EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2011-046
2011/10/11

CMS-SUS-10-008

Search for Physics Beyond the Standard Model Using Multilepton Signatures in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A search for physics beyond the standard model in events with at least three leptons and any number of jets is presented. The data sample corresponds to 35 pb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 7$ TeV collected by the CMS experiment at the LHC. A number of exclusive multileptonic channels are investigated and standard model backgrounds are suppressed by requiring sufficient missing transverse energy, invariant mass inconsistent with that of the Z boson, or high jet activity. Control samples in data are used to ascertain the robustness of background evaluation techniques and to minimise the reliance on simulation. The observations are consistent with background expectations. These results constrain previously unexplored regions of supersymmetric parameter space.

Submitted to Physics Letters B

---

*See Appendix A for the list of collaboration members

1 Introduction

Supersymmetry (SUSY) is a preferred candidate for a theory beyond the standard model (SM) because it solves the hierarchy problem, allows the unification of the gauge couplings, and may provide a candidate particle for dark matter [1–3]. The 7 TeV centre-of-mass energy of the Large Hadron Collider (LHC) makes it possible to search for squark and gluino production in previously unexplored regions of supersymmetric parameter space with the integrated luminosity delivered in the first few months of operation. Hadronic collisions yielding three or more electrons, muons, or taus ("multileptons") serve as an ideal hunting ground for physics beyond the SM, as leptonic SM processes are relatively rare at hadron colliders and multilepton events particularly so.

We report results from a search with broad sensitivity to the potentially large multilepton signals from SUSY particle production. Our strategy takes advantage of the strong background suppression obtained when requiring three or more leptons; this allows us to relax requirements for SM background reduction relative to other searches with fewer leptons or purely hadronic searches at the LHC [4, 5].

The multilepton search presented here is not tailored for any particular SUSY scenario. Nonetheless, it probes multiple new regions of the supersymmetric parameter space beyond previous multilepton searches at the Tevatron [6–12]. Overall, this search complements the Tevatron searches, which are mostly sensitive to electroweak gaugino production, while this search is mostly sensitive to squark-gluino production. As in the case of Tevatron searches, we interpret results in the mSUGRA/CMSSM [13, 14] scenario of supersymmetry in which the superpartner masses and gauge couplings become unified at the grand unification scale, resulting in common masses m_0 ($m_{1/2}$) for all spin 0 (1/2) superpartners at this scale. The remaining CMSSM parameters are $A_0, \tan\beta$, and μ. For illustration, we define a CMSSM benchmark point called "TeV3", characterised by $m_0 = 60\,\mathrm{GeV}/c^2, m_{1/2} = 230\,\mathrm{GeV}/c^2, A_0 = 0, \tan\beta = 3, \mu > 0$, and a next-to-leading order (NLO) cross section of 10 pb for all supersymmetric processes.

In this article we also study scenarios with gravitinos as the lightest supersymmetric particle (LSP) and sleptons as the next-to-lightest supersymmetric particles (NLSPs). Scenarios of this type arise in a wide class of theories of gauge mediation with split messengers (GMSM) [15, 16]. Multilepton final states arise naturally in the subset of the GMSM parameter space where the right-handed sleptons are flavour-degenerate, the so-called slepton co-NLSP scenario [8, 15–17]. We define a slepton co-NLSP benchmark point, called ML01, characterised by a chargino mass $m_{\chi^\pm} = 385\,\mathrm{GeV}/c^2$ and gluino mass $m_{\tilde{g}} = 450\,\mathrm{GeV}/c^2$. The other superpartner masses are then given by the generic relationships $m_{\tilde{\ell}_R} = 0.3 m_{\chi^\pm}, m_{\chi_1^0} = 0.5 m_{\chi^\pm}, m_{\tilde{\ell}_L} = 0.8 m_{\chi^\pm}$, and $m_{\tilde{q}_L} = 0.8 m_{\tilde{g}}$. ML01 has an estimated 45 pb NLO cross section for all supersymmetric processes. Finally, we also consider the possibility that the LSP is unstable.

2 Detector

The data sample used in this search corresponds to the integrated luminosity of 35 pb^{-1} recorded in 2010 with the Compact Muon Solenoid (CMS) detector at the LHC, running at 7 TeV centre-of-mass energy. The CMS detector has cylindrical symmetry around the pp beam axis with tracking and muon detector pseudorapidity coverage to $|\eta| < 2.4$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle with respect to the counterclockwise beam. The azimuthal angle ϕ is measured in the plane perpendicular to the beam direction. Charged particle tracks are identified with a 200 m^2, fully silicon-based tracking system composed of a pixel detector with three barrel layers at radii between 4.4 cm and 10.2 cm and a silicon strip tracker with 10 barrel detection layers, of which four are double sided, extending outwards to a radius of 1.1 m. Each system is completed by endcaps extending the acceptance of the tracker up to a pseudorapidity of $|\eta| < 2.5$. The lead-tungstate scintillating crystal electromagnetic calorimeter (ECAL) and brass/scintillator hadron calorimeter hermetically surrounding the tracking system measure the energy of showering particles with $|\eta| < 3.0$. These subdetectors are placed inside a 13 m long and 6 m diameter superconducting solenoid with a central field of 3.8 T. Outside the magnet is the tail-catcher of the hadronic calorimeter followed by the instrumented iron return yoke, which serves as a multilayered muon detection system in the range $|\eta| < 2.4$. The CMS detector has extensive forward calorimetry, extending the pseudorapidity coverage to $|\eta| < 5.0$. The performance of all detector components as measured with cosmic rays has been reported in Ref. [18] and references therein. A much more detailed description of CMS can be found elsewhere [19].

3 Event Trigger

The data used for this search came from single- and double-lepton triggers. The Level-1 (L1) and High Level Trigger (HLT) configurations of the CMS trigger were adapted to changing beam conditions and increasing LHC luminosities during data collection. For example, the transverse momentum (p_T) threshold for the unprescaled single muon trigger was raised from $9\,\mathrm{GeV}/c$ to $15\,\mathrm{GeV}/c$ near the end of data taking. The analogous single electron trigger went from a transverse energy (E_T) threshold of 10 GeV in the early part of data taking to 17 GeV. Double-lepton trigger thresholds were set at $p_T > 5\,\mathrm{GeV}/c$ for muons and $E_T > 10\,\mathrm{GeV}$ for electrons.

The efficiencies of the single-lepton triggers are determined with the tag-and-probe technique. Events with Z boson decays into two electrons or muons are selected by requiring one lepton and another track as a lepton candidate, with an invariant mass in the Z-mass window of 80 to $100\,\mathrm{GeV}/c^2$. The fraction of probed tracks that are reconstructed correctly as leptons including the trigger requirements determines the lepton efficiency. The average trigger efficiency determined for $p_T > 15\,\mathrm{GeV}/c$ is $97.5 \pm 1.5\%$ for the electrons and $89.1 \pm 0.9\%$ for the muons.

4 Lepton Identification

Leptons in this search can be either electrons, muons, or taus. Electrons and muons are selected with $p_T \geq 8\,\mathrm{GeV}/c$ and $|\eta| < 2.1$ as reconstructed from measured quantities from the tracker, calorimeter, and muon system. Since a large fraction of the data set was collected with the highest trigger threshold implemented at high luminosity, we require at least one identified muon with $p_T > 15\,\mathrm{GeV}/c$ or an electron with $E_T > 20$ GeV. The matching candidate tracks must satisfy quality requirements and spatially match with the energy deposits in the ECAL and the tracks in the muon detectors, as appropriate. Details of reconstruction and identification can be found in Ref. [20] for electrons and in Ref. [21] for muons. Jets are reconstructed using particles with $|\eta| \leq 2.5$ via the particle-flow (PF) algorithm, as described in Ref. [22].

Although the reconstruction of taus presents challenges, we include these because there are regions of parameter space where signatures that include taus are enhanced. Taus decay either leptonically or hadronically. The electrons or muons from the leptonic decays are identified as above. The hadronic decays yield either a single charged track (one-prong decays) or three charged tracks (three-prong decays) with or without additional electromagnetic energy from neutral pion decays. We explore two strategies for hadronic decay reconstruction in this search and combine the results in the end. In the first selection, the one-prong hadronic decays are reconstructed as isolated tracks with $p_{\mathrm{T}} > 8\,\mathrm{GeV}/c$. In the second selection, hadronic decays are reconstructed with the PF algorithm [23, 24], which also includes the three-prong decays and decays with associated ECAL activity. This algorithm defines an energy-dependent signal cone in the η-ϕ region around the candidate track with an angular radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ of $5\,\mathrm{GeV}/E_{\mathrm{T}}(\mathrm{jet})$. This "shrinking cone" is limited to the range $0.07 \leq \Delta R \leq 0.15$. Inside the signal cone one or three charged tracks are required. PF tau candidates that are also electron or muon candidates are explicitly rejected.

These two algorithms have complementary benefits. Isolated tracks originating from one-prong decays make up only about 18% of hadronic tau decays, but have relatively low backgrounds. Additionally, some electrons and muons that fail normal requirements described above are accepted with the isolated track reconstruction. The PF algorithm reconstructs all hadronic tau decays including the larger-background three-prong decays, necessitating tighter kinematic requirements for some event topologies. After event selection, the tau channel efficiencies are similar for both selections.

Sources of background leptons include genuine leptons occurring inside or near jets, hadrons simulating leptons by punch-through into the muon system, hadronic showers with large electromagnetic fractions, or photon conversions. An isolation requirement strongly reduces the background from misidentified leptons, since most of them occur inside jets. We define the relative isolation I_{rel} as the ratio of the sum of calorimeter energy and p_{T} of any other tracks in the cone defined by $\Delta R < 0.3$ around the lepton to the p_{T} of the lepton. For electrons, muons, and isolated tracks, we require $I_{\mathrm{rel}} < 0.15$. For PF taus, tracking and ECAL isolation requirements are applied [24] in the annular region between the signal cone and an isolation cone with $\Delta R = 0.5$.

Leptons from SUSY decays considered in this search originate from the collision point ("prompt" leptons). After the isolation selection, the most significant background sources are residual nonprompt leptons from heavy quark decays, where the lepton tends to be more isolated because of the high p_{T} with respect to the jet axis. This background is reduced by requiring that the leptons originate from within one centimeter of the primary vertex in z and that the impact parameter d_{xy} between the track and the event vertex in the plane transverse to the beam axis be small. For electrons, muons, and isolated tracks, the impact parameter requirement is $d_{xy} \leq 0.02$ cm, while $d_{xy} \leq 0.03$ cm is required for PF taus. The isolation and promptness criteria are efficient for the SUSY signal but almost eliminate misidentified leptons.

5 Search Strategy

5.1 Multilepton channels

Candidate events in this search must have at least three leptons, of which at least one must be an electron or a muon, and may contain two or fewer hadronic tau candidates. We classify multilepton events into search channels on the basis of the number of leptons, lepton flavour, and relative charges as well as charge and flavour combinations and other kinematic quantities described below.

We use the following symbols and conventions in describing the search. The symbol ℓ stands for an electron or a muon, including those from tau decays. In describing pairs of leptons, OS stands for opposite-sign, SS for same-sign, and SF for same (lepton) flavour. To explicitly denote differing lepton flavours in a pair, we use the symbol $\ell\ell'$. The symbol τ refers to hadronic tau decays reconstructed using the PF tau algorithm and T refers to decays reconstructed as isolated tracks.

The level of SM background varies considerably across the channels. Channels with hadronic tau decays or containing OS–SF ($\ell^\pm\ell^\mp$) pairs suffer from large backgrounds, but channels such as $\ell^\pm\ell^\pm\ell'$ have smaller backgrounds because they do not contain OS–SF pairs. High-background channels play two distinct roles in this search, depending on the scenario of new physics. For models that predict a small signal yield in these channels, they act as ”control” samples that give confidence in predictions for the discovery channels that have small background. But it is also possible that new physics may preferentially manifest itself in the high-background channels. For example, taus can greatly outnumber electrons and muons in the case of supersymmetry with large $\tan\beta$ values. Therefore, we retain channels such as those with two hadronic tau decays although they contribute only modestly to scenarios of new physics which we discuss later. In comparison, dilepton searches have higher backgrounds and are thus less sensitive to tau-rich signals because of additional requirements necessary to reduce these backgrounds to a manageable level. We avoid using kinematic quantities such as $E_{\mathrm{T}}^{\mathrm{miss}}$ or H_{T} in defining datasets used in background determination. Such loose selection criteria minimize signal contamination between high and low background channels. Even for tau-rich mSUGRA scenarios, the signal contamination is below 5%.

5.2 Background reduction

Other searches for new physics such as those requiring dileptons or single leptons suffer from large SM backgrounds and are hence forced to require substantial jet activity as well as missing transverse energy. For the multilepton search described here, the presence of a third lepton results in lower SM backgrounds, thus reducing reliance on other requirements and increasing sensitivity to diverse signatures of new physics. The presence of hadronic activity in an event is characterised by the variable H_{T}, defined as the scalar sum of the transverse jet energies for all jets with $E_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$. Jets used for the H_{T} determination must be well separated from any identified leptons; jets are required to have no lepton in a cone $\Delta R < 0.3$ around the jet axis. The missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the magnitude of the vectorial sum of the momenta of all lepton candidates and jets with $E_{\mathrm{T}} > 20$ GeV and $|\eta| < 5.0$. Comparison between data and simulation [25, 26] shows good modelling of $E_{\mathrm{T}}^{\mathrm{miss}}$.

Both H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ are good discriminating observables for physics beyond the SM, as demonstrated in Fig. 1. In specific regions of parameter space one observable may be more effective than the other. Figure 1 suggests that H_{T} has slightly superior discriminating power for the models we happen to consider here. On the other hand, H_{T} would be suppressed if the supersymmetric production were dominated by electroweak processes, as would be the case at the Tevatron [6]. Another possibility is that the sparticle mass ordering in the supersymmetric particle spectrum may result in reduced participation of hadronic sparticles in the decay chain despite strong production, resulting in negligible jet activity. Figure 2 illustrates this situation, showing the product of cross section, branching fraction, and efficiency, i.e., event yield per unit integrated luminosity, as a function of the mass difference between the squark and lightest neutralino. The slepton co-NLSP supersymmetric topology illustrated here has degenerate squarks with vanishing left-right mixing and right-handed sleptons with masses of 500 and 185 GeV/c^2, respectively, with a variable lightest neutralino mass, and other superpartners decoupled. The figure shows that the H_{T} requirement suppresses sensitivity when neutralino and squark masses are similar because squarks and gluinos fail to participate in the decay chain, resulting in minimal hadronic activity. By comparison, $E_{\mathrm{T}}^{\mathrm{miss}}$ is an appropriate discriminant in a multilepton search because neutrino production generally accompanies e, μ, and τ production. Nonetheless, in order to retain search sensitivity beyond that of dilepton searches, both $E_{\mathrm{T}}^{\mathrm{miss}}$

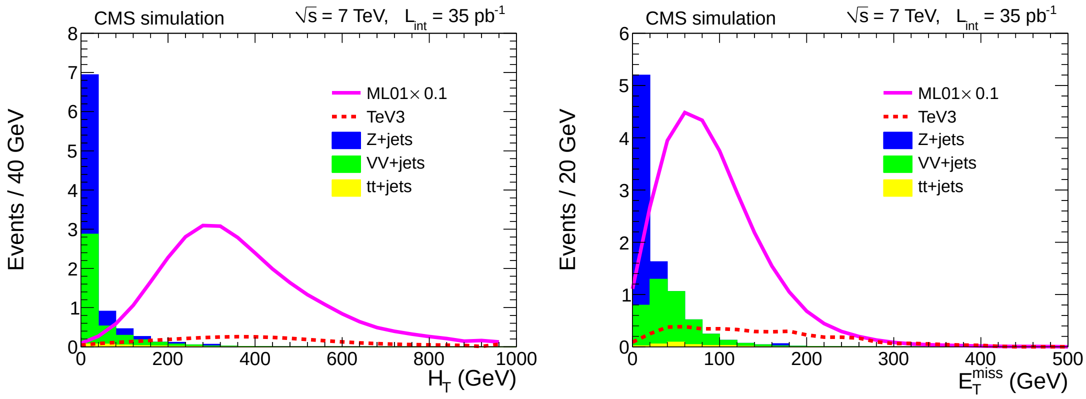

Figure 1: The H_T (left) and $E_\mathrm{T}^\mathrm{miss}$ (right) distributions for SM background channels (Z+jets, $\mathrm{t\bar{t}}$, and VV+jets, where $\mathrm{V} = \mathrm{W}, \mathrm{Z}$ and two SUSY benchmark points for the simulation events that pass all other requirements for the three-lepton events. The ML01 and TeV3 benchmark points are defined in Section 1 and details of the simulation are given in Section 6.

and H_T selections should be used as sparingly as possible. The flexibility of the multichannel approach allows us to selectively impose the $E_\mathrm{T}^\mathrm{miss}$ or H_T requirements in specific channels. Doing so maximises sensitivity to new physics.

We exploit the background reduction ability of both $E_\mathrm{T}^\mathrm{miss}$ and H_T as follows. Events with $E_\mathrm{T}^\mathrm{miss} > 50\,\mathrm{GeV}$ ($H_\mathrm{T} > 200\,\mathrm{GeV}$) are said to satisfy the $E_\mathrm{T}^\mathrm{miss}$ (H_T) requirement. The justification for the values chosen is evident from Fig. 1. Another criterion for background reduction is the "Z veto", in which the invariant mass of the OS–SF lepton pairs is required to be outside the 75–105 GeV/c^2 window. A possible source of background is from the final state radiation in $\mathrm{Z} \to 2\ell(\ell = e, \mu)$ events undergoing a $\gamma \to 2\ell$ conversion. Therefore, the Z veto requirement is also applied to the invariant mass $M(3\ell)$ of three leptons for 3e and $\mu\mu e$ events which have low $E_\mathrm{T}^\mathrm{miss}$ and H_T. As described below, these kinematic selection criteria are applied together or separately as warranted by the background level of the channel under consideration.

5.3 Final kinematic selections

In order to maximise sensitivity to diverse new physics scenarios, we group the final selections into two broadly complementary domains. As the name suggests, the *hadronic* selection makes a uniform H_T requirement ($H_\mathrm{T} > 200\,\mathrm{GeV}$). It reduces backgrounds to practically negligible values for channels with electrons and muons. Both one- and three-prong hadronic tau decays are reconstructed using the PF technique. For channels with OS–SF $\ell\ell$ pairs plus τ's, the residual background from Z+jets is further reduced with the $E_\mathrm{T}^\mathrm{miss}$ requirement ($E_\mathrm{T}^\mathrm{miss} > 50\,\mathrm{GeV}$). Only the $\mathrm{t\bar{t}}$ background then remains nonnegligible; about one event is expected in 35 pb^{-1} after the full selection.

The *inclusive* selection is based on the combined $E_\mathrm{T}^\mathrm{miss} > 50$ GeV and Z-veto requirements for events with an OS–SF lepton pair. These events also must satisfy $M(2\ell) > 12$ GeV/c^2 to reject low mass Drell–Yan production and the $\mathrm{J}/\psi(1\mathrm{S})$ and Υ resonances. In addition, candidate events are binned in exclusive channels characterised by total charge, number of lepton candidates, lepton flavours, high or low $E_\mathrm{T}^\mathrm{miss}$, and whether the Z veto described above is satisfied or not. Isolated tracks are used to reconstruct the single-prong tau decays.

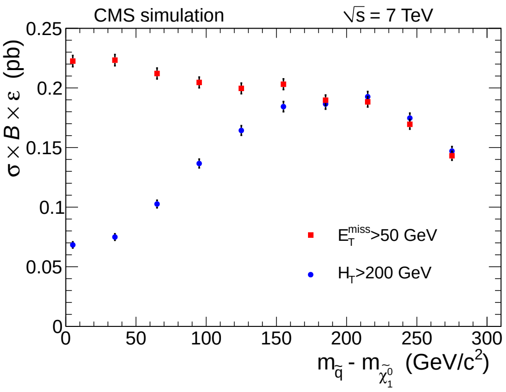

Figure 2: Effect of mass difference between squark and lightest neutralino on cross section times branching fraction times efficiency for an $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ requirement (red squares) or for an $H_{\mathrm{T}} > 200\,\mathrm{GeV}$ requirement (blue circles). Less hadronic energy is released if this difference becomes small, so the H_{T} requirement loses sensitivity in this region of parameter space. The example is for channels containing two muons plus at least one electron or a tau. The slepton co-NLSP topology used here is described in the text.

6 Background Estimation

The main SM backgrounds in multilepton plus jet events originate from Z+jets, double vector boson production (VV+jets), $\mathrm{t\bar{t}}$ production, and QCD multijets. Leptons associated with jets can be from heavy quark decays, or with a lower probability, can be misidentified hadrons. Leptons from heavy quark decays are suppressed by the isolation requirement. The probability that a QCD event includes three misidentified leptons is negligible. Backgrounds from cosmic rays are also found to be negligible. Backgrounds from beam-halo muons are included in the background estimate discussed below.

The largest background remaining after the basic three-lepton reconstruction originates from the Z+jets process, which in our nomenclature includes the Drell–Yan process as well. The dileptons resulting from these processes, together with misidentified isolated tracks give rise to a trilepton background. The probability that such an isolated track is misidentified as a lepton is measured in control samples where no signal should be present, such as in dijet samples. We measure the probability for an isolated track to produce a misidentified muon (electron) to be $2.2 \pm 0.6\%$ ($1.3^{+1.8}_{-0.3}\%$). The misidentification SM background for the three-lepton sample is then obtained by multiplying the number of isolated tracks in the two-lepton sample by this probability. In a similar way we estimate the misidentified background for four-lepton events by examining two-lepton events with two additional isolated tracks. The large systematic uncertainty on this rate is due to the difference in jet environment in QCD and Z+jets control samples. Such differences are expected due to the variation of heavy quark content across the control samples.

For channels with isolated tracks, we measure the SM background by using the isolation sideband $0.2 < I_{\mathrm{rel}} < 1.0$ to extrapolate to the signal region $I_{\mathrm{rel}} < 0.15$. In order to improve the statistical error as well as to gain a systematic understanding of the extrapolation process, we study the isolation distribution in various QCD samples with different levels of jet activity and then evaluate the ratio of events in the two isolation regions in the QCD sample that most resembles the dilepton sample where the ratio is eventually applied. The ratio of the numbers of isolated tracks in the two regions is measured to be $15 \pm 3\%$. The 3% systematic uncertainty is derived from the extent of variation of the ratio in these QCD control samples. The ratio is then applied to the 2ℓ event sample. Because the number of events after the $E_{\mathrm{T}}^{\mathrm{miss}}$ selection is too small to be useful, we derive the SM background in these channels by applying the isolation probability ratio as well as the probability of a 2ℓ event to pass the $E_{\mathrm{T}}^{\mathrm{miss}}$ selection to the full sample.

Understanding of SM backgrounds at the three-lepton selection level as above is essential before implementing the final kinematic selections. We perform a detailed simulation of the detector response using GEANT4 [27] for Z/γ^* + jets, $\mathrm{t\bar{t}}$ quark pairs, and double vector boson production events generated using MADGRAPH [28], and QCD events generated with PYTHIA 8.1 [29]. We use CTEQ6.6 parton distribution functions [30]. Already at the dilepton level, comparisons between data and simulation for distributions of the opposite-sign pair mass and for H_{T} show good agreement for both muons and electrons. Figure 3 shows the mass spectrum for dimuon events and the H_{T} distribution for dielectron events. After requiring a third lepton, the kinematic selections efficiently eliminate the Z+jets background. The $\mathrm{t\bar{t}}$ and double vector boson backgrounds then come to the fore.

There is not sufficient data yet for a data-based estimate of the $\mathrm{t\bar{t}}$ background, so we use simulation, with the contribution scaled to the measured $\mathrm{t\bar{t}}$ cross section [31]. The $\mathrm{t\bar{t}}$ background comes primarily from leptonic decays of both W bosons accompanied by a lepton from the b jets. In order to verify the adequacy of simulation for background estimation, we examine the $\mathrm{e}\mu$ dilepton distribution since $\mathrm{t\bar{t}}$ contributes dominantly to it. In particular, the spectrum of muons in this sample which fail isolation requirements is described well by the simulation whether the muon originated promptly or not. The same is true of nonisolated tracks. Agreement of these distributions with the simulation gives confidence that the semileptonic branching fractions of the b quark and semileptonic form factors are reproduced correctly by the simulation. The VV+jets channels include the irreducible background from WZ+jets with both vector bosons decaying leptonically and the neutrino yielding missing energy, as well as from ZZ+jets. The simulation is used as these processes do include prompt leptons, which are reasonably well described by simulation [32].

The lepton charge misidentification probability is generally less than 1% for the lepton momenta typical for this search. The data-based background estimation techniques described above automatically account for charge misidentification background associated with the Z+jets processes because the dilepton data sample used for multilepton background estimation contains events with charge misidentification. The probability of acquiring WZ trilepton events with total charge of three units because of charge misidentification is too small for the quantity of data considered here.

As a cross-check, the SM background events are binned in the two-dimensional isolation versus impact parameter plane. The background in the signal region, characterised by small isolation ($I_{\mathrm{rel}} < 0.15$) and impact parameters ($d_{xy} < 0.02$ cm), is extrapolated from the three outside regions ("sidebands") in this two-dimensional plot by assuming the two variables I_{rel} and d_{xy} to be uncorrelated, so both can be independently extrapolated. This cross-check technique presently suffers from large statistical uncertainties, but the resulting background estimates are consistent with those described above.

In summary, the nonprompt backgrounds from Z+jets are measured from data, and the methods described above successfully predict the number of events in data samples dominated by SM processes. The irreducible/prompt backgrounds from $\mathrm{t\bar{t}}$ and VV+jets are then obtained from simulation with high confidence.

Table 1: Summary of numbers of events in the various search channels (rows). Channels with electrons and muons have been combined as $\ell\ell$, with $\ell = \mathrm{e}$ or μ, or $\ell\ell'$, if the flavours are different. For the $\ell\ell\ell\ell$ channels different flavour combinations are implied. For the inclusive selection (upper table) isolated tracks are used as proxy for the hadronic tau decays (T channels), while for the hadronic selection (lower table) PF tau reconstruction (τ channels) is used. The rows for inclusive selection are aggregations of selected subsets of channels used in the search. The first three columns give the expected SM background events for the dominant backgrounds after requiring the corresponding number of leptons for each channel. The comparison with data at this stage is given in the next two columns. The SM backgrounds are further reduced using either inclusive or hadronic selection (see text) and compared with data and signal expectations from the ML01 benchmark point in the last columns. Uncertainties are a combination of statistics plus systematics relevant for SM background expectations.

	After Lepton ID Requirements					Inclusive Selection		
	Z+jets	$t\bar{t}$	VV+jets	ΣSM	Data	ΣSM	Data	ML01
Channel	three-lepton channels							
OS($\ell\ell$) e	1.7	0.1	1.2	4.4 ± 1.5	6	0.1 ± 0.1	0	121
OS($\ell\ell$) μ	2.8	0.2	1.7	4.7 ± 0.5	6	0.1 ± 0.1	0	124
OS($\ell\ell$) T	122	0.5	0.7	123 ± 16	127	0.4 ± 0.1	0	80
$\ell\ell' T$	0.7	0.5	0.2	1.7 ± 0.7	3	0.4 ± 0.2	2	18.6
SS($\ell\ell$) ℓ'	0.13	0.1	0.0	0.2 ± 0.1	0	0.2 ± 0.1	0	2.8
SS($\ell\ell$) T	0.25	0.0	0.1	0.7 ± 0.4	3	0.1 ± 0.1	0	9.0
ℓTT	47	0.3	0.1	48 ± 9	30	0.4 ± 0.1	0	8.0
Σ $\ell\ell(\ell/T)$	127	1.4	3.8	135 ± 16	145	1.3 ± 0.2	2	356
Channel	four-lepton channels							
$\ell\ell\ell\ell$	0	0	0.2	0.2 ± 0.1	2	0	0	164
$\ell\ell\ell T$	0	0	0.1	0.1 ± 0.1	0	0	0	62
$\ell\ell TT$	0	0	0	0.0 ± 0.1	0	0	0	21
Σ $\ell\ell(\ell/T)(\ell/T)$	0	0	0.3	0.3 ± 0.1	2	0	0	247

	After Lepton ID Requirements					Hadronic Selection		
	Z+jets	$t\bar{t}$	VV+jets	ΣSM	Data	ΣSM	Data	ML01
Channel	three-lepton channels							
OS($\ell\ell$) e	1.7	0.1	1.2	4.4 ± 1.5	6	0.2 ± 0.1	1	142
OS($\ell\ell$) μ	2.8	0.2	1.7	4.7 ± 0.5	6	0.1 ± 0.1	0	121
OS($\ell\ell$) τ	476	2.7	3.9	484 ± 77	442	0.6 ± 0.2	1	68
$\ell\ell'\tau$	4.7	2.9	0.6	11.2 ± 2.5	10	0.4 ± 0.1	1	12.3
SS($\ell\ell$) ℓ'	0.13	0.1	0.0	0.2 ± 0.1	0	0.1 ± 0.1	0	2.8
SS($\ell\ell$) τ	1.4	0.0	0.1	3.0 ± 1.1	3	0.0 ± 0.1	0	6.9
Σ $\ell\ell(\ell/\tau)$	487	6.0	7.5	507 ± 77	467	1.3 ± 0.3	3	350
Channel	four-lepton channels							
$\ell\ell\ell\ell$	0	0	0.2	0.2 ± 0.1	2	0	0	149
$\ell\ell\ell\tau$	0	0	0.1	0.1 ± 0.1	0	0	0	33
$\ell\ell\tau\tau$	3.1	0.1	0.1	3.2 ± 0.7	5	0	0	17
Σ $\ell\ell(\ell/\tau)(\ell/\tau)$	3.1	0.1	0.4	3.5 ± 0.7	5	0	0	199

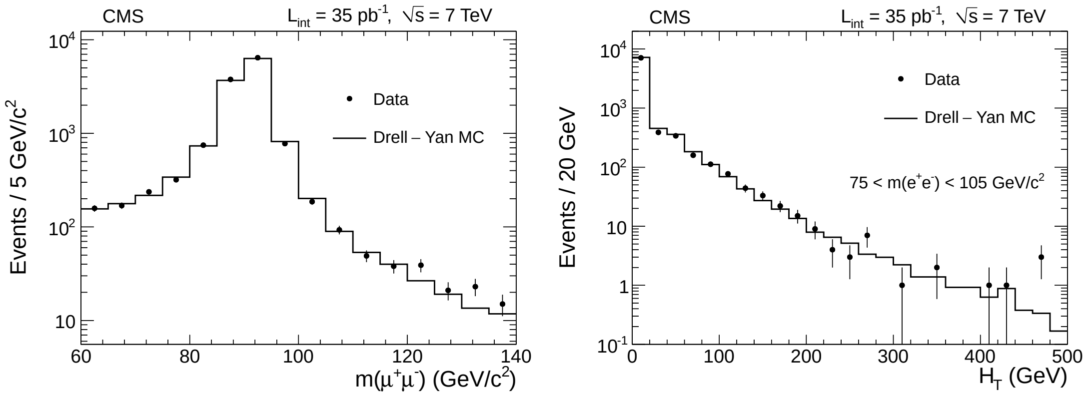

Figure 3: Two-lepton events in data, compared with the SM simulation. Left: mass spectrum for $Z \to \mu\mu$. Right: H_T distribution for $Z \to ee$. Processes other than Drell–Yan are too rare to be visible in these distributions.

7 Observations

Table 1 shows the expected and observed numbers of three- and four-lepton events in this search before and after the final kinematic selections. A tau candidate is indicated by T for an isolated track as proxy for a hadronic tau decay and τ for the PF tau selection. Channels containing OS–SF lepton pairs are listed separately because they suffer from a larger SM background expectation. The main SM backgrounds are given in the first three columns followed by the total SM background, which can be slightly larger than the sum of the previous columns, since it includes less significant backgrounds such as those involving initial and final state radiation. Columns for the inclusive and hadronic kinematic selections show the number of events surviving all requirements. For the inclusive selection only the signal channels are shown, which require $E_T^{miss} > 50$ GeV, Z-veto, and $M(2\ell) > 12$ GeV/c^2 for events with an OS–SF pair as discussed in Section 5.3. The control channels used in the limit setting are discussed in Section 7.1. For the hadronic selection the background reduction comes from the $H_T > 200$ GeV requirement. The sum of the SM backgrounds, mainly from $t\bar{t}$ and the irreducible VV+jets backgrounds, is given as well.

Table 1 also shows signal expectations for the slepton co-NLSP benchmark point ML01 described earlier. All cross sections for the benchmark point and those used in the following exclusion plots include next-to-leading-order corrections calculated using PROSPINO [33], which yields K factors in the range 1.3–1.5.

Observations and SM expectations agree reasonably well. We observe five three-lepton events worth noting. An $e^+e^-\tau^+$ event with $H_T = 246\,\text{GeV}$ satisfies both the $H_T > 200\,\text{GeV}$ and $E_T^{miss} > 50\,\text{GeV}$ requirements. So does an $e^+\mu^+\tau^+$ event with $H_T = 384\,\text{GeV}$. A $\mu^+\mu^-e^+$ event satisfies the $H_T > 200\,\text{GeV}$ requirement but not E_T^{miss}. Two $e^+\mu^-T^-$ events with E_T^{miss} of 70 and 101 GeV fail the H_T requirement. The largest background in the $e\mu T$ channel is expected from $t\bar{t}$ events, and one event is indeed selected as a $t\bar{t}$ event in the CMS top selection [31], but the other fails the lepton p_T requirement.

The four-lepton $\ell\ell\ell\ell$ row in Table 1 also merits discussion since we observe two $\mu^+\mu^-\mu^+\mu^-$ events despite the SM expectation of only 0.21 events. One of the events is completely consistent with the $ZZ \to \mu^+\mu^-\mu^+\mu^-$ hypothesis. The ZZ invariant mass for this event is 212 GeV/c^2 and it has negligible E_T^{miss}. The second event is unlikely to be a ZZ event, but it contains a $\mu^+\mu^-$ pair with an invariant mass of 80 GeV/c^2 which is too close to the Z mass to pass the

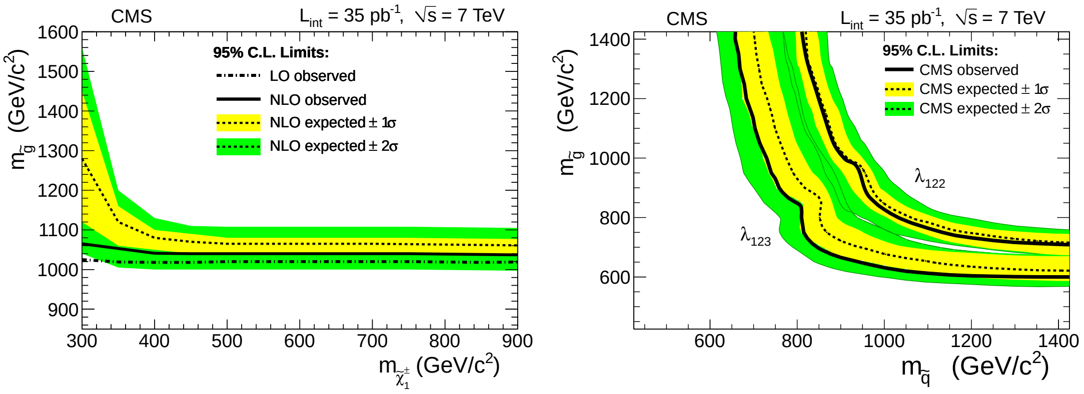

Figure 4: Left: Limits on the slepton co-NLSP model as a function of the gluino and wino-like chargino masses obtained by comparing with leading order (LO) or next to leading order (NLO) cross sections. Right: Limits for the R-parity violating scenario as a function of the gluino and degenerate squark masses with either $\lambda_{122} \neq 0$ or $\lambda_{123} \neq 0$. For both exclusions, squark and slepton universality is enforced with vanishing left-right mixing; mass relationships for other superpartner masses are described in the text.

Z veto criterion. Both events have small $E_{\mathrm{T}}^{\mathrm{miss}}$, leptons originating from the same vertex, and minimal other activity.

7.1 Systematic uncertainties and statistical procedures

We discuss the sources of systematic uncertainty and how they impact the search sensitivity before extracting upper limits on the contributions from physics outside the SM. All channels share systematic uncertainties for luminosity (11%), renormalization scales (10%), parton distribution functions ($\leq$ 14%), and trigger efficiency ($\sim$ 5%). (Note that the luminosity uncertainty subsequently decreased to 4%, but the improvement does not have significant implications for this result.) The precision of lepton selection efficiencies increases with lepton p_{T}. For a typical slepton co-NLSP signal scenario which has leptons with p_{T} in excess of 20 GeV/c, the lepton identification and isolation efficiency systematic uncertainty is $\sim$ 1.5% per lepton for muons and electrons, as well as for isolated tracks. However, CMSSM signals result in lower p_{T} leptons, leading to a higher systematic uncertainty on efficiency of $\sim$ 3% per lepton for muons and for isolated tracks. For low-energy electrons the systematic uncertainty on the isolation efficiency can be as large as $\sim$ 10% because of effects of synchrotron radiation in the high CMS solenoidal magnetic field. The uncertainty on the efficiency of PF tau identification is studied using a comparison of $\mathrm{Z} \to \tau\tau$ events in data and simulation. For this study, events with a muon plus hadronic tau decay are analysed, yielding a 30% systematic uncertainty [34].

The impact of uncertainty from the jet energy scale for the H_{T} selection is $\leq$ 14% as determined by varying the H_{T} requirement by $\pm$5%. The jet-energy scale uncertainty [35] has a small effect on the signal, since the signal efficiency is high given the jet energy requirements; it varies in the range of 2–4%, where the larger number is for the tau modes.

SM backgrounds derived from data suffer from large systematic uncertainties because of the limited quantity of data in hand; uncertainties on the misidentification rates are 30% for the PF taus, 20% for tracks, $\sim$ 30% for muons, and $\sim$ 80% for electrons. These uncertainties are derived from extensive studies in which misidentification rates are factorised into contributing components such as isolation efficiency and the factorised pieces are studied in different data sets. Although these uncertainties appear to be large, they do not affect the results significantly as the backgrounds are small. The uncertainties on backgrounds derived from simulation are dominated by the $\sim 30\%$ uncertainty on the measured SM cross sections.

We utilise the agreement between the expected SM backgrounds and observations shown in Table 1 to constrain new physics scenarios. While being complementary in their approach, the two kinematic selections overlap substantially. This overlap must be removed in the combination of the two selections to evaluate the search sensitivity for new physics. For this purpose, we retain all events from the inclusive selection that satisfy the additional requirement of $H_T < 200$ GeV and all events from the hadronic selection, which have by definition $H_T > 200$ GeV.

There are 55 channels in the combination used for limit setting. We include both $H_T > 200$ GeV and $H_T < 200$ GeV versions of the following 24 three- and four-lepton channels: 2 OS$(\ell\ell)$e; 2 OS$(\ell\ell)\mu$; 2 OS$(\ell\ell)\tau$; 2 $\ell\ell'\tau$; 2 SS$(\ell\ell)\ell'$; 2 SS$(\ell\ell)\tau$; 5 $\ell\ell\ell\ell$; 4 $\ell\ell\ell\tau$; and 3 $\ell\ell\tau\tau$, where τ refers to either tau algorithm. For the remaining seven channels, three require $H_T < 200$ GeV and more than four leptons, with up to two taus, and four require three leptons with two taus: $\Sigma Q = \pm 3$; $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and $H_T > 200$ GeV; $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and on-Z; and $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV and on-Z.

The statistical model uses a Poisson distribution for the number of events in each channel, while the nuisance parameters are modeled with a Gaussian, truncated to be always positive. The significant nuisance parameters are the luminosity uncertainty, trigger efficiency, and lepton identification efficiencies. The expected value in the model is the sum of the signal and the expected backgrounds. We set 95% confidence level (CL) upper limits on the signal parameters and cross sections using a Bayesian method with a flat prior. We check the stability of the result with respect to nuisance constraints selection by substituting log-normal constraints for the Gaussian ones, and find the upper limit results to be stable within 3%. The statistical model is implemented in the program package ROOSTATS [36]. We apply these upper limits on the contribution of new physics for the following SUSY scenarios.

7.2 Slepton co-NLSP

In supersymmetry, multilepton final states arise naturally in the subset of GMSM parameter space where the right-handed sleptons are flavour-degenerate and at the bottom of the Minimal Supersymmetric Standard Model (MSSM) mass spectrum. The Higgsinos are decoupled. Supersymmetric production proceeds mainly through pairs of squarks and/or gluinos. Cascade decays of these states eventually pass sequentially through the lightest neutralino ($\tilde{g}, \tilde{q} \rightarrow \chi^0 + X$), which decays into a slepton and a lepton ($\chi^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp}$). Each of the essentially degenerate right-handed sleptons promptly decays to the Goldstino component of the almost massless and non-interacting gravitino and a lepton ($\tilde{\ell} \rightarrow \tilde{G}\ell$) thus yielding events with four or more hard leptons and missing energy. Such scenarios have a high cross section with little background [17].

The 95% CL exclusion limits for the slepton co-NLSP model is shown in the left panel of Fig. 4. Deviation from the expected limit is due to a modest data excess. The result corresponds to a limit of ≈ 6 events on the signal yield, and a slepton co-NLSP benchmark 95% CL upper limit on the cross section of $\sigma_{95} = 0.2$–0.4 pb. Squark and gluino masses of up to 830 GeV/c^2 and 1040 GeV/c^2 are excluded.

7.3 R-parity violation

Although R-parity is often assumed to be conserved, the most general formulation of the MSSM superpotential contains R-parity violating couplings λ_{ijk}, where i, j, and k are generation indices. We study models in which lepton-number-violating decays are allowed, but baryon

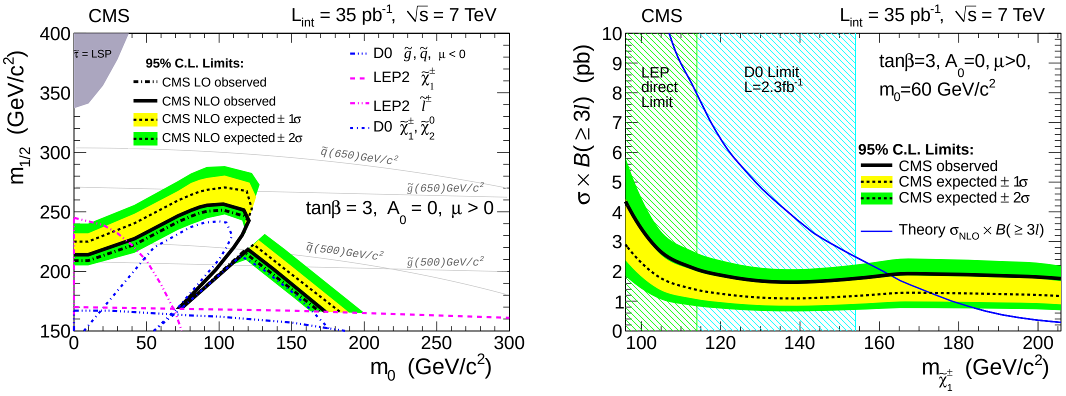

Figure 5: Left: excluded region for the mSUGRA/CMSSM scenario along with the limits from the multilepton searches from the Tevatron [9] and the exclusion derived from slepton and chargino limits from LEP [38–43]. The region below the lines is excluded at 95% CL. Right: the expected and observed upper limits on the cross section times branching ratio $\sigma \times B(3\ell)$ as a function of the chargino mass. The theoretical curve crosses the observed 95% CL upper limit on the cross section at 163 GeV/c^2, thus excluding charginos below this mass for the values of m_0, A_0, and $\tan\beta$ indicated in the figure. For comparison the regions excluded by LEP (from slepton limits [38–43]), Tevatron chargino-neutralino production [9], and Tevatron squark-gluino production [44] are indicated as well. This and other results have the other MSSM parameters fixed at $\tan\beta = 3$, $A_0 = 0$, and $\mu > 0$ except [44], which uses $\mu < 0$.

number is conserved, so these models are not constrained by limits on proton lifetime which require both B and L violation.

Events with four or more charged leptons in the final state originate from the production of pairs of squarks or gluinos, each of which cascade decays down to the LSP, which in the model considered here is the neutralino. Each neutralino decays to two charged leptons and a neutrino. Any nonzero value of λ_{ijk} causes the neutralino to decay, yielding multilepton final states. The actual value of λ_{ijk} simply determines the lifetime and hence the decay length of the neutralino. We consider λ_{ijk} to be sufficiently large so that the decay is prompt, the exclusion limits are independent of λ_{ijk} value, and thus the search is sensitive only to the sparticle masses. We consider the cases of nonzero λ_{122} and nonzero λ_{123} separately. For the λ_{122} coupling, the two charged leptons in each neutralino decay are electron and/or muon, while for λ_{123}, one of the charged leptons is a tau, and the other an electron or muon [37].

The 95% exclusion limits in the squark-gluino mass plane obtained using the inclusive kinematic selection are shown in the right panel of Fig. 4 for a topology with fixed $m_{\chi_1^0} = 300\,\mathrm{GeV}/c^2$, $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = 1000\,\mathrm{GeV}/c^2$, and with the wino and the Higgsino decoupled. The bumps in the contour plot are due to the fact that when the squark mass is larger than the gluino mass there are two additional jets in the event. This lowers the efficiency of the lepton isolation requirement and therefore decreases the signal acceptance. The limits for the λ_{123} coupling are lower because of the lower acceptance for taus. These results substantially extend previous exclusion limits from CDF and D0 based on integrated luminosities of 350 pb^{-1} [11, 12].

7.4 mSUGRA/CMSSM scenario

For the mSUGRA/CMSSM [13, 14] scenario, limits in the m_0-$m_{1/2}$ plane are shown in Fig. 5 for $A_0 = 0, \tan\beta = 3$, and $\mu > 0$. The TeV3 benchmark point defined above is close to the excluded limit from the Tevatron data; the total number of expected events after all cuts is

≈ 7 for the 35 pb^{-1} data sample. As can be seen, our results extend the excluded region in comparison with previous results from LEP and the Tevatron. For small values of m_0 the sleptons can become lighter than the gauginos, so the gauginos will decay into slepton and lepton (two-body decay), although for larger values of m_0 three-body decays will dominate. While for two-body decays the branching fraction into leptons is 100%, it decreases rapidly for three-body decays. In the transition region from two- to three-body decays the leptons become soft and fail the p_T requirement [6]. Exclusion is therefore not possible, as shown by the non-excluded region between the two- and three-body decay regions. We exclude gluino masses up to 628 GeV/c^2 for this choice of parameters. The 95% CL upper limit on the cross section times branching fraction into 3ℓ varies from $\sigma_{95} = 0.8$ to 2 pb. The sensitivity to the chargino mass can be seen in the right panel of Fig. 5, where the NLO cross section for $m_0 = 60$ GeV/c^2 equals the 95% CL experimental limit of $\sigma_{95} = 2$ pb for chargino mass of 163 GeV/c^2. Therefore, chargino masses above this value cannot be excluded.

8 Conclusion

We have performed a search for physics beyond the SM using multilepton final states. Taking advantage of the high centre-of-mass energy at the LHC, we were able to probe new regions of the MSSM parameter space. Our search complements those at the Tevatron, which are mostly sensitive to electroweak gaugino production via quark-antiquark interaction, while the result presented here is mostly sensitive to gluino and squark production via quark-gluon or gluon-gluon interactions.

The results of this search are consistent with SM expectations. In the CMSSM parameter space, gluino masses up to 628 GeV/c^2 are thus excluded for specific SUSY parameters. This result is better than the prior multilepton results from the Tevatron, but is in the region already ruled out by other hadronic searches at the LHC [4, 5]. However, the following two regions of MSSM are not accessible to hadronic searches. With gravitinos as LSP and sleptons as co-NLSP, we are able to exclude squark and gluino masses of up to 830 GeV/c^2 and 1040 GeV/c^2, respectively. We are also able to exclude models with leptonic R-parity violation for gluino masses up to 600–700 GeV/c^2 depending on the choice of parameters. In both cases our search significantly extends into the regions of SUSY parameter space not accessible to multilepton searches at the Tevatron.

Acknowledgements

We thank Michael Park and Yue Zhao (Rutgers) for assistance in simulating theoretical models.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies

(Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (Italy); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); and the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium).

References

[1] H. P. Nilles, "Supersymmetry, Supergravity and Particle Physics", *Phys. Rept.* **110** (1984) 1. `doi:10.1016/0370-1573(84)90008-5`.

[2] H. E. Haber and G. L. Kane, "The Search for Supersymmetry: Probing Physics Beyond the Standard Model", *Phys. Rept.* **117** (1985) 75. `doi:10.1016/0370-1573(85)90051-1`.

[3] W. de Boer, "Grand unified theories and supersymmetry in particle physics and cosmology", *Prog. Part. Nucl. Phys.* **33** (1994) 201. `doi:10.1016/0146-6410(94)90045-0`.

[4] CMS Collaboration, "Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy", *Phys. Lett.* **B698** (2011) 196. `doi:10.1016/j.physletb.2011.03.021`.

[5] ATLAS Collaboration, "Search for Supersymmetry Using Final States with One Lepton, Jets, and Missing Transverse Momentum with the ATLAS Detector in $\sqrt{s}$=7 TeV pp Collisions", *Phys. Rev. Lett.* **106** (2011) 131802. `doi:10.1103/PhysRevLett.106.131802`.

[6] CDF Collaboration, "Search for Supersymmetry in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV Using the Trilepton Signature for Chargino-Neutralino Production", *Phys. Rev. Lett.* **101** (2008) 251801. `doi:10.1103/PhysRevLett.101.251801`.

[7] S. Dube et al., "Addressing the Multi-Channel Inverse Problem at High Energy Colliders: A Model Independent Approach to the Search for New Physics with Trileptons", (2008). `arXiv:0808.1605`.

[8] J. T. Ruderman and D. Shih, "Slepton co-NLSPs at the Tevatron", (2010). `arXiv:1009.1665`.

[9] D0 Collaboration, "Search for associated production of charginos and neutralinos in the trilepton final state using 2.3 fb^{-1} of data", *Phys. Lett.* **B680** (2009) 34. `doi:10.1016/j.physletb.2009.08.011`.

[10] CDF Collaboration, "Search for Supersymmetry in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using the Trilepton Signature of Chargino-Neutralino Production", (2009). `arXiv:0910.1931`.

[11] D0 Collaboration, "Search for R-parity violating supersymmetry via the $LL\overline{E}$ couplings λ_{121}, λ_{122} or λ_{133} in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV", *Phys. Lett.* **B638** (2006) 441. `doi:10.1016/j.physletb.2006.05.077`.

[12] CDF Collaboration, “Search for anomalous production of multilepton events in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV”, *Phys. Rev. Lett.* **98** (2007) 131804. `doi:10.1103/PhysRevLett.98.131804`.

[13] A. H. Chamseddine, R. Arnowitt, and P. Nath, “Locally Supersymmetric Grand Unification”, *Phys. Rev. Lett.* **49** (1982) 970. `doi:10.1103/PhysRevLett.49.970`.

[14] G. Kane et al., “Study of constrained minimal supersymmetry”, *Phys. Rev.* **D49** (1994) 6173. `doi:10.1103/PhysRevD.49.6173`.

[15] S. Dimopoulos, S. D. Thomas, and J. D. Wells, “Implications of low energy supersymmetry breaking at the Fermilab Tevatron”, *Phys. Rev.* **D54** (1996) 3283. `doi:10.1103/PhysRevD.54.3283`.

[16] SUSY Working Group Collaboration, “Low-scale and gauge-mediated supersymmetry breaking at the Fermilab Tevatron Run II”, (2000). `arXiv:hep-ph/0008070`.

[17] D. Alves et al., “Simplified Models for LHC New Physics Searches”, (2011). `arXiv:1105.2838`.

[18] CMS Collaboration, “Commissioning of the CMS Experiment and the Cosmic Run at Four Tesla”, *JINST* **5** (2010) T03001. `doi:10.1088/1748-0221/5/03/T03001`.

[19] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004. `doi:10.1088/1748-0221/3/08/S08004`.

[20] CMS Collaboration, “Electron Reconstruction and Identification at $\sqrt{s} = 7$ TeV”, *CMS Physics Analysis Summary* **CMS-PAS-EGM-10-004** (2010).

[21] CMS Collaboration, “Performance of muon identification in pp collisions at $\sqrt{s}$ = 7 TeV”, *CMS Physics Analysis Summary* **CMS-PAS-MUO-10-002** (2010).

[22] CMS Collaboration, “Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-10-002** (2010).

[23] CMS Collaboration, “Study of tau reconstruction algorithms using pp collisions data collected at $\sqrt{s} = 7$ TeV with CMS detector at LHC”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-10-004** (2010).

[24] CMS Collaboration, “CMS Strategies for tau reconstruction and identification using particle-flow techniques”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-08-001** (2009).

[25] CMS Collaboration, “Missing Transverse Energy Performance in Minimum-Bias and Jet Events from Proton-Proton Collisions at $\sqrt{s} = 7$ TeV”, *CMS Physics Analysis Summary* **CMS-PAS-JME-10-004** (2010).

[26] CMS Collaboration, “CMS MET Performance in Events Containing Electroweak Bosons from pp Collisions at $\sqrt{s} = 7$ TeV”, *CMS Physics Analysis Summary* **CMS-PAS-JME-10-005** (2010).

[27] GEANT4 Collaboration, “GEANT4: A simulation toolkit”, *Nucl. Instrum. Meth.* **A506** (2003) 250. `doi:10.1016/S0168-9002(03)01368-8`.

[28] F. Maltoni and T. Stelzer, “MadEvent: Automatic event generation with MadGraph”, *JHEP* **02** (2003) 027. `doi:10.1088/1126-6708/2003/02/027`.

[29] T. Sjöstrand, S. Mrenna, and P. Skands, "A Brief Introduction to PYTHIA 8.1", *Comput. Phys. Commun.* **178** (2008) 852. `doi:10.1016/j.cpc.2008.01.036`.

[30] P. M. Nadolsky et al., "Implications of CTEQ global analysis for collider observables", *Phys. Rev.* **D78** (2008) 013004, `arXiv:0802.0007`. `doi:10.1103/PhysRevD.78.013004`.

[31] CMS Collaboration, "First Measurement of the Cross Section for Top-Quark Pair Production in Proton-Proton Collisions at $\sqrt{s}$=7 TeV", *Phys. Lett.* **B695** (2011) 424. `doi:10.1016/j.physletb.2010.11.058`.

[32] CMS Collaboration, "Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV", *JHEP* **01** (2011) 1. `doi:10.1007/JHEP01(2011)080`.

[33] W. Beenakker, R. Hoepker, and M. Spira, "PROSPINO: A program for the Production of Supersymmetric Particles in Next-to-leading Order QCD", (1996). `arXiv:hep-ph/9611232`.

[34] S. Maruyama, "Supersymmetry Search in Multilepton Final States with Taus Using the CMS Detector at the LHC". PhD thesis, University of California at Davis, 2011. CERN-THESIS-2011-023.

[35] CMS Collaboration, "Determination of the Jet Energy Scale in CMS with pp Collisions at $\sqrt{s} = 7$ TeV", *CMS Physics Analysis Summary* **CMS-PAS-JME-10-010** (2010).

[36] L. Moneta et al., "The RooStats Project", (2010). `arXiv:1009.1003`.

[37] D. Hits, "A multi-lepton search for new physics in 35 pb^{-1} proton-proton collisions at the LHC with a center mass energy of $\sqrt{s} = 7$ TeV using the CMS detector". PhD thesis, Rutgers, The State University of New Jersey, 2011. CERN-THESIS-2011-040.

[38] LEP2 SUSY Working Group Collaboration, "Combined LEP Selectron/Smuon/Stau Results, 183-208 GeV", (2004).

[39] ALEPH Collaboration, "Search for scalar leptons in e^+e^- collisions at center-of-mass energies up to 209 GeV", *Phys. Lett.* **B526** (2002) 206. `doi:10.1016/S0370-2693(01)01494-0`.

[40] ALEPH Collaboration, "Absolute mass lower limit for the lightest neutralino of the MSSM from e^+e^- data at $\sqrt{s}$ up to 209 GeV", *Phys. Lett.* **B583** (2004) 247. `doi:10.1016/j.physletb.2003.12.066`.

[41] DELPHI Collaboration, "Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM", *Eur. Phys. J.* **C31** (2003) 421. `doi:10.1140/epjc/s2003-01355-5`.

[42] L3 Collaboration, "Search for scalar leptons and scalar quarks at LEP", *Phys. Lett.* **B580** (2004) 37. `doi:10.1016/j.physletb.2003.10.010`.

[43] OPAL Collaboration, "Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s} = 183$ - 209 GeV", *Eur. Phys. J.* **C32** (2004) 453. `doi:10.1140/epjc/s2003-01466-y`.

[44] D0 Collaboration, "Search for squarks and gluinos in events with jets and missing transverse energy using 2.1 fb^{-1} of p$\bar{\text{p}}$ collision data at $\sqrt{s} = 1.96$ TeV", *Phys. Lett.* **B660** (2008) 449. `doi:10.1016/j.physletb.2008.01.042`.

A The CMS Collaboration

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

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer[1], S. Hänsel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

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

Universiteit Antwerpen, Antwerpen, Belgium
S. Bansal, L. Benucci, E.A. De Wolf, X. Janssen, J. Maes, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere[1], D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, S. Ovyn, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, L. Brito, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
C.A. Bernardes[2], F.A. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores[2], C. Lagana, F. Marinho, P.G. Mercadante[2], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
N. Darmenov[1], V. Genchev[1], P. Iaydjiev[1], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia
A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, K. Lelas, R. Plestina[3], D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[4], S. Khalil[5], M.A. Mahmoud[6]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola, G. Fedi

Helsinki Institute of Physics, Helsinki, Finland
S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[7], C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch[8], A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[9], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[9], F. Drouhin[9], C. Ferro, J.-C. Fontaine[9], D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim[9], A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, E. Dietz-Laursonn, M. Erdmann, T. Hebbeker, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz[10], A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung[1], M. Kasemann, I. Katkov[11], P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann[10], R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt[10], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, M. Görner,

K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, M. Schröder, T. Schum, J. Schwandt, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Bauer, J. Berger, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov[11], E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu[1], P. Hidas, D. Horvath[12], A. Kapusi, K. Krajczar[13], F. Sikler[1], G.I. Veres[13], G. Vesztergombi[13]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J. Singh, S.P. Singh

University of Delhi, Delhi, India
S. Ahuja, B.C. Choudhary, P. Gupta, S. Jain, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, R. Khurana, S. Sarkar

Bhabha Atomic Research Centre, Mumbai, India
R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty[1], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, M. Guchait[14], A. Gurtu, M. Maity[15], D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad, N.K. Mondal

Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi[16], S.M. Etesami, A. Fahim[16], M. Hashemi, A. Jafari[16], M. Khakzad,

A. Mohammadi[17], M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali[18]

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c,1], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], N. Manna[a,b], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], G.A. Pierro[a], A. Pompili[a,b], G. Pugliese[a,c], F. Romano[a,c], G. Roselli[a,b], G. Selvaggi[a,b], L. Silvestris[a], R. Trentadue[a], S. Tupputi[a,b], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a], S. Braibant-Giacomelli[a,b], L. Brigliadori[a], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], M. Giunta[a], C. Grandi[a], S. Marcellini[a], G. Masetti[b], M. Meneghelli[a,b], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b,1], S. Costa[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], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,1]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[19], F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b], F. De Guio[a,b,1], L. Di Matteo[a,b], S. Gennai[1], A. Ghezzi[a,b], S. Malvezzi[a], A. Martelli[a,b], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a,1], N. Cavallo[a,20], A. De Cosa[a,b], F. Fabozzi[a,20], A.O.M. Iorio[a,1], L. Lista[a], M. Merola[a,b], P. Paolucci[a]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino, S. Lacaprara[a,21], I. Lazzizzera[a,c], M. Margoni[a,b], M. Mazzucato[a], A.T. Meneguzzo[a,b], M. Nespolo[a,1], L. Perrozzi[a,1], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
P. Baesso[a,b], U. Berzano[a], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b], C. Viviani[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], B. Caponeri[a,b], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,1], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], F. Romeo[a,b], A. Santocchia[a,b], S. Taroni[a,b,1], M. Valdata[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], J. Bernardini[a,b], T. Boccali[a,1], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c], R. Dell'Orso[a], F. Fiori[a,b], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,22], A. Messineo[a,b], F. Palla[a], G. Segneri[a], A.T. Serban[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b,1], A. Venturi[a,1], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma "La Sapienza" [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], D. Franci[a,b], M. Grassi[a,1], E. Longo[a,b], P. Meridiani, S. Nourbakhsh[a], G. Organtini[a,b], F. Pandolfi[a,b,1], R. Paramatti[a], S. Rahatlou[a,b], C. Rovelli[1]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], C. Botta[a,b,1], N. Cartiglia[a], R. Castello[a,b], M. Costa[a,b], N. Demaria[a], A. Graziano[a,b,1], C. Mariotti[a], M. Marone[a,b], S. Maselli[a], E. Migliore[a,b], G. Mila[a,b], V. Monaco[a,b], M. Musich[a,b], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a,b], A. Potenza[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], A. Vilela Pereira[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], D. Montanino[a,b], A. Penzo[a]

Kangwon National University, Chunchon, Korea
S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, K.S. Sim

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

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

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, R. Lopez-Fernandez, R. Magaña Villalba, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck, J. Tam

University of Canterbury, Christchurch, New Zealand
P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland
T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela[1], P.Q. Ribeiro, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, I. Belotelov, P. Bunin, I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov[1], A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
E. Boos, M. Dubinin[23], L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[1], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[24], M. Djordjevic, D. Krpic[24], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini[25], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez[26], T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell[27], D. Benedetti, C. Bernet[3], W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold[1], M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi[28], T. Rommerskirchen, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas[29], M. Spiropulu[23], M. Stoye, P. Tropea, A. Tsirou, P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[30], A. Starodumov[31]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, L. Caminada[32], N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica[32], P. Martinez Ruiz del Arbol, P. Milenovic[33], F. Moortgat, C. Nägeli[32], P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland
E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[34], S. Cerci[35], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[36], A. Polatoz, K. Sogut[37], D. Sunar Cerci[35], B. Tali[35], H. Topakli[34], D. Uzun, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
M. Deliomeroglu, D. Demir[38], E. Gülmez, B. Isildak, M. Kaya[39], O. Kaya[39], M. Özbek, S. Ozkorucuklu[40], N. Sonmez[41]

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

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, D. Hartley, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold[42], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[43], K.W. Bell, A. Belyaev[43], C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko[31], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi[44], D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA
K. Hatakeyama, H. Liu

The University of Alabama, Tuscaloosa, USA
C. Henderson

Boston University, Boston, USA
T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA
A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA
V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA
J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[45], F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA
L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, M. Saelim, E. Salvati, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcherding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko[46], C. Newman-Holmes, V. O'Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, C. Prescott, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde[47], F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya[48], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Dudero, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe

University of Mississippi, University, USA
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith, J. Zennamo

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, M. De Mattia, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
P. Jindal, N. Parashar

Rice University, Houston, USA
C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA
O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA
N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA
E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, F. Palmonari, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at Universidade Federal do ABC, Santo Andre, Brazil
3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
4: Also at Suez Canal University, Suez, Egypt
5: Also at British University, Cairo, Egypt
6: Also at Fayoum University, El-Fayoum, Egypt
7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
8: Also at Massachusetts Institute of Technology, Cambridge, USA
9: Also at Université de Haute-Alsace, Mulhouse, France
10: Also at Brandenburg University of Technology, Cottbus, Germany
11: Also at Moscow State University, Moscow, Russia
12: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
13: Also at Eötvös Loránd University, Budapest, Hungary
14: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
15: Also at University of Visva-Bharati, Santiniketan, India
16: Also at Sharif University of Technology, Tehran, Iran
17: Also at Shiraz University, Shiraz, Iran
18: Also at Isfahan University of Technology, Isfahan, Iran
19: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
20: Also at Università della Basilicata, Potenza, Italy
21: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
22: Also at Università degli studi di Siena, Siena, Italy
23: Also at California Institute of Technology, Pasadena, USA
24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
25: Also at University of California, Los Angeles, Los Angeles, USA
26: Also at University of Florida, Gainesville, USA
27: Also at Université de Genève, Geneva, Switzerland
28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
29: Also at University of Athens, Athens, Greece
30: Also at The University of Kansas, Lawrence, USA
31: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
32: Also at Paul Scherrer Institut, Villigen, Switzerland
33: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
34: Also at Gaziosmanpasa University, Tokat, Turkey
35: Also at Adiyaman University, Adiyaman, Turkey
36: Also at The University of Iowa, Iowa City, USA
37: Also at Mersin University, Mersin, Turkey
38: Also at Izmir Institute of Technology, Izmir, Turkey
39: Also at Kafkas University, Kars, Turkey
40: Also at Suleyman Demirel University, Isparta, Turkey
41: Also at Ege University, Izmir, Turkey
42: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
43: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
44: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
45: Also at Utah Valley University, Orem, USA
46: Also at Institute for Nuclear Research, Moscow, Russia

47: Also at Los Alamos National Laboratory, Los Alamos, USA
48: Also at Erzincan University, Erzincan, Turkey