncertainty related to the PDFs is estimated from the 100 NNPDF 3.0 replicas by computing the deviation with respect to the nominal yields for each of them, and for each signal region (the cross section and acceptance effects are considered together) [86]. The root mean square of the variations is taken as the value of the systematic uncertainty. Since no significant variations among the different signal regions are seen, a flat uncertainty of 3(2)% is applied to the $t\bar{t}W$ ($t\bar{t}Z$) background. This value also includes the deviation resulting from varying the strong coupling strength $\alpha_S(M_Z)$, which is added in quadrature, and whose magnitude is similar to or smaller than that of the PDF set uncertainty. For the $t\bar{t}H$ process, the same uncertainties as estimated for $t\bar{t}Z$ are applied. A theoretical uncertainty of 50% is assigned to the remaining rare processes.

In signal samples, the uncertainty due to initial-state radiation is computed as a function of the $p_T$ of the gluino pair using the methods described in Ref. [87]. For values below 400 GeV, no uncertainty is applied. For values between 400 and 600 GeV, a 15% uncertainty is assigned, and above 600 GeV this uncertainty is increased to 30%.

The limited size of the generated MC samples represents an additional source of uncertainty. The uncertainty in signal processes and backgrounds such as $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$, is calculated from the number of MC events entering each of the signal regions.

For the nonprompt and misidentified lepton background, we assign several systematic uncertainties. The statistical uncertainty resulting from the limited number of events in the application region used to estimate this background contribution varies from 1 to 100%. The regions where these uncertainties are large are generally regions where the overall contribution of this background is small. When no events are observed in the application region, the upper limit of the background expectation is set to 0.35, which is found by applying the most probable tight-to-loose ratio as if the application region contained an event count equal to the variance of a Poisson distribution with a mean of zero.

The systematic uncertainties related to the extrapolation from the control regions to the SRs for the nonprompt lepton background are estimated to be 30%. This magnitude has been extracted from the level of closure achieved in a test that was performed with MC samples yielding nonprompt leptons to validate background predictions based on control samples in data, as described in Sect. 5.

The uncertainty associated with the electroweak (EW) background subtraction in the tight-to-loose ratio computation is propagated through the full analysis process by replacing the nominal tight-to-loose ratio with another value obtained when the scale factor applied to the electroweak processes in the measurement region is varied by 100% of its difference from unity. The overall effect on the nonprompt background yield lies between 1 and 5% depending on the SR considered.

The estimate of the WZ background is assigned a 15% normalization uncertainty using the measurement in a dedicated control region. This uncertainty is compatible with the one quoted for the experimental measurement of this process in Ref. [33]. Additional uncertainties for the extrapolation from the control region to the signal regions of 10–30% are taken into account depending on the SR. These uncertainties are dominated by the JES and b tagging uncertainties described earlier.

Finally the uncertainty on the integrated luminosity is 2.7% [88].

## 7 Results and interpretations

Expected event yields are compared to the observation in Tables 3 and 4. Comparisons of distributions of $H_T$, $p_T^{miss}$, $N_j$, $N_b$, leading lepton $p_T$, subleading lepton $p_T$, and trailing lepton $p_T$ measured in data with those predicted by the background estimation methods are shown in Fig. 2 (Fig. 3), using all the events satisfying the off-Z (on-Z) SR selection criteria. The nonprompt lepton background comes from the technique described in Sect. 5. The hatched band represents the total background uncertainty in each bin. A graphical summary of predicted backgrounds and observed event yields in individual SRs is also shown. In these figures, the "rare" component is the sum over several SM processes, such as triboson production, associated Higgs production, $t\bar{t}t\bar{t}$, and other lower cross section processes.

The number of events observed in data is found to be consistent with predicted SM background yields. The results

**Table 3** Off-Z SRs: Comparison of observed event yields in data with predicted background yields

| $N_b$ | $H_T$ (GeV) | $p_T^{miss}$ (GeV) | Predicted | Observed | SR (off-Z) |
|---|---|---|---|---|---|
| 0 b-tags | 60–400 | 50–150 | $19.26^{+4.81}_{-4.80}$ | 18 | SR 1 |
| | | 150–300 | $1.16^{+0.31}_{-0.20}$ | 4 | SR 2 |
| | 400–600 | 50–150 | $1.20^{+0.47}_{-0.40}$ | 3 | SR 3 |
| | | 150–300 | $0.29^{+0.44}_{-0.09}$ | 0 | SR 4 |
| 1 b-tags | 60–400 | 50–150 | $16.57 \pm 4.52$ | 24 | SR 5 |
| | | 150–300 | $2.32^{+0.80}_{-0.76}$ | 1 | SR 6 |
| | 400–600 | 50–150 | $0.67^{+0.45}_{-0.09}$ | 2 | SR 7 |
| | | 150–300 | $0.48^{+0.29}_{-0.07}$ | 0 | SR 8 |
| 2 b-tags | 60–400 | 50–150 | $4.49^{+1.81}_{-1.79}$ | 4 | SR 9 |
| | | 150–300 | $0.31^{+0.44}_{-0.09}$ | 1 | SR 10 |
| | 400–600 | 50–150 | $0.40^{+0.27}_{-0.26}$ | 0 | SR 11 |
| | | 150–300 | $0.08^{+0.43}_{-0.08}$ | 0 | SR 12 |
| $\geq 3$ b-tags | 60–600 | 50–300 | $0.13^{+0.43}_{-0.09}$ | 0 | SR 13 |
| $\geq 0$ b-tags | >600 | 50–300 | $1.84^{+0.44}_{-0.37}$ | 3 | SR 14 |
| $\geq 0$ b-tags | $\geq 0$ | $\geq 300$ | $1.62^{+1.22}_{-1.19}$ | 0 | SR 15 |

**Table 4** On-Z SRs: Comparison of observed event yields in data with predicted background yields

| $N_b$ | $H_T$ (GeV) | $p_T^{miss}$ (GeV) | Predicted | Observed | SR (on-Z) |
|---|---|---|---|---|---|
| 0 b-tags | 60–400 | 50–150 | $38.01 \pm 5.92$ | 39 | SR 1 |
| | | 150–300 | $4.48^{+0.84}_{-0.75}$ | 3 | SR 2 |
| | 400–600 | 50–150 | $4.88^{+1.49}_{-1.47}$ | 4 | SR 3 |
| | | 150–300 | $1.88^{+0.47}_{-0.39}$ | 3 | SR 4 |
| 1 b-tags | 60–400 | 50–150 | $11.84^{+2.28}_{-2.26}$ | 14 | SR 5 |
| | | 150–300 | $1.53^{+0.42}_{-0.34}$ | 1 | SR 6 |
| | 400–600 | 50–150 | $1.18^{+0.49}_{-0.23}$ | 1 | SR 7 |
| | | 150–300 | $0.42^{+0.44}_{-0.10}$ | 3 | SR 8 |
| 2 b-tags | 60–400 | 50–150 | $2.55^{+0.67}_{-0.51}$ | 2 | SR 9 |
| | | 150–300 | $0.72^{+0.76}_{-0.28}$ | 0 | SR 10 |
| | 400–600 | 50–150 | $0.55^{+0.45}_{-0.13}$ | 0 | SR 11 |
| | | 150–300 | $0.31^{+0.51}_{-0.17}$ | 0 | SR 12 |
| $\geq 3$ b-tags | 60–600 | 50–300 | $0.21^{+0.44}_{-0.13}$ | 0 | SR 13 |
| $\geq 0$ b-tags | >600 | 50–300 | $4.22^{+0.68}_{-0.63}$ | 5 | SR 14 |
| $\geq 0$ b-tags | $\geq 0$ | $\geq 300$ | $1.41^{+0.50}_{-0.25}$ | 1 | SR 15 |

are used to calculate upper limits on the production cross section of gluinos or squarks for the various models discussed in Sect. 4, as a function of the gluino or squark, and the chargino or neutralino masses. For each mass hypothesis, the observation, background predictions, and expected signal yields from all on-Z and off-Z SRs are combined to extract an upper limit on the cross section, at 95% confidence level (CL) using the asymptotic formulation of the LHC-style CL$_s$ method [89–92]. Log-normal nuisance parameters are used to describe the systematic uncertainties listed in Sect. 6.

These upper limits are used to calculate exclusion contours on the concerned sparticles mass plane, shown in Fig. 4 for the simplified models under consideration. In these figures, the thick black lines delineate the observed exclusion region, which is at the lower masses side. The uncertainty in the observed limit, represented by the thinner black lines, is the propagation of the NLO + NLL cross section uncertainties for the relevant signal process [78–81]. The red dashed lines represent the expected limits with the uncertainties reflecting those discussed in Sect. 6.

**Fig. 2** Off-Z samples: from left to right, top to bottom, distributions of $H_T$, $p_T^{miss}$, $N_j$, $N_b$, $p_T$ of leptons for the predicted backgrounds and for the data in the off-Z baseline selection region, in these plots the rightmost bin contains the overflow from counts outside the range of the plot. On the bottom-right corner the total predicted background and the number of events observed in the 15 off-Z SRs is shown
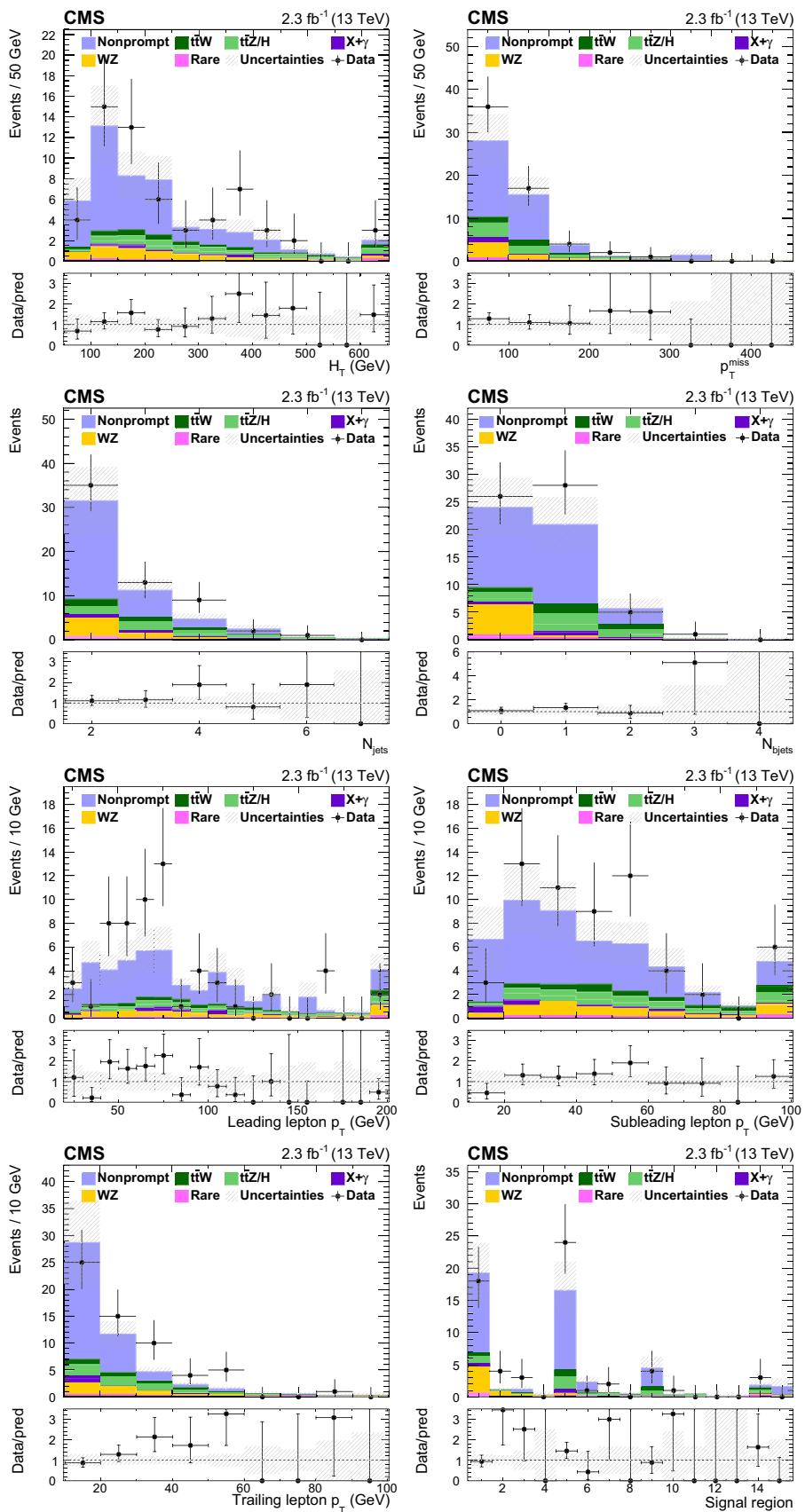
**Fig. 3** On-Z samples: from left to right, top to bottom, distributions of $H_T$, $p_T^{miss}$, $N_j$, $N_b$, $p_T$ of leptons for the predicted backgrounds and for the data in the on-Z baseline selection region, in these plots the rightmost bin contains the overflow from counts outside the range of the plot. On the bottom-right corner the total predicted background and the number of events observed in the 15 on-Z SRs is shown
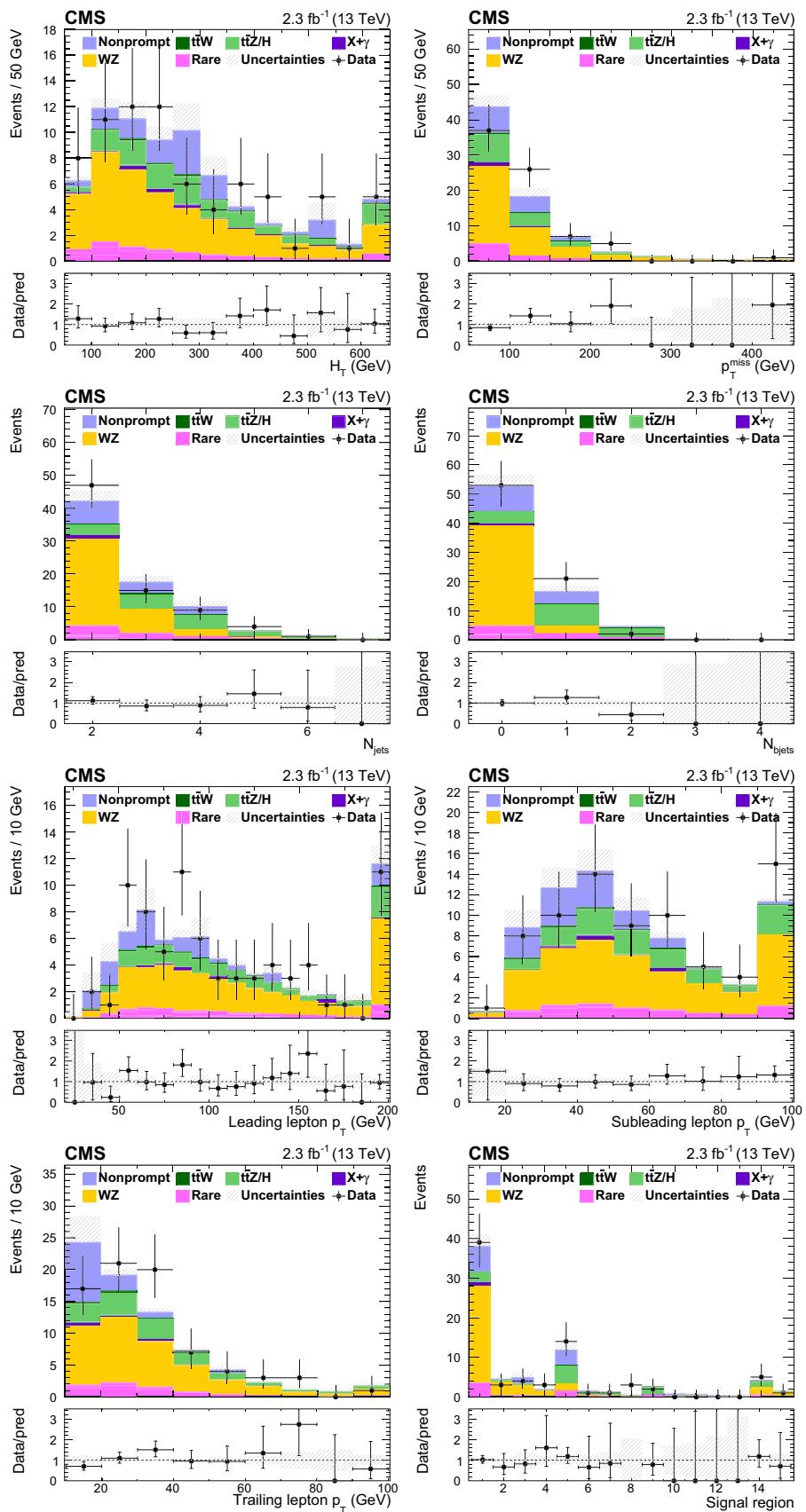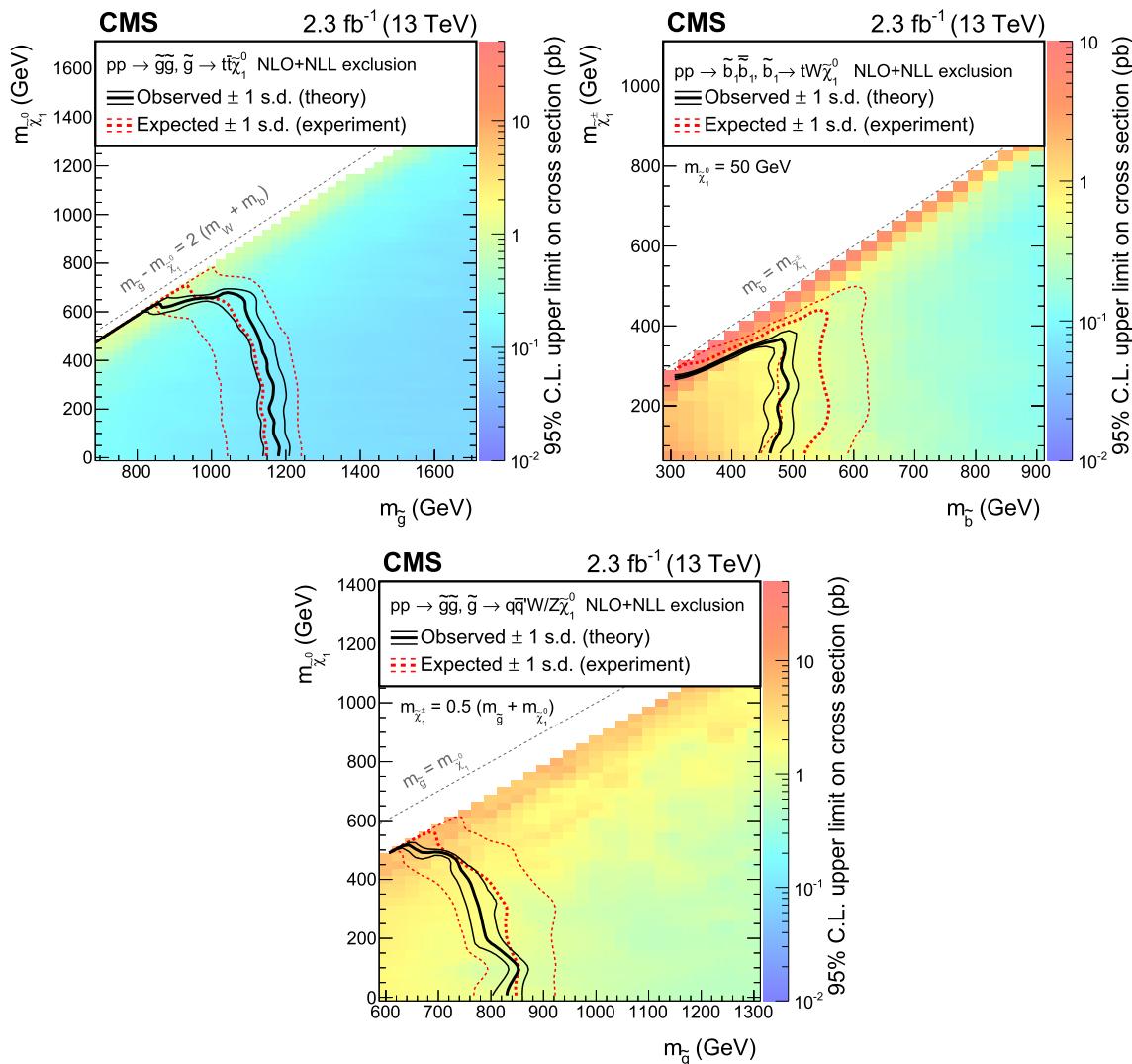
**Fig. 4** Exclusion contours as a function of $m_{\tilde{g}}$ or $m_{\tilde{b}}$, and $m_{\tilde{\chi}^0}$ or $m_{\tilde{\chi}^\pm}$, for the simplified SUSY models (top-left) T1tttt, (top-right) T6ttWW, and (bottom) T5qqqqWZ. The color scale indicates the 95% CL observed upper limits on the cross section. The observed (expected) exclusion curves are indicated by the solid (dashed) lines using NLO+NLL production cross sections, along with the corresponding $\pm 1$ s.d. theoretical (experimental) uncertainties

The yields and background predictions can be used to test additional BSM physics scenarios. To facilitate such reinterpretations, we provide limits on the number of multilepton events as a function of the $p_T^{miss}$ threshold in the kinematic tails of this search. These limits are obtained based on the tails of our SRs, in particular we consider events with $H_T > 400$ GeV, both with and without an on-Z lepton pair, employing the LHC-style $CL_s$ method carried out with pseudo-experiments [89–91]. They are shown in Fig. 5 in terms of the product of cross section ($\sigma$), detector acceptance ($A$), and selection efficiency ($\epsilon$). As we increase the $p_T^{miss}$ threshold, the observed and expected limits converge to 1.3 fb.

## 8 Summary

We have presented the search for beyond-the-standard-model physics in final states with at least 3 leptons, electrons or muons, using proton–proton data collected with the CMS detector at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 2.3 fb$^{-1}$. The analysis makes use of techniques based on control samples in data to estimate reducible backgrounds and to validate the simulation for use in estimating irreducible backgrounds. To maximize sensitivity to a broad range of possible signal models, we investigate 30 exclusive signal regions. The event yields observed in data are in agreement with the standard model background predictions.
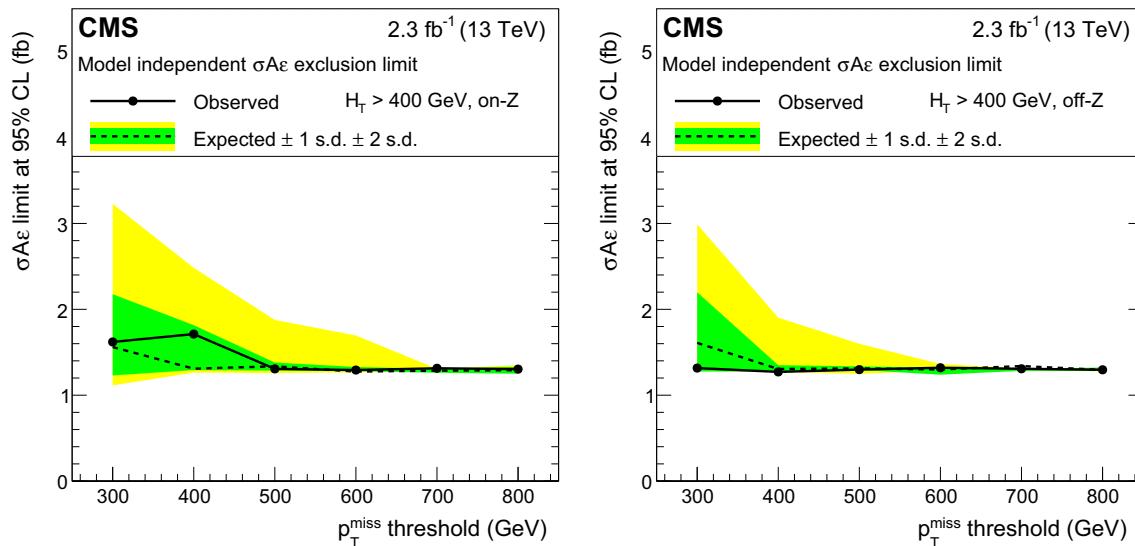
**Fig. 5** Limits on the product of cross section, detector acceptance, and selection efficiency, $\sigma A \epsilon$, for the production of multilepton events with (left) or without (right) an on-Z lepton pair as a function of the $p_T^{miss}$ threshold

This search is designed to be sensitive to multiple BSM models. As an example, we interpret the result in the context of a gluino-pair production model that features cascade decays producing four top quarks in the final state. In this simplified model, we exclude gluinos with a mass of up to 1175 GeV in the case of a massless lightest supersymmetric particle (LSP). For gluino masses up to approximately 1150 GeV, neutralino masses below 650 GeV are excluded. These are the first CMS results reported in this final state at $\sqrt{s} = 13$ TeV.

In a bottom squark pair production model with cascade decays that contain two top quarks and two additional $W^{\pm}$ bosons, we also set limits on the masses of the bottom squark and the chargino. We exclude bottom squarks with a mass of up to 450 GeV in the case of a chargino with a mass of 200 GeV. For bottom squark masses up to approximately 450 GeV, neutralino masses below 300 GeV are excluded. In a similar search at $\sqrt{s} = 8$ TeV [42], the bottom squark mass limit was slightly larger and the chargino mass limit was approximately the same.

An additional interpretation is presented in a gluino pair production model with four light quarks and two vector bosons in the final state. For the case of one W and one Z boson in the final state, we exclude gluino masses up to 825 GeV when the LSP mass is 100 GeV, and LSP masses up to 500 GeV for 700 GeV gluinos.

Finally, limits on the number of multilepton events with $H_T > 400$ GeV as a function of $p_T^{miss}$ threshold are also presented in terms of the product of cross section, detector acceptance, and selection efficiency. For a $p_T^{miss}$ threshold greater than 500 GeV, the observed and expected limits are 1.3 fb.

# References

1. O.J.P. Eboli, R. Zukanovich, T.L.Lungov Funchal, Multilepton signatures for leptoquarks. Phys. Rev. D **59**, 035002 (1999). doi:10.1103/PhysRevD.59.035002. arXiv:hep-ph/9808288
2. N. Craig et al., Searching for $t \rightarrow ch$ with multileptons. Phys. Rev. D **86**, 075002 (2012). doi:10.1103/PhysRevD.86.075002. arXiv:1207.6794
3. N. Craig et al., Heavy Higgs bosons at low tan $\beta$: from the LHC to 100 TeV. JHEP **01**, 018 (2017). doi:10.1007/JHEP01(2017)018. arXiv:1605.08744
4. N. Craig et al., Multi-lepton signals of multiple Higgs bosons. JHEP **02**, 033 (2013). doi:10.1007/JHEP02(2013)033. arXiv:1210.0559
5. C.-S. Chen, Y.-J. Zheng, LHC signatures for the cascade see-saw mechanism. PTEP **2015**, 103B02 (2015). doi:10.1093/ptep/ptv134. arXiv:1312.7207
6. P. Ramond, Dual theory for free fermions. Phys. Rev. D **3**, 2415 (1971). doi:10.1103/PhysRevD.3.2415
7. Y.A. Gol'fand, E.P. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance. JETP Lett. **13** (1971) 323. http://www.jetpletters.ac.ru/ps/1584/article_24309.pdf
8. A. Neveu, J.H. Schwarz, Factorizable dual model of pions. Nucl. Phys. B **31**, 86 (1971). doi:10.1016/0550-3213(71)90448-2
9. D.V. Volkov, V.P. Akulov, Possible universal neutrino interaction. JETP Lett.**16** 438 (1972). http://www.jetpletters.ac.ru/ps/1766/article_26864.pdf
10. J. Wess, B. Zumino, A lagrangian model invariant under super-gauge transformations. Phys. Lett. B **49**, 52 (1974). doi:10.1016/0370-2693(74)90578-4
11. J. Wess, B. Zumino, Supergauge transformations in four-dimensions. Nucl. Phys. B **70**, 39 (1974). doi:10.1016/0550-3213(74)90355-1
12. P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino. Nucl. Phys. B **90**, 104 (1975). doi:10.1016/0550-3213(75)90636-7
13. H.P. Nilles, Supersymmetry, supergravity and particle physics. Phys. Rep. **110**, 1 (1984). doi:10.1016/0370-1573(84)90008-5
14. S.P. Martin, A Supersymmetry Primer, in *Perspectives on Supersymmetry II*, vol. 21 Adv. Ser. Direct. High Energy Phys. G.L. Kane, ed., (World Scientific, 2010), p. 1. doi:10.1142/9789814307505_0001. arXiv:hep-ph/9709356
15. H. Baer, C. Chen, F. Paige, X. Tata, Signals for minimal supergravity at the CERN Large Hadron Collider. 2: Multilepton channels. Phys. Rev. D **53**, 6241 (1996). doi:10.1103/PhysRevD.53.6241. arXiv:hep-ph/9512383
16. A. Lazopoulos, T. McElmurry, K. Melnikov, F. Petriello, Next-to-leading order QCD corrections to t̄tZ production at the LHC. Phys. Lett. B **666**, 62 (2008). doi:10.1016/j.physletb.2008.06.073. arXiv:0804.2220
17. A. Kardos, Z. Trocsanyi, C. Papadopoulos, Top quark pair production in association with a Z-boson at NLO accuracy. Phys. Rev. D **85**, 054015 (2012). doi:10.1103/PhysRevD.85.054015. arXiv:1111.0610
18. J.M. Campbell, R.K. Ellis, t̄tW$^{\pm}$ production and decay at NLO. JHEP **07**, 052 (2012). doi:10.1007/JHEP07(2012)052. arXiv:1204.5678
19. J. Campbell, R.K. Ellis, R. Röntsch, Single top production in association with a Z boson at the LHC. Phys. Rev. D **87**, 114006 (2013). doi:10.1103/PhysRevD.87.114006. arXiv:1302.3856
20. A. Kulesza, L. Motyka, T. Stebel, V. Theeuwes, Soft gluon resummation for associated t̄tH production at the LHC. JHEP **03**, 065 (2016). doi:10.1007/JHEP03(2016)065. arXiv:1509.02780
21. A. Broggio et al., Associated production of a top pair and a Higgs boson beyond NLO. JHEP **03**, 124 (2016). doi:10.1007/JHEP03(2016)124. arXiv:1510.01914
22. M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann, W$^{\pm}$Z production at the LHC: fiducial cross sections and distributions in NNLO QCD. JHEP **05**, 139 (2017). doi:10.1007/JHEP05(2017)139. arXiv:1703.09065
23. F. Cascioli et al., ZZ production at hadron colliders in NNLO QCD. Phys. Lett. B **735**, 311 (2014). doi:10.1016/j.physletb.2014.06.056. arXiv:1405.2219
24. F. Caola, K. Melnikov, R. Röntsch, L. Tancredi, QCD corrections to ZZ production in gluon fusion at the LHC. Phys. Rev. D **92**, 094028 (2015). doi:10.1103/PhysRevD.92.094028. arXiv:1509.06734
25. J.M. Campbell, R.K. Ellis, M. Czakon, S. Kirchner, Two loop correction to interference in gg → ZZ. JHEP **08**, 011 (2016). doi:10.1007/JHEP08(2016)011. arXiv:1605.01380

26. T. Binoth, G. Ossola, C.G. Papadopoulos, R. Pittau, NLO QCD corrections to tri-boson production. JHEP **06**, 082 (2008). doi:10.1088/1126-6708/2008/06/082. arXiv:0804.0350

27. D.T. Nhung, L.D. Ninh, M.M. Weber, NLO corrections to WWZ production at the LHC. JHEP **12**, 096 (2013). doi:10.1007/JHEP12(2013)096. arXiv:1307.7403

28. S. Yong-Bai et al., NLO QCD + NLO EW corrections to WZZ productions with leptonic decays at the LHC. JHEP **10**, 186 (2015). doi:10.1007/JHEP10(2016)156. arXiv:1507.03693. [Erratum: JHEP 10 (2016) 156. doi:10.1007/JHEP10(2015)186]

29. Y.-B. Shen et al., NLO QCD and electroweak corrections to WWW production at the LHC. Phys. Rev. D **95**, 073005 (2017). doi:10.1103/PhysRevD.95.073005. arXiv:1605.00554

30. W. Hong et al., NLO QCD + EW corrections to ZZZ production with subsequent leptonic decays at the LHC. J. Phys. G **43**, 115001 (2016). doi:10.1088/0954-3899/43/11/115001. arXiv:1610.05876

31. ATLAS Collaboration, Measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections in multilepton final states using 3.2 fb$^{-1}$ of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector. Eur. Phys. J. C **77**, 40 (2017). doi:10.1140/epjc/s10052-016-4574-y. arXiv:1609.01599

32. ATLAS Collaboration, Measurement of the $W^{\pm}Z$ boson pair-production cross section in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector. Phys. Lett. B **762**, 1 (2016). doi:10.1016/j.physletb.2016.08.052. arXiv:1606.04017

33. CMS Collaboration, Measurement of the WZ production cross section in pp collisions at $\sqrt{s}$ = 13 TeV. Phys. Lett. B **766**, 268 (2017). doi:10.1016/j.physletb.2017.01.011. arXiv:1607.06943

34. ATLAS Collaboration, Measurement of the $ZZ$ production cross section in $pp$ collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector. Phys. Rev. Lett. **116**, 101801 (2016). doi:10.1103/PhysRevLett.116.101801. arXiv:1512.05314

35. CMS Collaboration, Measurement of the ZZ production cross section and Z $\rightarrow \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$ branching fraction in pp collisions at $\sqrt{s}$=13 TeV. Phys. Lett. B **763**, 280 (2016). doi:10.1016/j.physletb.2016.10.054. arXiv:1607.08834

36. ATLAS Collaboration, Search for supersymmetry at $\sqrt{s}$ = 8 TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector. JHEP **06**, 035 (2014). doi:10.1007/JHEP06(2014)035. arXiv:1404.2500

37. ATLAS Collaboration, Search for strong production of supersymmetric particles in final states with missing transverse momentum and at least three b-jets at $\sqrt{s}$= 8 TeV proton-proton collisions with the ATLAS detector. JHEP **10**, 024 (2014). doi:10.1007/JHEP10(2014)024. arXiv:1407.0600

38. ATLAS Collaboration, Search for squarks and gluinos in events with isolated leptons, jets and missing transverse momentum at $\sqrt{s}$ = 8 TeV with the ATLAS detector. JHEP **04**, 116 (2015). doi:10.1007/JHEP04(2015)116. arXiv:1501.03555

39. ATLAS Collaboration, Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector. Eur. Phys. J. C **75**, 299, (2015). doi:10.1140/epjc/s10052-015-3517-3. arXiv:1502.01518. [Erratum: *Eur. Phys. J. C***75**, 408, (2015). doi:10.1140/epjc/s10052-015-3639-7]

40. CMS Collaboration, Search for anomalous production of events with three or more leptons in pp collisions at $\sqrt{s}$ = 8 TeV. Phys. Rev. D **90**, 032006 (2014). doi:10.1103/PhysRevD.90.032006. arXiv:1404.5801

41. CMS Collaboration, Search for top-squark pairs decaying into Higgs or Z bosons in pp collisions at $\sqrt{s}$=8 TeV. Phys. Lett. B **736**, 371 (2014). doi:10.1016/j.physletb.2014.07.053. arXiv:1405.3886

42. CMS Collaboration, Searches for supersymmetry based on events with b jets and four W bosons in pp collisions at 8 TeV. Phys. Lett. B **745**, 5 (2015). doi:10.1016/j.physletb.2015.04.002. arXiv:1412.4109

43. CMS Collaboration, Search for top squarks in *R*-parity-violating supersymmetry using three or more leptons and b-tagged jets. Phys. Rev. Lett. **111**, 221801 (2013). doi:10.1103/PhysRevLett.111.221801. arXiv:1306.6643

44. CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s}$ = 8 TeV in final states with boosted W bosons and b jets using razor variables. Phys. Rev. D **93**, 092009 (2016). doi:10.1103/PhysRevD.93.092009. arXiv:1602.02917

45. ATLAS Collaboration, Search for supersymmetry at $\sqrt{s}$ = 13 TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector. Eur. Phys. J. C **76**, 259 (2016). doi:10.1140/epjc/s10052-016-4095-8. arXiv:1602.09058

46. ATLAS Collaboration, Search for squarks and gluinos in final states with jets and missing transverse momentum at $\sqrt{s}$ = 13 TeV with the ATLAS detector. Eur. Phys. J. C **76**, 392 (2016). doi:10.1140/epjc/s10052-016-4184-8. arXiv:1605.03814

47. ATLAS Collaboration, Search for gluinos in events with an isolated lepton, jets and missing transverse momentum at $\sqrt{s}$ = 13 TeV with the ATLAS detector. Eur. Phys. J. C **76**, 565 (2016). doi:10.1140/epjc/s10052-016-4397-x. arXiv:1605.04285

48. ATLAS Collaboration, Search for pair production of gluinos decaying via stop and sbottom in events with b-jets and large missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector. Phys. Rev. D **94**, 032003 (2016). doi:10.1103/PhysRevD.94.032003. arXiv:1605.09318

49. CMS Collaboration, Search for supersymmetry in the multijet and missing transverse momentum final state in pp collisions at 13 TeV. Phys. Lett. B **758**, 152 (2016). doi:10.1016/j.physletb.2016.05.002. arXiv:1602.06581

50. CMS Collaboration, Search for new physics with the M$_{T2}$ variable in all-jets final states produced in pp collisions at $\sqrt{s}$ = 13 TeV. JHEP **10**, 006 (2016). doi:10.1007/JHEP10(2016)006. arXiv:1603.04053

51. CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s}$ = 13 TeV in the single-lepton final state using the sum of masses of large-radius jets. JHEP **08**, 122 (2016). doi:10.1007/JHEP08(2016)122. arXiv:1605.04608

52. CMS Collaboration, Search for new physics in same-sign dilepton events in proton–proton collisions at $\sqrt{s}$ = 13 TeV. Eur. Phys. J. C **76**, 439 (2016). doi:10.1140/epjc/s10052-016-4261-z. arXiv:1605.03171

53. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). doi:10.1088/1748-0221/3/08/S08004

54. CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s}$ = 8 TeV. JINST **10**, P06005 (2015). doi:10.1088/1748-0221/10/06/P06005. arXiv:1502.02701

55. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s}$ = 7 TeV. JINST **7**, P10002 (2012). doi:10.1088/1748-0221/7/10/P10002. arXiv:1206.4071

56. M. Cacciari, G.P. Salam, G. Soyez, The anti-$k_t$ jet clustering algorithm. JHEP **04**, 063 (2008). doi:10.1088/1126-6708/2008/04/063. arXiv:0802.1189

57. M. Cacciari, G.P. Salam, G. Soyez, FastJet User Manual. Eur. Phys. J. C **72**, 1896 (2012). doi:10.1140/epjc/s10052-012-1896-2. arXiv:1111.6097

58. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. JINST (2017) (**Accepted**). arXiv:1706.04965

59. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. JINST **6**, P11002 (2011). doi:10.1088/1748-0221/6/11/P11002. arXiv:1107.4277

60. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV. JINST **12**, P02014 (2017). doi:10.1088/1748-0221/12/02/P02014. arXiv:1607.03663

61. CMS Collaboration, Jet algorithms performance in 13 TeV data. CMS physics analysis summary CMS-PAS-JME-16-003 (2010). https://cds.cern.ch/record/2256875

62. CMS Collaboration, Identification of b-quark jets with the CMS experiment. JINST **8**, P04013 (2013). doi:10.1088/1748-0221/8/04/P04013. arXiv:1211.4462

63. CMS Collaboration, Identification of b quark jets at the CMS experiment in the LHC run 2. CMS physics analysis summary CMS-PAS-BTV-15-001 (2016). https://cds.cern.ch/record/2138504

64. CMS Collaboration, Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV. JINST **10**, P02006 (2015). doi:10.1088/1748-0221/10/02/P02006. arXiv:1411.0511

65. J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. JHEP **07**, 079 (2014). doi:10.1007/JHEP07(2014)079. arXiv:1405.0301

66. J. Alwall et al., Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions. Eur. Phys. J. C **53**, 473 (2008). doi:10.1140/epjc/s10052-007-0490-5. arXiv:0706.2569

67. R. Frederix, S. Frixione, Merging meets matching in MC@NLO. JHEP **12**, 061 (2012). doi:10.1007/JHEP12(2012)061. arXiv:1209.6215

68. P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms. JHEP **11**, 040 (2004). doi:10.1088/1126-6708/2004/11/040. arXiv:hep-ph/0409146

69. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. JHEP **11**, 070 (2007). doi:10.1088/1126-6708/2007/11/070. arXiv:0709.2092

70. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP **06**, 043 (2010). doi:10.1007/JHEP06(2010)043. arXiv:1002.2581

71. T. Melia, P. Nason, R. Rontsch, G. Zanderighi, $W^+W^-$, WZ and ZZ production in the POWHEG BOX. JHEP **11**, 078 (2011). doi:10.1007/JHEP11(2011)078. arXiv:1107.5051

72. P. Nason, G. Zanderighi, $W^+W^-$, WZ and ZZ production in the POWHEG-BOX-V2. Eur. Phys. J. C **74**, 2702 (2014). doi:10.1140/epjc/s10052-013-2702-5. arXiv:1311.1365

73. NNPDF Collaboration, Parton distributions for the LHC run II. JHEP **04** 040, (2015). doi:10.1007/JHEP04(2015)040 arXiv:1410.8849

74. T. Sjöstrand et al., An introduction to PYTHIA 8.2. Comput. Phys. Commun. **191**, 159 (2015). doi:10.1016/j.cpc.2015.01.024. arXiv:1410.3012

75. CMS Collaboration, Underlying event tunes and double parton scattering. CMS physics analysis summary CMS-PAS-GEN-14-001 (2014). https://cds.cern.ch/record/1697700

76. GEANT4 Collaboration, Geant4—a simulation toolkit. Nucl. Instrum. Meth. A **506**, 250 (2003). doi:10.1016/S0168-9002(03)01368-8

77. D. Orbaker (on behalf of the CMS Collaboration), Fast simulation of the CMS detector. J. Phys. Conf. Ser. **219**, 032053 (2010). doi:10.1088/1742-6596/219/3/032053

78. A. Kulesza, L. Motyka, Threshold resummation for squark–antisquark and gluino-pair production at the LHC. Phys. Rev. Lett. **102**, 111802 (2009). doi:10.1103/PhysRevLett.102.111802. arXiv:0807.2405

79. A. Kulesza, L. Motyka, Soft gluon resummation for the production of gluino–gluino and squark–antisquark pairs at the LHC. Phys. Rev. D **80**, 095004 (2009). doi:10.1103/PhysRevD.80.095004. arXiv:0905.4749

80. W. Beenakker et al., Soft-gluon resummation for squark and gluino hadroproduction. JHEP **12**, 041 (2009). doi:10.1088/1126-6708/2009/12/041. arXiv:0909.4418

81. W. Beenakker et al., Squark and gluino hadroproduction. Int. J. Mod. Phys. A **26**, 2637 (2011). doi:10.1142/S0217751X11053560. arXiv:1105.1110

82. M. Krämer et al., Supersymmetry production cross sections in pp collisions at $\sqrt{s} = 7$ TeV. (2012). arXiv:1206.2892

83. C. Borschensky et al., Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV. Eur. Phys. J. C **74**, 3174 (2014). doi:10.1140/epjc/s10052-014-3174-y. arXiv:1407.5066

84. D. Alves et al., Simplified models for LHC new physics searches. J. Phys. G **39**, 105005 (2012). doi:10.1088/0954-3899/39/10/105005. arXiv:1105.2838

85. CMS Collaboration, Interpretation of searches for supersymmetry with simplified models. Phys. Rev. D **88**, 052017 (2013). doi:10.1103/PhysRevD.88.052017. arXiv:1301.2175

86. J. Butterworth et al., PDF4LHC recommendations for LHC run II. J. Phys. G **43**, 023001 (2016). doi:10.1088/0954-3899/43/2/023001. arXiv:1510.03865

87. CMS Collaboration, Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s} = 8$ TeV. Eur. Phys. J. C **73**, 2677 (2013). doi:10.1140/epjc/s10052-013-2677-2. arXiv:1308.1586

88. CMS Collaboration, CMS luminosity measurement for the 2015 data taking period. CMS physics analysis summary CMS-PAS-LUM-15-001, CERN (2016). https://cds.cern.ch/record/2138682

89. T. Junk, Confidence level computation for combining searches with small statistics. Nucl. Instrum. Meth. A **434**, 435 (1999). doi:10.1016/S0168-9002(99)00498-2. arXiv:hep-ex/9902006

90. A.L. Read, Presentation of search results: the $CL_s$ technique. J. Phys. G **28**, 2693 (2002). doi:10.1088/0954-3899/28/10/313

91. ATLAS and CMS Collaborations, Procedure for the LHC Higgs boson search combination in summer 2011. Technical report CMS NOTE-2011/005, ATL-PHYS-PUB-2011-11 (2011). https://cdsweb.cern.ch/record/1379837

92. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics. Eur. Phys. J. C **71**, 1554 (2011). doi:10.1140/epjc/s10052-011-1554-0. arXiv:1007.1727. [Erratum: Eur. Phys. J. C 73 (2013) 2501. doi:10.1140/epjc/s10052-013-2501-z]

## CMS Collaboration

**Yerevan Physics Institute, Yerevan, Armenia**
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

**Institut für Hochenergiephysik, Vienna, Austria**
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck[1], J. Strauss, W. Waltenberger, C.-E. Wulz[1]

**Institute for Nuclear Problems, Minsk, Belarus**
O. Dvornikov, V. Makarenko, V. Zykunov

**National Centre for Particle and High Energy Physics, Minsk, Belarus**
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

**Universiteit Antwerpen, Antwerpen, Belgium**
S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

**Vrije Universiteit Brussel, Brussels, Belgium**
S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

**Université Libre de Bruxelles, Brussels, Belgium**
H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Van der Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[2]

**Ghent University, Ghent, Belgium**
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

**Université Catholique de Louvain, Louvain-la-Neuve, Belgium**
H. Bakhshiansohi, C. Beluffi[3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

**Université de Mons, Mons, Belgium**
N. Beliy

**Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**
W. L. Aldá Júnior, F. L. Alves, G. A. Alves, L. Brito, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles

**Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil**
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[4], A. Custódio, E. M. Da Costa, G. G. Da Silveira[5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote[4], A. Vilela Pereira

**Universidade Estadual Paulista[a], Universidade Federal do ABC[b], São Paulo, Brazil**
S. Ahuja[a], C. A. Bernardes[b], S. Dogra[a], T. R. Fernandez Perez Tomei[a], E. M. Gregores[b], P. G. Mercadante[b], C. S. Moon[a], S. F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J. C. Ruiz Vargas

**Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

**Beihang University, Beijing, China**
W. Fang[6]

**Institute of High Energy Physics, Beijing, China**
M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, Y. Chen[7], T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**
Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

**Universidad de Los Andes, Bogotá, Colombia**
C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, C. F. González Hernández, J. D. Ruiz Alvarez, J. C. Sanabria

**Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia**
N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano, T. Sculac

**University of Split, Faculty of Science, Split, Croatia**
Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**
V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

**University of Cyprus, Nicosia, Cyprus**
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, D. Tsiakkouri

**Charles University, Prague, Czech Republic**
M. Finger[8], M. Finger Jr.[8]

**Universidad San Francisco de Quito, Quito, Ecuador**
E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**
Y. Assran[9,10], T. Elkafrawy[11], S. Khalil[12]

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**
B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**
P. Eerola, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**
J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**
J. Talvitie, T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France**
A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

**Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg , France**

J.-L. Agram[13], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte[13], X. Coubez, J.-C. Fontaine[13], D. Gelé, U. Goerlach, A.-C. Le Bihan, K. Skovpen, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C. A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, A. Popov[14], D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

A. Khvedelidze[8]

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze[8]

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

C. Autermann, S. Beranek, L. Feld, A. Heister, M. K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J. Schulz, T. Verlage, H. Weber, V. Zhukov[14]

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

V. Cherepanov, G. Flügge, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, I. M. Nugent, C. Pistone, O. Pooth, A. Stahl[15]

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. A. Bin Anuar, K. Borras[16], A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[17], J. Garay Garcia, A. Geiser, A. Gizhko, J. M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel[18], H. Jung, A. Kalogeropoulos, O. Karacheban[18], M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G. P. Van Onsem, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A. R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[15], T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann[15], S. M. Heindl, U. Husemann, I. Katkov[14], S. Kudella, P. Lobelle Pardo, H. Mildner, M. U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H. J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**
G. Anagnostou, G. Daskalakis, T. Geralis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

**National and Kapodistrian University of Athens, Athens, Greece**
S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

**University of Ioánnina, Ioannina, Greece**
I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**
N. Filipovic

**Wigner Research Centre for Physics, Budapest, Hungary**
G. Bencze, C. Hajdu, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20], A. J. Zsigmond

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**
M. Bartók[20], P. Raics, Z. L. Trocsanyi, B. Ujvari

**National Institute of Science Education and Research, Bhubaneswar, India**
S. Bahinipati, S. Choudhury[22], P. Mal, K. Mandal, A. Nayak[23], D. K. Sahoo, N. Sahoo, S. K. Swain

**Panjab University, Chandigarh, India**
S. Bansal, S. B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari,
A. Mehta, M. Mittal, J. B. Singh, G. Walia

**University of Delhi, Delhi, India**
Ashok Kumar, A. Bhardwaj, B. C. Choudhary, R. B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan,
R. Sharma, V. Sharma

**Saha Institute of Nuclear Physics, Kolkata, India**
R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal,
S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

**Indian Institute of Technology Madras, Madras, India**
P. K. Behera

**Bhabha Atomic Research Centre, Mumbai, India**
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty[15], P. K. Netrakanti, L. M. Pant, P. Shukla, A. Topkar

**Tata Institute of Fundamental Research-A, Mumbai, India**
T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G. B. Mohanty, B. Parida, N. Sur, B. Sutar

**Tata Institute of Fundamental Research-B, Mumbai, India**
S. Banerjee, S. Bhowmik[24], R. K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity[24], G. Majumder,
K. Mazumdar, T. Sarkar[24], N. Wickramage[25]

**Indian Institute of Science Education and Research (IISER), Pune, India**
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**
H. Behnamian, S. Chenarani[26], E. Eskandari Tadavani, S. M. Etesami[26], A. Fahim[27], M. Khakzad,
M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[28], F. Rezaei Hosseinabadi, B. Safarzadeh[29], M. Zeinali

**University College Dublin, Dublin, Ireland**
M. Felcini, M. Grunewald

**INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy**
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,15], R. Venditti[a,b], P. Verwilligen[a]

**INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy**
G. Abbiendi[a], C. Battilana, D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F. R. Cavallo[a], S. S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G. M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F. L. Navarria[a,b], A. Perrotta[a], A. M. Rossi[a,b], T. Rovelli[a,b], G. P. Siroli[a,b], N. Tosi[a,b,15]

**INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy**
S. Albergo[a,b], M. Chiorboli[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

**INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy**
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a,b,15]

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[15]

**INFN Sezione di Genova[a], Università di Genova[b], Genoa, Italy**
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M. R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

**INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milan, Italy**
L. Brianza[15], M. E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti, S. Malvezzi[a], R. A. Manzoni[a,b,15], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Pigazzini, S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

**INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy, Università della Basilicata[c], Potenza, Italy, Università G. Marconi[d], Rome, Italy**
S. Buontempo[a], N. Cavallo[a,c], G. De Nardo, S. Di Guida[a,d,15], M. Esposito[a,b], F. Fabozzi[a,c], F. Fienga[a,b], A. O. M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,15], P. Paolucci[a,15], C. Sciacca[a,b], F. Thyssen

**INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy, Università di Trento[c], Trento, Italy**
P. Azzi[a,15], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], A. T. Meneguzzo[a,b], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Zanetti, P. Zotto[a,b], G. Zumerle[a,b]

**INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy**
A. Braghieri[a], A. Magnani[a,b], P. Montagna[a,b], S. P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

**INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy**
L. Alunni Solestizi[a,b], G. M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b]

**INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy**
K. Androsov[a,30], P. Azzurri[a,15], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], R. Castaldi[a], M. A. Ciocci[a,30], R. Dell'Orso[a], S. Donato[a,c], G. Fedi, A. Giassi[a], M. T. Grippo[a,30], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,31], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P. G. Verdini[a]

**INFN Sezione di Roma[a], Università di Roma[b], Rome, Italy**
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b,15], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], F. Margaroli[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

**INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy, Università del Piemonte Orientale[c], Novara, Italy**
N. Amapane[a,b], R. Arcidiacono[a,c,15], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G. L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], A. Staiano[a], P. Traczyk[a,b]

**INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy**
S. Belforte[a], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], A. Zanetti[a]

**Kyungpook National University, Daegu, Korea**
D.H. Kim[38], G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

**Chonbuk National University, Jeonju, Korea**
A. Lee

**Institute for Universe and Elementary Particles, Chonnam National University, Kwangju, Korea**
H. Kim

**Hanyang University, Seoul, Korea**
J. A. Brochero Cifuentes, T. J. Kim

**Korea University, Seoul, Korea**
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

**Seoul National University, Seoul, Korea**
J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

**University of Seoul, Seoul, Korea**
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

**Sungkyunkwan University, Suwon, Korea**
Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

**Vilnius University, Vilnius, Lithuania**
V. Dudenas, A. Juodagalvis, J. Vaitkus

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**
S. Carpinteyro, I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**
A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**
D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**
P. H. Butler

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

**National Centre for Nuclear Research, Swierk, Poland**
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska,
M. Szleper, P. Zalewski

**Faculty of Physics, Institute of Experimental Physics, University of Warsaw, Warsaw, Poland**
K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski,
M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar,
N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela,
P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**
V. Alexakhin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev[36,37],
V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**
L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim[38], E. Kuznetsova[39], V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov,
A. Toropin

**Institute for Theoretical and Experimental Physics, Moscow, Russia**
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov,
A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**
A. Bylinkin[37]

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**
M. Chadeeva[40], O. Markin, E. Tarkovskii

**P.N. Lebedev Physical Institute, Moscow, Russia**
V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan, A. Leonidov[37], S. V. Rusakov, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin[41], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova,
I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**
V. Blinov[42], Y. Skovpen[42], D. Shtol[42]

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov,
R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**Faculty of Physics and Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**
P. Adzic[43], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**
J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz,
A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz,
P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, E. Navarro De Martino,
A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M. S. Soares

**Universidad Autónoma de Madrid, Madrid, Spain**

J. F. de Trocóniz, M. Missiroli, D. Moran

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon,
S. Sanchez Cruz, I. Suárez Andrés, J. M. Vizan Garcia

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

I. J. Cabrillo, A. Calderon, J. R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez,
A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro,
N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato,
C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte,
A. David, M. De Gruttola, A. De Roeck, E. Di Marco[44], M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser,
N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege,
D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler,
H. Kirschenmann, V. Knünz, A. Kornmayer[15], M. J. Kortelainen, K. Kousouris, M. Krammer[1], C. Lange, P. Lecoq,
C. Lourenço, M. T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi,
P. Milenovic[45], F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez,
M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[46], M. Rovere, M. Ruan,
H. Sakulin, J. B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas[47], J. Steggemann, M. Stoye,
Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[48], G. I. Veres[20], N. Wardle, H. K. Wöhri,
A. Zagozdzinska[35], W. D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

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

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits,
J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol,
M. Masciovecchio, M. T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss,
G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov[49], V. R. Tavolaro, K. Theofilatos,
R. Wallny

**Universität Zürich, Zurich, Switzerland**

T. K. Aarrestad, C. Amsler[50], L. Caminada, M. F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster,
J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang, A. Zucchetta

**National Central University, Chung-Li, Taiwan**

V. Candelise, T. H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C. M. Kuo, W. Lin, Y. J. Lu, A. Pozdnyakov, S. S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

Arun Kumar, P. Chang, Y. H. Chang, Y. W. Chang, Y. Chao, K. F. Chen, P. H. Chen, C. Dietz, F. Fiori, W.-S. Hou,
Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J. F. Tsai, Y. M. Tzeng

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

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

A. Adiguzel, S. Cerci[51], S. Damarseckin, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler,
I. Hos, E. E. Kangal[52], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut[53], K. Ozdemir[54],
D. Sunar Cerci[51], H. Topakli[55], S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

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

B. Bilin, S. Bilmis, B. Isildak[56], G. Karapinar[57], M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**
E. Gülmez, M. Kaya[58], O. Kaya[59], E. A. Yetkin[60], T. Yetkin[61]

**Istanbul Technical University, Istanbul, Turkey**
A. Cakir, K. Cankocak, S. Sen[62]

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine**
B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**
L. Levchuk, P. Sorokin

**University of Bristol, Bristol, UK**
R. Aggleton, F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes,
G. P. Heath, H. F. Heath, J. Jacob, L. Kreczko, C. Lucas, D. M. Newbold[63], S. Paramesvaran, A. Poll, T. Sakuma,
S. Seif El Nasr-storey, D. Smith, V. J. Smith

**Rutherford Appleton Laboratory, Didcot, UK**
K. W. Bell, A. Belyaev[64], C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder,
S. Harper, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams

**Imperial College, London, UK**
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe,
P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall,
G. Iles, T. James, R. Lane, C. Laner, R. Lucas[63], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash,
A. Nikitenko[49], J. Pela, B. Penning, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper,
K. Uchida, M. Vazquez Acosta[65], T. Virdee[15], J. Wright, S. C. Zenz

**Brunel University, Uxbridge, UK**
J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, D. Leslie, I. D. Reid, P. Symonds, L. Teodorescu, M. Turner

**Baylor University, Waco, USA**
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

**The University of Alabama, Tuscaloosa, USA**
O. Charaf, S. I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, USA**
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

**Brown University, Providence, USA**
G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J. M. Hogan, O. Jesus, K. H. M. Kwok, E. Laird,
G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

**University of California, Davis, Davis, USA**
R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway,
P. T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot,
S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

**University of California, Los Angeles, Los Angeles, USA**
C. Bravo, R. Cousins, A. Dasgupta, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg,
C. Schnaible, E. Takasugi, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**
K. Burt, R. Clare, J. Ellison, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix,
O. R. Long, M. Olmedo Negrete, M. I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

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

J. G. Branson, G. B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[66], C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

**Department of Physics, University of California, Santa Barbara, Santa Barbara, USA**

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S. D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

**California Institute of Technology, Pasadena, USA**

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J. M. Lawhorn, A. Mott, H. B. Newman, C. Pena, M. Spiropulu, J. R. Vlimant, S. Xie, R. Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

M. B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

**University of Colorado Boulder, Boulder, USA**

J. P. Cumalat, W. T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S. R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S. M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fairfield University, Fairfield, USA**

D. Winn

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla, K. Burkett, J. N. Butler, H. W. K. Cheung, F. Chlebana, S. Cihangir[†], M. Cremonesi, V. D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J. M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck, Y. Wu

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R. D. Field, I. K. Furic, J. Konigsberg, A. Korytov, J. F. Low, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

**Florida International University, Miami, USA**

S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

**Florida State University, Tallahassee, USA**

A. Ackert, J. R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K. F. Johnson, A. Khatiwada, H. Prosper, A. Santra

**Florida Institute of Technology, Melbourne, USA**

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi[67], M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

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

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, K. Jung, P. Kurt, C. O'Brien, I. D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

**The University of Iowa, Iowa City, USA**

B. Bilki[68], W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo,
H. Mermerkaya[69], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[70], A. Penzo, C. Snyder, E. Tiras,
J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, USA**

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, P. Maksimovic, C. Martin,
M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

**The University of Kansas, Lawrence, USA**

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R. P. Kenny III, S. Khalil,
A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J. D. Tapia Takaki, Q. Wang

**Kansas State University, Manhattan, USA**

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L. K. Saini, N. Skhirtladze, S. Toda

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S. C. Eno, C. Ferraioli, J. A. Gomez, N. J. Hadley, S. Jabeen,
R. G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A. C. Mignerey, F. Ricci-Tam, Y. H. Shin, A. Skuja, M. B. Tonjes, S. C. Tonwar

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

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I. A. Cali,
Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G. M. Innocenti, M. Klute,
D. Kovalskyi, K. Krajczar, Y. S. Lai, Y.-J. Lee, A. Levin, P. D. Luckey, B. Maier, A. C. Marini, C. Mcginn, C. Mironov,
S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G. S. F. Stephans, K. Sumorok, K. Tatar,
M. Varma, D. Velicanu, J. Veverka, J. Wang, T. W. Wang, B. Wyslouch, M. Yang, V. Zhukova

**University of Minnesota, Minneapolis, USA**

A. C. Benvenuti, R. M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S. C. Kao, Y. Kubota, Z. Lesko,
J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

**University of Mississippi, Oxford, USA**

J. G. Acosta, S. Oliveros

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

E. Avdeeva, R. Bartek, K. Bloom, D. R. Claes, A. Dominguez[71], C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin,
I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J. E. Siado, G. R. Snow, B. Stieger

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

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker,
S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D. M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima,
D. Trocino, R.-J. Wang, D. Wood

**Northwestern University, Evanston, USA**

S. Bhattacharya, K. A. Hahn, A. Kubik, A. Kumar, N. Mucia, N. Odell, B. Pollack, M. H. Schmitt, K. Sung, M. Trovato,
M. Velasco

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

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng,
C. Mueller, Y. Musienko[36], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

**The Ohio State University, Columbus, USA**
J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B. L. Winer, H. W. Wulsin

**Princeton University, Princeton, USA**
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, J. Mc Donald, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully, A. Zuranski

**University of Puerto Rico, Mayaguez, USA**
S. Malik

**Purdue University, West Lafayette, USA**
A. Barker, V. E. Barnes, S. Folgueras, L. Gutay, M. K. Jha, M. Jones, A. W. Jung, D. H. Miller, N. Neumeister, J. F. Schulte, X. Shi, J. Sun, F. Wang, W. Xie, L. Xu

**Purdue University Calumet, Hammond, USA**
N. Parashar, J. Stupak

**Rice University, Houston, USA**
A. Adair, B. Akgun, Z. Chen, K. M. Ecklund, F. J. M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

**University of Rochester, Rochester, USA**
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K. H. Lo, P. Tan, M. Verzetti

**Rutgers, The State University of New Jersey, Piscataway, USA**
A. Agapitos, J. P. Chou, E. Contreras-Campana, Y. Gershtein, T. A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, USA**
A. G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

**Texas A&M University, College Station, USA**
O. Bouhali[72], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon[73], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer

**Texas Tech University, Lubbock, USA**
N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P. R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S. W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

**Vanderbilt University, Nashville, USA**
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

**University of Virginia, Charlottesville, USA**
M. W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

**Wayne State University, Detroit, USA**
C. Clarke, R. Harr, P. E. Karchin, J. Sturdy

**University of Wisconsin - Madison, Madison, WI, USA**
D. A. Belknap, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W. H. Smith, D. Taylor, N. Woods

† **Deceased**

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

3: Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Universidade Federal de Pelotas, Pelotas, Brazil

6: Also at Université Libre de Bruxelles, Brussels, Belgium

7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Suez University, Suez, Egypt

10: Now at British University in Egypt, Cairo, Egypt

11: Also at Ain Shams University, Cairo, Egypt

12: Also at Zewail City of Science and Technology, Zewail, Egypt

13: Also at Université de Haute Alsace, Mulhouse, France

14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

17: Also at University of Hamburg, Hamburg, Germany

18: Also at Brandenburg University of Technology, Cottbus, Germany

19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

22: Also at Indian Institute of Science Education and Research, Bhopal, India

23: Also at Institute of Physics, Bhubaneswar, India

24: Also at University of Visva-Bharati, Santiniketan, India

25: Also at University of Ruhuna, Matara, Sri Lanka

26: Also at Isfahan University of Technology, Isfahan, Iran

27: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

28: Also at Yazd University, Yazd, Iran

29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

30: Also at Università degli Studi di Siena, Siena, Italy

31: Also at Purdue University, West Lafayette, USA

32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico

35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

36: Also at Institute for Nuclear Research, Moscow, Russia

37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

39: Also at University of Florida, Gainesville, USA

40: Also at P.N. Lebedev Physical Institute, Moscow, Russia

41: Also at California Institute of Technology, Pasadena, USA

42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

44: Also at INFN Sezione di Roma; Università di Roma, Rome, Italy

45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

46: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

47: Also at National and Kapodistrian University of Athens, Athens, Greece

48: Also at Riga Technical University, Riga, Latvia

49: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

50: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

51: Also at Adiyaman University, Adiyaman, Turkey

52: Also at Mersin University, Mersin, Turkey

53: Also at Cag University, Mersin, Turkey

54: Also at Piri Reis University, Istanbul, Turkey

55: Also at Gaziosmanpasa University, Tokat, Turkey

56: Also at Ozyegin University, Istanbul, Turkey

57: Also at Izmir Institute of Technology, Izmir, Turkey

58: Also at Marmara University, Istanbul, Turkey

59: Also at Kafkas University, Kars, Turkey

60: Also at Istanbul Bilgi University, Istanbul, Turkey

61: Also at Yildiz Technical University, Istanbul, Turkey

62: Also at Hacettepe University, Ankara, Turkey

63: Also at Rutherford Appleton Laboratory, Didcot, UK

64: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK

65: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain

66: Also at Utah Valley University, Orem, USA

67: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy

68: Also at Argonne National Laboratory, Argonne, USA

69: Also at Erzincan University, Erzincan, Turkey

70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

71: Now at The Catholic University of America, Washington, USA

72: Also at Texas A&M University at Qatar, Doha, Qatar

73: Also at Kyungpook National University, Daegu, Korea