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Search for direct slepton and gaugino production in final states with two leptons and missing transverse momentum with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV ☆

ATLAS Collaboration *

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ABSTRACT

A search for the electroweak pair production of charged sleptons and weak gauginos decaying into final states with two leptons is performed using 4.7 fb^{-1} of proton–proton collision data at $\sqrt{s} =$ 7 TeV recorded with the ATLAS experiment at the Large Hadron Collider. No significant excesses are observed with respect to the prediction from Standard Model processes. In the scenario of direct slepton production, if the sleptons decay directly into the lightest neutralino, left-handed slepton masses between 85 and 195 GeV are excluded at 95% confidence level for a 20 GeV neutralino. Chargino masses between 110 and 340 GeV are excluded in the scenario of direct production of wino-like chargino pairs decaying into the lightest neutralino via an intermediate on-shell charged slepton for a 10 GeV neutralino. The results are also interpreted in the framework of the phenomenological minimal supersymmetric Standard Model.

1. Introduction

Weak scale Supersymmetry (SUSY) [1–9] is an extension to the Standard Model (SM). It postulates for each known boson or fermion the existence of a particle whose spin differs by one-half unit from the SM partner. The introduction of these new particles provides solutions to the hierarchy problem [10–13] and, if R-parity is conserved [14–18], a dark matter candidate in the form of the lightest supersymmetric particle (LSP). R-parity conservation is assumed in this Letter, hence SUSY particles are always produced in pairs. In a large fraction of the SUSY parameter space the LSP is the weakly interacting lightest neutralino, $\tilde{\chi}_1^0$.

Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) are the SUSY partners of gluons and quarks. Charginos ($\tilde{\chi}_i^{\pm}$, $i = 1, 2$) and neutralinos ($\tilde{\chi}_j^0$, $j = 1, 2, 3, 4$) are the mass eigenstates formed from the linear superposition of the SUSY partners of the Higgses and electroweak gauge bosons: higgsinos, winos and the bino (collectively, gauginos). The SUSY partners of the charged leptons are the selectron, smuon and stau, collectively referred to as charged sleptons ($\tilde{\ell}^{\pm}$). The SUSY partners of the standard model left-handed leptons are referred to as left-handed sleptons. If the masses of the gluinos and squarks are greater than a few TeV and the weak gauginos and sleptons have masses of a few hundreds of GeV, the direct production of weak gauginos and sleptons may dominate the production of SUSY particles at the Large Hadron Collider (LHC). Such a scenario is possible in the general framework of the phenomenological minimal supersymmetric SM (pMSSM) [19]. Naturalness suggests that third generation sparticles, charginos and neutralinos should have masses of a few hundreds of GeV [20,21]. Light sleptons are expected in gauge mediated [22] and anomaly mediated [23,24] SUSY breaking scenarios. Light sleptons could also play a role in helping SUSY to provide a relic dark matter density consistent with observations [25,26].

This Letter presents the first search for direct left-handed slepton pair production at the LHC, and a dedicated search for direct chargino pair production in final states with two leptons (electrons, e, or muons, μ). Searches for the general pair production of gauginos decaying into two-lepton final states are also presented. The analysis presented in this Letter is not sensitive to right-handed slepton pair production which has much lower cross-section.

1.1. Direct slepton and chargino pair production

Sleptons can be produced directly in a process similar to Drell–Yan production [27]. The search in this Letter targets the direct pair production of left-handed charged sleptons, where each charged slepton $\tilde{\ell}$ (selectron or smuon) decays through $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\chi}_1^0$, yielding a final state with two same flavour (SF) charged leptons. The undetected $\tilde{\chi}_1^0$ gives rise to large missing transverse momentum in the event. Previous experimental searches for direct slepton production [28] assumed gaugino unification. In the present work this assumption is dropped, thereby removing the lower limit on the mass of the $\tilde{\chi}_1^0$. Direct chargino pair production, where each

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* *E-mail address:* atlas.publications@cern.ch.

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chargino decays through $\tilde{\chi}_1^{\pm} \to \ell^{\pm}\nu\tilde{\chi}_1^0$ leads to a signature similar to that of slepton pair production. The analysis presented also targets this production channel and subsequent decay, setting limits on the chargino mass, without the assumptions on the mass of the $\tilde{\chi}_2^0$ usually present in trilepton searches.

1.2. Other weak gaugino production

In the general framework of the pMSSM, several weak gaugino production channels can lead to final states with two leptons. Production modes such as $\tilde{\chi}_2^0\tilde{\chi}_{i=1,2}^{\pm}$ or $\tilde{\chi}_2^0\tilde{\chi}_{j=2,3,4}^0$, with the subsequent decays $\tilde{\chi}_2^0 \to \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ and $\tilde{\chi}_j^0, \tilde{\chi}_i^{\pm} \to q\bar{q}'\tilde{\chi}_1^0$ are addressed by a signal region containing two leptons and two jets. In order to complement existing and future trilepton searches a dedicated signal region with two same charge leptons is designed to be sensitive to trilepton final states from $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to (\ell^{\mp}\ell^{\mp}\tilde{\chi}_1^0) + (\ell^{\mp}\nu\tilde{\chi}_1^0)$ where one lepton is not identified. All final states yield missing transverse energy due to the presence of two $\tilde{\chi}_1^0$'s.

Model-independent visible cross-section upper limits are obtained in each signal region to address the large variety of possible production and decay modes in the gaugino sector. The results are also interpreted in the framework of the pMSSM. This search is not sensitive to weak gaugino decays via on-shell Z bosons. Previous limits on weak chargino and neutralino production have been placed at LEP [28], the Tevatron [29,30] and at the LHC [31,32].

2. The ATLAS detector

The ATLAS experiment [33] is a multi-purpose particle physics detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] It contains four superconducting magnet systems, which include a thin solenoid surrounding the inner tracking detector (ID), and barrel and end-cap toroids supporting a muon spectrometer. The ID occupies the pseudorapidity region $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). In the pseudorapidity region $|\eta| < 3.2$, high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides coverage for hadron detection over $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimeters for both EM and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of a system of precision tracking chambers ($|\eta| < 2.7$), and detectors for triggering ($|\eta| < 2.4$).

3. Simulated samples

3.1. Standard Model production

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to evaluate the SM backgrounds in the signal region. The dominant backgrounds include fully-leptonic $t\bar{t}$, $Z/\gamma^* +$jets, single top and dibosons (WW, WZ and ZZ). Production of top-quark pairs is simulated with POWHEG [34], using a top-quark mass of 172.5 GeV. Samples of W to $l\nu$ and Z/γ^* to ll, produced with accompanying jets (of both light and heavy flavour), are obtained with ALPGEN [35]. Diboson (WW, WZ, ZZ) production is simulated with SHERPA [36] in signal regions requiring jets and with HERWIG [37] elsewhere. Single top production is modelled with MC@NLO [38–40]. Fragmentation and hadronisation for the ALPGEN and MC@NLO samples are performed with HERWIG, using JIMMY [41] for the underlying event, and with PYTHIA [42] for the POWHEG sample. Expected diboson yields are normalised using NLO QCD predictions obtained with MCFM [43,44]. The top-quark contribution is normalised to approximate next-to-next-to-leading order (NNLO) calculations [45]. The inclusive W and Z/γ^* production cross-sections are normalised to the next-to-next-to-leading order (NNLO) cross-sections obtained using FEWZ [46]. MC@NLO samples are used to assess the systematic uncertainties associated with the choice of generator for $t\bar{t}$ production, and AcerMC [47] samples are used to assess the uncertainties associated with initial and final state radiation (ISR/FSR) [48]. ALPGEN, HERWIG and SHERPA samples are used to assess the systematic uncertainties associated with the choice of generator for diboson production. SHERPA is used to evaluate the small contribution from internal conversions.

3.2. Direct slepton and direct gaugino production

Four signal regions are designed, optimised for the discovery of various SUSY models where sleptons or gauginos are directly produced in the pp interaction. The pMSSM framework is used to produce two sets of signal samples, one where sleptons are directly produced and one where gauginos are directly produced. These samples are used to set the limits on the masses of the directly produced sleptons and gauginos. Samples are also produced in a simplified model at given LSP and chargino masses, and are then used to set limits on the chargino mass, independently of the $\tilde{\chi}_2^0$ mass. In all SUSY models the masses of the squarks, gluinos and third generation supersymmetric partners of the fermions are large (2.5 TeV in the direct slepton production pMSSM models and 2 TeV in the direct gaugino pMSSM and simplified models).

The direct slepton models are based on those described in Ref. [49]. Masses of all gauginos apart from the $\tilde{\chi}_1^0$ are set to 2.5 TeV. The sensitivity of the present search to a given model is determined by the slepton production cross-section and by the mass of the $\tilde{\chi}_1^0$, which affects the kinematics of the final state leptons. The mass of the bino-like $\tilde{\chi}_1^0$ is varied by scanning values of gaugino mass parameter M_1 in steps of 20 GeV in the range 20–160 GeV. The common selectron and smuon mass is generated in the range 70–190 GeV, scanned in steps of 20 GeV with the constraint $m_{\tilde{\ell}} > m_{\tilde{\chi}_1^0} + 30$ GeV. The cross-section for direct slepton pair production in these models decreases from 3.9 to 0.05 pb independently of neutralino mass as the slepton mass increases from 70 to 190 GeV.

In the considered simplified models, the masses of the relevant particles ($\tilde{\chi}_1^0$, $\tilde{\nu}$, $\tilde{\ell}_L$, $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$) are the only free parameters. The latter are wino-like and $\tilde{\chi}_1^0$ is bino-like. The $\tilde{\chi}_1^{\pm}$ are pair-produced via the s-channel exchange of a virtual gauge boson and decay via left-handed sleptons, including $\tilde{\tau}$, and $\tilde{\nu}$ of mass $m_{\tilde{\nu}} = m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^{\pm}})/2$ with a branching ratio of 50% each. The cross-section for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ pair production in these models is as high as 3 pb for a chargino mass of 50 GeV and decreases rapidly at higher masses, reaching below ~ 0.2 pb for masses above 200 GeV.

For the other weak gaugino production channels, a set of pMSSM models with intermediate sleptons in the gaugino decay chain are generated. The right-handed sleptons, with a common mass for all three generations, are inserted halfway between the two lightest neutralino masses while left-handed slepton masses are kept beyond reach.

The masses of the charginos and the neutralinos depend on the gaugino and Higgsino mass parameters M_1, M_2 and μ and the

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis along the beam pipe. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln\tan(\theta/2)$.

ratio of the expectation values of the two Higgs doublets ($\tan\beta$) via mixing matrices [50]. The chargino masses are given by the solution of a 2×2 matrix equation which is dependent on M_2, μ and $\tan\beta$ [51]. The neutralino masses are found by solving a 4×4 matrix equation; solutions to which are given in Refs. [52–54]. The parameters M_1, M_2 and μ are varied independently while $\tan\beta$ is set to 6. In the pMSSM model the cross-sections vary significantly (between 0.5 and 100 pb for $M_1 = 250$ GeV, with the highest cross-sections at low M_2 and μ). The present direct gaugino production search is only sensitive to models with intermediate sleptons.

Signal samples for the pMSSM and slepton model points are generated with HERWIG, whereas Herwig++ [55] is used to generate the simplified model points. Signal cross-sections are calculated to next-to-leading order in the strong coupling constant (NLO) using PROSPINO [56]. The nominal cross-section and the uncertainty are taken from an envelope of cross-section predictions using different parton distribution function (PDF) sets and factorisation and renormalisation scales, as described in Ref. [57].

All MC samples are produced using a GEANT4 [58] based detector simulation [59]. The effect of multiple proton–proton collisions from the same or different bunch crossings is incorporated into the simulation by overlaying additional minimum bias events onto hard scatter events using PYTHIA. Simulated events are weighted to match the distribution of the number of interactions per bunch crossing observed in data.

4. Data and event selection

The 7 TeV proton–proton collision data analysed were recorded between March and October 2011. Application of beam, detector and data-quality requirements yields a total integrated luminosity of 4.7 fb^{-1}. Events are triggered using a combination of single and double lepton triggers. The single electron triggers vary with the data taking period, and the tightest trigger has an efficiency of $\sim 97\%$ for offline electrons with $p_T > 25$ GeV. The single muon trigger used for all data taking periods reaches an efficiency plateau of $\sim 75\%$ ($\sim 90\%$) in the barrel (end-caps) for muons with $p_T > 20$ GeV. All quoted efficiencies have been measured with respect to reconstructed leptons. The double lepton triggers reach similar plateau efficiencies, but at lower p_T thresholds: > 17 GeV for the dielectron trigger, and > 12 GeV for the dimuon trigger; for the electron-muon trigger the thresholds are 15 and 10 GeV respectively. One or two signal leptons are required to have triggered the event, and be matched to the online triggered leptons: one lepton if one is above the appropriate single lepton trigger plateau threshold, or two leptons if there is no such lepton. An exception to this rule is applied in the $\mu\mu$ channel. In this case when one lepton is above the single lepton trigger plateau threshold, and the other above the double lepton threshold, a logical OR of both triggers is used to recover efficiency.

Jet candidates are reconstructed using the anti-k_t jet clustering algorithm [60] with a distance parameter of 0.4. The jet candidates are corrected for the effects of calorimeter non-compensation and inhomogeneities by using p_T and η-dependent calibration factors based on MC simulations and validated with extensive test-beam and collision-data studies [61]. Only jet candidates with transverse momenta $p_T > 20$ GeV and $|\eta| < 4.5$ are subsequently retained. Jets likely to have arisen from detector noise or cosmic rays are rejected [61]. Electron candidates are required to have $p_T > 10$ GeV, $|\eta| < 2.47$, and pass the "medium" shower shape and track selection criteria of Ref. [62]. Muon candidates are reconstructed using either a full muon spectrometer track matched to an ID track, or a partial muon spectrometer track matched to an ID track. They are then required to have $p_T > 10$ GeV and $|\eta| < 2.4$. They must be reconstructed with sufficient hits in the pixel, SCT and TRT detectors.

The measurement of the missing transverse momentum two-vector, $\mathbf{p}_T^{\text{miss}}$, and its magnitude, E_T^{miss}, is based on the transverse momenta of all electron and muon candidates, all jets, and all clusters of calorimeter energy with $|\eta| < 4.9$ not associated to such objects. The quantity $E_T^{\text{miss,rel.}}$ is defined as

$$E_T^{\text{miss,rel.}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geqslant \pi/2, \\ E_T^{\text{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2, \end{cases}$$

where $\Delta\phi_{\ell,j}$ is the azimuthal angle between the direction of $\mathbf{p}_T^{\text{miss}}$ and that of the nearest electron, muon or jet. In a situation where the momentum of one of the jets or leptons is significantly mis-measured, such that it is aligned with the direction of $\mathbf{p}_T^{\text{miss}}$, only the E_T^{miss} component perpendicular to that object is considered. This is used to significantly reduce mis-measured E_T^{miss} in processes such as $Z/\gamma^* \to e^+e^-, \mu^+\mu^-$ [63].

Signal electrons, muons and jets are then selected. Signal electrons are further required to pass the "tight" [62] quality criteria, which place additional requirements on the ratio of calorimetric energy to track momentum, and the number of high-threshold hits in the TRT. They are also required to be isolated: the p_T sum of tracks above 1 GeV within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around each electron candidate (excluding the electron candidate itself) is required to be less than 10% of the electron p_T. Signal muons must also be isolated: the p_T sum of tracks within a cone of size $\Delta R = 0.2$ around the muon candidate is required to be less than 1.8 GeV.

Signal jets are subject to the further requirements $p_T > 30$ GeV, $|\eta| < 2.5$ and a "jet vertex fraction" greater than 0.75. The jet vertex fraction is defined as the total track momentum associated to the jet and coming from the primary vertex divided by the total track transverse momentum in the jet.

The jet vertex fraction quantifies the fraction of track transverse momentum from the primary vertex, associated to a jet. This variable is used to remove jets that originated from other collisions, and also discards jets without reconstructed tracks.

A b-tagging algorithm [64], which exploits the long lifetime of weak b- and c-hadron decays inside a candidate jet, is used to identify jets containing a b-hadron decay. The mean nominal b-tagging efficiency, determined from $t\bar{t}$ MC events, is 80%, with a misidentification (mis-tag) rate for light-quark/gluon jets of less than 1%. Scale factors (which depend on p_T and η) are applied to all MC samples to correct for small discrepancies in the b-tagging performance observed in data with respect to simulation.

Basic data quality requirements are then applied. Selected events in each signal region (SR-) and control region must satisfy the following requirements. The primary vertex in the event must have at least five associated tracks and each event must contain exactly two signal leptons of opposite-sign (OS) or same sign (SS). Both of these leptons must additionally satisfy the full list of lepton requirements, and the dilepton invariant mass, $m_{\ell\ell}$, must be greater than 20 GeV across all flavour combinations.

5. Signal regions

In this analysis four signal regions are defined. The first and main signal region (labelled SR-m_{T2}) exploits the "stransverse" mass variable, m_{T2} [65,66], to provide sensitivity to both $\tilde{\chi}_1^{\pm}$ and $\tilde{\ell}^{\pm}$ pair production. This variable is defined as: $m_{T2} = \min_{\mathbf{q}_T+\mathbf{r}_T=\mathbf{p}_T^{\text{miss}}}[\max(m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T))]$, where $\mathbf{p}_T^{\ell_1}$ and $\mathbf{p}_T^{\ell_2}$ are the transverse momenta of the two leptons, and $\mathbf{q}_T$ and $\mathbf{r}_T$

Table 1
Decay modes targeted by each signal region, $\tilde{\chi}_i$ denotes either a chargino or a neutralino. In decays producing three real leptons, one must be mis-reconstructed or fall outside the acceptance of the detector.

Targeted process	Signal region
Two-lepton final states	
$\tilde{\ell}^{\pm}\tilde{\ell}^{\mp} \to (\ell^{\mp}\tilde{\chi}_1^0) + (\ell^{\mp}\tilde{\chi}_1^0)$	SR-m_{T2}
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to (\ell^{\mp}\nu\tilde{\chi}_1^0) + (\ell^{\mp}\nu\tilde{\chi}_1^0)$	SR-m_{T2}, SR-OSjveto
$\tilde{\chi}_2^0\tilde{\chi}_i \to (\ell^{\mp}\ell^{\mp}\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$	SR-2jets
Three-lepton final states	
$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to (\ell^{\mp}\ell^{\mp}\tilde{\chi}_1^0) + (\ell^{\mp}\nu\tilde{\chi}_1^0)$	SR-OSjveto, SR-SSjveto

Table 2
Signal regions. OS (SS) denotes two opposite-sign (same-sign) signal leptons, of same (SF) or different (DF) flavour. The Z-veto rejects events with $m_{\ell\ell}$ within 10 GeV of the Z boson mass (91.2 GeV). The m_{CT}-veto rejects events kinematically consistent with $t\bar{t}$ (Section 5.2). The values quoted for $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ and m_{T2} are in units of GeV.

SR-	m_{T2}	OSjveto	SSjveto	2jets
charge	OS	OS	SS	OS
flavour	any	any		SF
$m_{\ell\ell}$	Z-veto	Z-veto	–	Z-veto
signal jets	$=0$	$=0$		$\geqslant 2$
signal b-jets	–	–		$=0$
$E_{\mathrm{T}}^{\mathrm{miss,rel.}}$	>40	>100		>50
other	$m_{\mathrm{T2}} > 90$	–		m_{CT}-veto

are two vectors which satisfy $\mathbf{q}_{\mathrm{T}} + \mathbf{r}_{\mathrm{T}} = \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$. m_{T} indicates the transverse mass, $m_{\mathrm{T}} = \sqrt{2E_{\mathrm{T,p}}^{\ell_1}E_{\mathrm{T,q}}(1-\cos\phi)}$, where E_{T} is the transverse energy of a particle and ϕ the angle between the two particles in the transverse plane. The minimisation is performed over all possible decompositions of $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$.

The search for $\tilde{\ell}^{\pm}$ pair production uses only the same flavour channels e^+e^- and $\mu^+\mu^-$, while the $\tilde{\chi}_1^{\pm}$ pair production search also relies on $e^{\pm}\mu^{\mp}$. Additional sensitivity to $\tilde{\chi}_1^{\pm}$ pair production is provided by the second signal region, SR-OSjveto, which selects OS lepton pairs with high $E_{\mathrm{T}}^{\mathrm{miss}}$ in events with no signal jets.

The production modes $\tilde{\chi}_2^0\tilde{\chi}_i^{\pm}$ or $\tilde{\chi}_2^0\tilde{\chi}_i^0$, with the subsequent decays $\tilde{\chi}_2^0 \to \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ and $\tilde{\chi}_i^0, \tilde{\chi}_i^{\pm} \to q\bar{q}'\tilde{\chi}_1^0$ are targeted by a region called SR-2jets, which selects events with two signal jets and two OS leptons.

In this Letter the region SR-OSjveto and an equivalent region, SR-SSjveto, which instead selects the events with SS lepton pairs, also target a three lepton final state. The explicit veto in this analysis on a third lepton makes the results in these regions orthogonal to results from direct gaugino searches with three or more leptons [32]. These regions recover events which are not reconstructed in searches for $\geqslant 3$ leptons because one of the three leptons falls outside the acceptance of the detector and selection criteria. The processes directly targeted by each signal region are stated explicitly in Table 1.

The exact requirements on the values to be taken by each variable in each signal region were determined by optimising the expected reach using a significance measure [67] in either the neutralino–slepton mass plane of the pMSSM model (SR-m_{T2}), the neutralino–chargino mass plane of the simplified model (SR-OSjveto and SR-SSjveto) or the M_1–μ mass plane of the pMSSM (SR-2jets). Table 2 summarises the requirements for entering each signal region.

5.1. Direct slepton and chargino pair production

In SR-m_{T2} the properties of m_{T2} are exploited to search for $\tilde{\ell}^{\pm}\tilde{\ell}^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production followed by decay to final states containing exactly two OS leptons (of different flavour, DF, or same flavour, SF), no signal jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ from the two $\tilde{\chi}_1^0$. In this signal region $t\bar{t}$ and WW are dominant backgrounds. For large mass differences between the sleptons (charginos) and the lightest neutralino, the m_{T2} distribution for signal events extends significantly beyond the distributions for $t\bar{t}$ and diboson backgrounds. The optimised value for the lower m_{T2} requirement is 90 GeV, just above the W boson mass (which is the approximate end-point of the WW and $t\bar{t}$ distributions).

A rejection of events with $m_{\ell\ell}$ within 10 GeV of the Z mass reduces Z/γ^* backgrounds. For the direct slepton pMSSM models with a 20 GeV neutralino, the product of the kinematic and geometrical acceptance and reconstruction and event selection efficiencies varies between 0.1 and 4.0% in this SR for slepton masses between 90 and 190 GeV. For fixed 190 GeV slepton mass, this product increases from 0.2 to 4.0% as the neutralino mass decreases from 140 to 20 GeV. In the simplified models, for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ pair production, the product of acceptance and efficiency ranges between 1 and 7%, increasing towards higher chargino and lower neutralino masses.

In SR-OSjveto a different approach to reducing the backgrounds is taken. The m_{T2} variable is not used, and instead more stringent requirements are replaced on $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ to suppress the $t\bar{t}$ background. The dominant Z background is suppressed by rejecting events with $m_{\ell\ell}$ within 10 GeV of the Z boson mass. The final requirement, on $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$, further increases sensitivity to the signals which are associated with much higher $E_{\mathrm{T}}^{\mathrm{miss}}$ than the SM backgrounds. In the simplified models, for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ pair production, the product of acceptance and efficiency ranges between 1 and 8%, increasing towards higher chargino and lower neutralino masses.

In SR-m_{T2} the expected number of direct slepton signal events for $m_{\tilde{\ell}} = 130$ GeV and $m_{\tilde{\chi}_1^0} = 20$ GeV is $20.7 \pm 0.8(\mathrm{syst}) \pm 0.6(\mathrm{theory})$, where the first uncertainty denotes experimental uncertainties detailed below, while the theory uncertainty contains PDF and scale uncertainties. In SR-OSjveto the expected number of direct chargino pair events with $m_{\tilde{\chi}_1^{\pm}} = 175$ GeV and $m_{\tilde{\chi}_1^0} = 25$ GeV is $67.8 \pm 3.4(\mathrm{syst}) \pm 2.3(\mathrm{theory})$.

5.2. Other weak gaugino production

In the production channel and decay $\tilde{\chi}_2^0\tilde{\chi}_i \to (\ell^{\mp}\ell^{\pm}\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$ the resulting OS two-lepton final state has significant $E_{\mathrm{T}}^{\mathrm{miss}}$ and at least two signal jets. The region SR-2jets is thus sensitive to these decays. In SR-2jets, top background is reduced using a "top-tag" veto. The top-tagging requirement is imposed through the use of the contransverse mass variable m_{CT} [68]. This observable can be calculated from the four-momenta of the selected signal jets and leptons:

$$m_{\mathrm{CT}}^2(v_1, v_2) = \left[E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)\right]^2 - \left[\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)\right]^2,$$

where v_i can be a lepton (l), jet (j) or a lepton-jet combination. Transverse momentum vectors are defined by $\mathbf{p}_{\mathrm{T}}$ and transverse energies E_{T} are defined as $E_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$. The quantities $m_{\mathrm{CT}}(j, j)$, $m_{\mathrm{CT}}(l, l)$ and $m_{\mathrm{CT}}(jl, jl)$ are bounded from above by analytical functions of the top-quark and W boson masses. A top-tagged event must have at least two jets with $p_{\mathrm{T}} > 30$ GeV, and the scalar sum of the p_{T} of at least one combination of two signal jets and the two signal leptons in the event must exceed 100 GeV. Furthermore, top-tagged events are required to possess m_{CT} values calculated from combinations of signal jets and leptons consistent with the expected bounds from $t\bar{t}$ events

Table 3
Requirements for entering each control region for top, WW and $Z+X$ background estimation in the OS signal regions. These are used to estimate the top background in all OS signal regions, WW in SR-OSjveto and $Z+X$ in all SF channels of the OS signal regions. When each OS signal region requires differing control region definitions, the conditions are given as a comma separated list (SR-OSjveto, SR-2jets, SR-m_{T2}). The Z-veto is a rejection of events with $m_{\ell\ell}$ within 10 GeV of the Z-mass (91.2 GeV), whereas the Z-window defines the reverse. In the WW control region the b-jets considered are those with $p_T > 20$ GeV. The values quoted for $E_T^{miss,rel.}$ are in units of GeV.

	top	WW	$Z+X$
$m_{\ell\ell}$	Z-veto	Z-veto	Z-window
signal jets	$\geqslant 2$	$=0$	$=0, \geqslant 2, \geqslant 0$
signal b-jets	$\geqslant 1$	$=0$	$\geqslant 0, =0, \geqslant 0$
$E_T^{miss,rel.}$	$> 100, 50, 40$	70–100	$> 100, 50, 40$
other	–	–	–, m_{CT}-veto, –

as described in Ref. [69]. Further top rejection is achieved using a veto on any events containing a signal jet tagged as a b-jet. Z backgrounds are reduced using the Z-veto, and sensitivity increased by searching at high $E_T^{miss,rel.}$. The expected number of signal events in SR-2jets from $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\ell^\mp\ell^\pm\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$ for a pMSSM point with $M_1 = 100$ GeV, $M_2 = 120$ GeV, $\mu = 100$ GeV is $37.6 \pm 4.9(\text{syst}) \pm 7.0(\text{theory})$.

In the regions targeting fully-leptonic $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ decays (SR-OSjveto and SR-SSjveto), a veto on events containing a signal jet reduces hadronic backgrounds, and high $E_T^{miss,rel.}$ increases the sensitivity to SUSY decays. The final state leptons can be of either OS or SS. In the absence of significant expected Z background in the SS signal region, no Z-veto is applied. The expected number of signal events in SR-SSjveto from fully-leptonic $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ decays for a simplified model with $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = 200$ GeV and $m_{\tilde{\chi}_1^0} = 50$ GeV, is $12.4 \pm 1.4(\text{syst}) \pm 0.7(\text{theory})$.

6. Background evaluation

6.1. Backgrounds in SR-m_{T2}

In this Letter, SR-m_{T2} is used to search for $\tilde{\ell}^\pm$ pair production and provides the best sensitivity to $\tilde{\chi}_1^\pm$ pair production. The main backgrounds in this region are: fully-leptonic $t\bar{t}$ and single top, $Z/\gamma^* +$jets and dibosons (WW, WZ and ZZ).

Fully-leptonic $t\bar{t}$ is comparable in size to the WW background in all flavour channels. $Z/\gamma^* +$jets, WZ and ZZ processes (collectively, $Z+X$) are a small proportion of events in the DF channel, but comparable in size to the WW and $t\bar{t}$ backgrounds in the SF channels. The remainder of the SM background is accounted for by fake lepton backgrounds. The methods used to evaluate these backgrounds in SR-m_{T2} are described in the following sections.

6.1.1. Top

The combined contribution from $t\bar{t}$ and single top events in each channel (ee, $e\mu$ or $\mu\mu$) is evaluated by normalising MC simulation to data in an appropriate control region. Events in the control region (Table 3) must contain at least two signal jets, one of which must be b-tagged, and pass the requirement that $E_T^{miss,rel.}$ must be greater than 40 GeV. The corresponding control region is dominated by top events. The contamination from non-top events is less than 4%. The number of top events in the signal region (N_{top}^{SR}) is estimated from the number of data events in the control region (N_{top}^{CR}), after the subtraction of non-top backgrounds, using a transfer factor $\mathcal{T}$:

$$N_X^{SR} = N_X^{CR} \times \mathcal{T} \times S_{\mathcal{T}}.$$

The factor, $\mathcal{T}$, the ratio of top events in the signal to those in the control region is derived using MC

$$\mathcal{T} = \left(\frac{N_X^{SR}}{N_X^{CR}}\right)_{MC}.$$

The factor $S_{\mathcal{T}}$ corrects for possible differences in jet-veto efficiency between data and MC simulation. Good agreement is observed in separate samples of $t\bar{t}$ and $Z/\gamma^* +$jets events and so this factor is taken to be equal to 1.0, with an uncertainty of 6%. The transfer factor is evaluated before the m_{T2} requirement is applied in the signal region since this requirement is designed to eliminate all but the tail of the m_{T2} distribution for $t\bar{t}$. The efficiency of this requirement is then evaluated using MC simulation for a looser selection (which is assumed not to change the m_{T2} shape) and used to obtain the final estimate in SR-m_{T2}. The efficiency of the m_{T2} requirement is found to be $\sim 2\%$ in each channel for top events with an uncertainty of $\sim 50\%$. The uncertainty is largely dominated by MC statistical uncertainty, generator uncertainties and jet and lepton scales and resolutions.

The evaluated $t\bar{t}$ components in each channel are consistent with pure MC estimates normalised to cross-sections to within 1σ. Data and MC simulation are also consistent at this level in the control region. Negligible contamination from the SUSY signal models generated, in the region of the expected reach, is predicted.

6.1.2. $Z+X$

The $Z/\gamma^* +$jets background in the SF channels is also estimated by normalising MC simulation to data in a suitable control region. This procedure is important in order to handle appropriately possible detector imperfections affecting E_T^{miss} measurement. This technique also estimates the ZW and ZZ components, providing a combined estimate of the total $Z+X$ background in the SF channels.

In the DF channel the $Z/\gamma^* +$jets contribution is significantly smaller and arises mainly from $Z/\gamma^* \to \tau\tau$ decays. This and the diboson components of the $Z+X$ background in the DF channel are estimated using MC simulation.

The control region (Table 3) used to estimate the $Z+X$ background in the SF channels is defined to be identical to the signal region but with the Z-veto reversed. The normalisation is evaluated before the m_{T2} requirement, and the efficiency of the m_{T2} requirement is measured separately using MC simulation. The population of data events inside the control region not produced by $Z+X$ processes is estimated using data $e\mu$ events inside the Z-window, correcting for the differences between electron and muon reconstruction efficiencies. This subtraction removes less than 2% of the events in the control region. This procedure also subtracts contributions from $Z/\gamma^* \to \tau\tau +$jets events which must be estimated using MC simulation. The MC m_{T2} requirement efficiency for $Z+X$ events is taken to be 0.004 (0.003) for e^+e^- ($\mu^+\mu^-$) events with $\sim 50\%$ uncertainty.

The estimated $Z+X$ background is consistent within statistics with the MC prediction. No significant signal contamination is expected for the SUSY model points considered in the region of sensitivity for the searches reported in this Letter.

6.1.3. WW

The WW background is evaluated using MC normalised to cross-section and luminosity. The predictions from a variety of generators (see Section 3) were compared before application of the m_{T2} requirement (to maximise acceptance for comparison), in order to assess the theoretical uncertainty on this estimate. The m_{T2} distribution in data agrees well with that in MC simulation, and

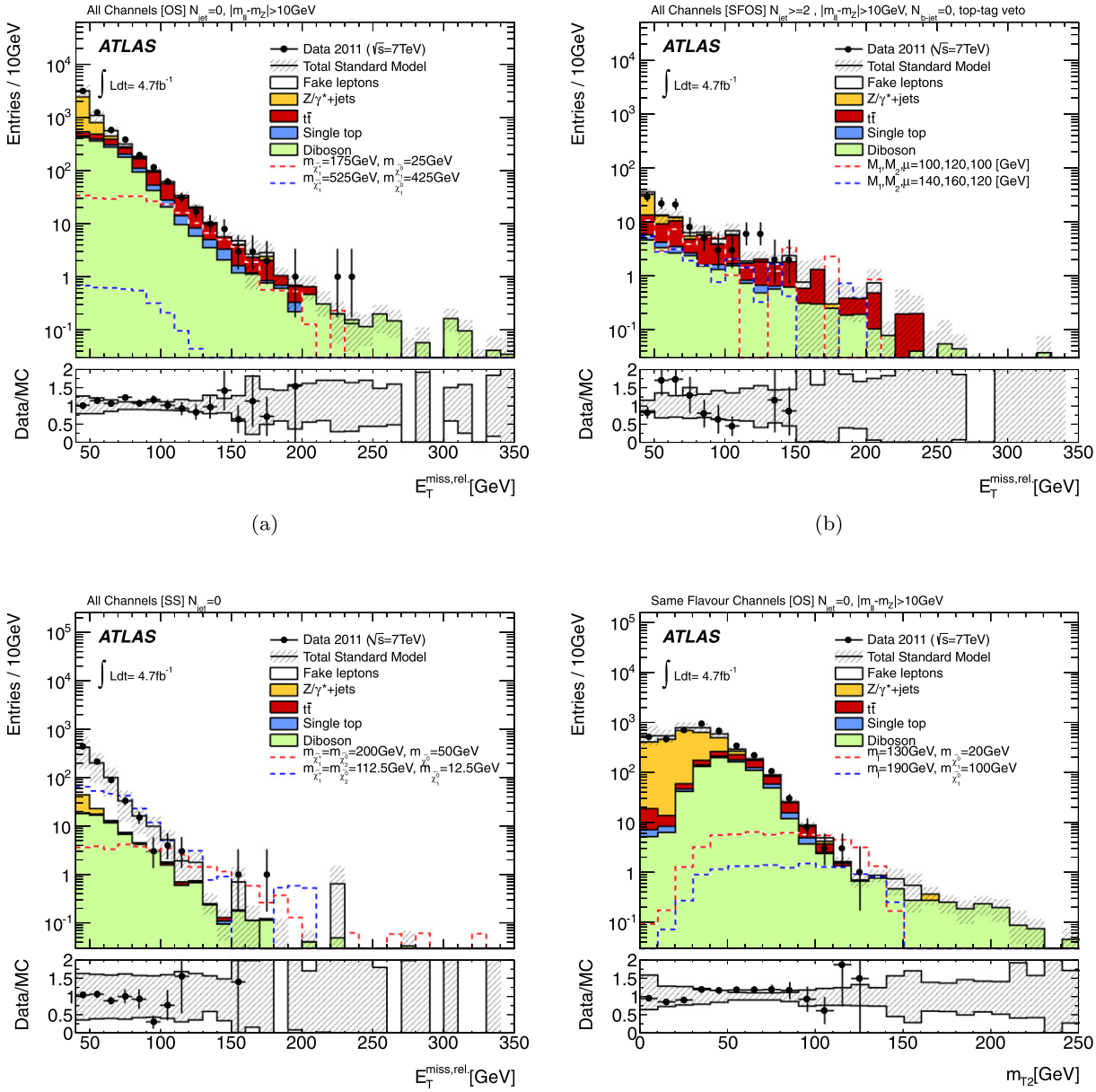


Fig. 1. The $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ distributions prior to the final requirement on $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ for (a) SR-OSjveto, (b) SR-2jets and (c) SR-SSjveto, and (d) m_{T2} in SR-m_{T2}, prior to the application of the m_{T2} requirement. In (d) only the SF channels are shown. The hatched bands indicate the experimental uncertainties on the background expectations. All components are from MC except for that labelled "Fake leptons". The contribution labelled "Diboson" accounts for WW, WZ and ZZ processes. The bottom panels show the ratio of the data to the expected background (points) and the systematic uncertainty on the background (shaded area). In each figure two signal points are illustrated. In (d) two models of direct slepton pair production are illustrated, with $(\tilde{\ell}, \tilde{\chi}_1^0)$ masses of (130, 20) and (190, 100) GeV. In (a) the two points illustrated are for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production in the simplified model with $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ masses of (175, 25) and (525, 425) GeV. In (c) the simplified model points illustrated have $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ masses of (200, 50) and (112.5, 12.5) GeV. In (b) two pMSSM model points with masses (M_1, M_2, M_μ) of (100, 120, 100) and (140, 160, 300) GeV are illustrated.

the $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ region under consideration (> 40 GeV) is close to the bulk of the WW sample.

6.1.4. Fake leptons

In this Letter the term "fake leptons" refers to both misidentified jets and real leptons that arise from decays or conversions. The numbers of fake lepton events are estimated using the "matrix method" [70]. First, fake leptons are identified as those satisfying a loose set of identification requirements corresponding to medium-level identification requirements and no isolation. The real efficiency r is calculated using data as the fraction of these loose leptons passing the signal lepton identification and isolation requirements in events with a lepton pair of mass lying within 5 GeV of the Z boson mass. The fake efficiency f is calculated separately for misidentified jets or decays and conversions. The combined fake efficiency for misidentified jets or decays is calculated using MC events with $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ between 40 and 100 GeV, and validated using low-$E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ regions in data. This region of moderate $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ is expected to give a sample composition that is representative of the various signal regions. The fake efficiency for conversions is estimated in a data sample dominated by this process, with two muons of invariant mass within 10 GeV of the Z-mass, $E_{\mathrm{T}}^{\mathrm{miss,rel.}} < 50$ GeV and at least one loose electron with

Table 4
Systematic uncertainties (%) on the total background estimated in each signal region for all flavours combined. The total statistical uncertainty includes limited MC event numbers in the control and signal regions. Jet systematic uncertainties include: JES, JER and $E_{\mathrm{T}}^{\mathrm{miss}}$ cluster and pile-up uncertainties. Lepton systematic uncertainties include: all lepton scales and resolutions, reconstruction and trigger efficiencies. MC modelling uncertainties include choice of generator, ISR/FSR and modelling of the $Z/\gamma^* +$ jets line-shape.

SR-	m_{T2}	OSjveto	SSjveto	2jets
Total statistical	9	4	13	6
Total systematic	19	19	35	49
Jet uncertainties	9	8	3	5
Lepton uncertainties	14	1	1	5
b-Tagging efficiency	1	1	0	14
MC modelling	7	17	4	45
Fake leptons	5	5	35	4

$m_{\mathrm{T}} < 40$ GeV (the conversion candidate). The overall f used is then the weighted (according to the relative proportions of each component present in the signal region) average of these two fake efficiencies. Then, in the signal region the observed numbers of events in data with two loose leptons, two signal leptons, or one of each are counted. The number of events containing fake leptons in each signal region is finally obtained by acting on these observed counts with a 4×4 matrix with terms containing f and r that relates real–real, real–fake, fake–real and fake–fake lepton event counts to tight–tight, tight–loose, loose–tight and loose–loose counts.

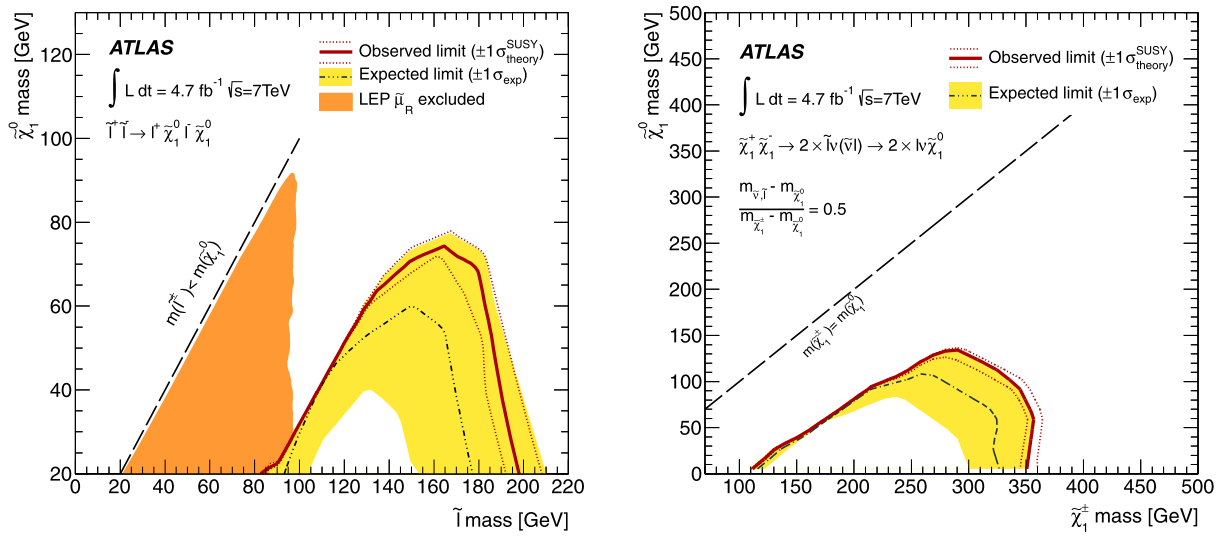
6.2. Backgrounds in SR-OSjveto, SR-SSjveto and SR-2jets

The same techniques are used to estimate the backgrounds in each remaining signal region, with two exceptions which are detailed in this section. Table 3 details any changes to control region definitions used.

1. Due to the high $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ requirement (> 100 GeV) in SR-OSjveto, WW is estimated using MC normalised to data in a control region. The control region used for its estimate is defined using the same requirements as the signal region but with slightly lower $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ (for orthogonality with the signal region) and an additional b-jet veto to suppress $t\bar{t}$ (Table 3). This control region is subject to a 24% contamination from top events, which is estimated and removed using MC simulation.

Table 5
Evaluated SM backgrounds in each signal region separated by flavour (ee, $e\mu$, $\mu\mu$) and combined in an "all" channel. In SR-m_{T2} the evaluated background components in the SF channel are quoted separately as the $e\mu$ channel is not appropriate for a direct slepton search. The second quoted error is the total systematic uncertainty whereas the first is the statistical uncertainty arising from limited numbers of MC events. The effect of limited data events in the control region is included in the systematic uncertainty. In all OS signal regions and channels the component $Z + \mathrm{X}$ includes the contributions from $Z/\gamma^* +$ jets, WZ and ZZ events. All statistical uncertainties are added in quadrature whereas the systematic uncertainties are obtained after taking full account of all correlations between sources, backgrounds and channels. Quoted also are the observed (expected) 95% confidence limits on the visible cross-section for non-SM events in each signal region, $\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$.

SR-m_{T2}					
	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	all	SF
$Z + \mathrm{X}$	$3.2 \pm 1.1 \pm 1.7$	$0.3 \pm 0.1 \pm 0.2$	$3.6 \pm 1.3 \pm 1.7$	$7.1 \pm 1.7 \pm 2.1$	$6.8 \pm 1.7 \pm 2.1$
WW	$2.3 \pm 0.3 \pm 0.4$	$4.8 \pm 0.4 \pm 0.7$	$3.5 \pm 0.3 \pm 0.5$	$10.6 \pm 0.6 \pm 1.5$	$5.8 \pm 0.4 \pm 0.9$
$t\bar{t}$, single top	$2.6 \pm 1.2 \pm 1.3$	$6.2 \pm 1.6 \pm 2.9$	$4.1 \pm 1.3 \pm 1.6$	$12.9 \pm 2.4 \pm 4.6$	$6.8 \pm 1.8 \pm 2.3$
Fake leptons	$1.0 \pm 0.6 \pm 0.6$	$1.1 \pm 0.6 \pm 0.8$	$-0.02 \pm 0.01 \pm 0.05$	$2.2 \pm 0.9 \pm 1.4$	$1.0 \pm 0.6 \pm 0.6$
Total	$9.2 \pm 1.8 \pm 2.5$	$12.4 \pm 1.7 \pm 3.1$	$11.2 \pm 1.9 \pm 3.0$	$32.8 \pm 3.2 \pm 6.3$	$20.4 \pm 2.6 \pm 3.9$
Data	7	9	8	24	15
$\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb)	1.5 (1.8)	1.6 (2.0)	1.6 (1.9)	2.5 (3.3)	1.9 (2.5)
SR-OSjveto					
	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	all	
$Z + \mathrm{X}$	$4.5 \pm 1.2 \pm 1.2$	$3.0 \pm 0.9 \pm 0.5$	$4.7 \pm 1.1 \pm 1.2$	$12.2 \pm 1.8 \pm 1.8$	
WW	$8.8 \pm 1.8 \pm 4.4$	$20.9 \pm 2.6 \pm 6.2$	$13.3 \pm 1.9 \pm 3.5$	$43.0 \pm 3.7 \pm 12.2$	
$t\bar{t}$, single top	$21.1 \pm 2.3 \pm 4.2$	$47.7 \pm 3.4 \pm 20.5$	$27.5 \pm 2.5 \pm 9.0$	$96.2 \pm 4.8 \pm 29.5$	
Fake leptons	$2.9 \pm 1.2 \pm 1.2$	$6.9 \pm 1.8 \pm 2.6$	$0.4 \pm 0.6 \pm 0.3$	$10.3 \pm 2.2 \pm 4.1$	
Total	$37.2 \pm 3.3 \pm 6.4$	$78.5 \pm 4.7 \pm 20.9$	$45.9 \pm 3.4 \pm 9.4$	$161.7 \pm 6.7 \pm 30.8$	
Data	33	66	40	139	
$\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb)	3.3 (3.8)	6.8 (7.8)	4.0 (4.6)	9.8 (11.9)	
SR-SSjveto					
	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	all	
Charge flip	$0.49 \pm 0.03 \pm 0.17$	$0.34 \pm 0.02 \pm 0.11$	–	$0.83 \pm 0.04 \pm 0.18$	
Dibosons	$0.62 \pm 0.13 \pm 0.18$	$1.93 \pm 0.23 \pm 0.36$	$0.94 \pm 0.16 \pm 0.26$	$3.50 \pm 0.31 \pm 0.54$	
Fake leptons	$3.2 \pm 0.9 \pm 1.7$	$2.9 \pm 0.9 \pm 1.9$	$0.6 \pm 0.6 \pm 0.3$	$6.6 \pm 1.4 \pm 3.8$	
Total	$4.3 \pm 0.9 \pm 1.7$	$5.1 \pm 1.0 \pm 1.9$	$1.5 \pm 0.6 \pm 0.4$	$11.0 \pm 1.5 \pm 3.9$	
Data	1	5	3	9	
$\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb)	0.7 (1.1)	1.6 (1.6)	1.3 (0.9)	1.9 (2.1)	
SR-2jets					
	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	SF	
$Z + \mathrm{X}$	$3.8 \pm 1.3 \pm 2.7$	–	$5.8 \pm 1.6 \pm 3.9$	$9.6 \pm 2.0 \pm 5.1$	
WW	$6.4 \pm 0.5 \pm 4.3$	–	$8.4 \pm 0.6 \pm 5.7$	$14.8 \pm 0.7 \pm 9.9$	
$t\bar{t}$, single top	$14.8 \pm 1.9 \pm 9.2$	–	$22.1 \pm 2.1 \pm 20.7$	$36.9 \pm 2.9 \pm 29.6$	
Fake leptons	$2.5 \pm 1.2 \pm 1.5$	–	$1.7 \pm 1.3 \pm 0.8$	$4.2 \pm 1.8 \pm 2.3$	
Total	$27.5 \pm 2.6 \pm 10.6$	–	$37.9 \pm 3.0 \pm 21.0$	$65.5 \pm 4.0 \pm 31.8$	
Data	39	–	39	78	
$\sigma_{\mathrm{vis}}^{\mathrm{obs(exp)}}$ (fb)	6.9 (5.3)	–	7.7 (7.6)	13.6 (12.5)	



(a) (b)

Fig. 2. 95% CL exclusion limits for $\tilde{\ell}^{\pm}$ pair production in the $m_{\tilde{\ell}}$–$m_{\tilde{\chi}_1^0}$ mass plane of (a) the direct slepton pMSSM and (b) $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ pair production in the simplified model. The dashed and solid lines show the 95% CL_s expected and observed limits, respectively, including all uncertainties except for the theoretical signal cross-section uncertainty (PDF and scale). The solid band around the expected limit shows the $\pm 1\sigma$ result where all uncertainties, except those on the signal cross-sections, are considered. The $\pm 1\sigma$ lines around the observed limit represent the results obtained when moving the nominal signal cross-section up or down by the $\pm 1\sigma$ theoretical uncertainty. Illustrated also in (a) is the LEP limit [28] on the mass of the right-handed smuon, $\tilde{\mu}_R$. The LEP limit is a conservative limit on slepton pair production: if right-handed slepton masses are excluded, left-handed sleptons of equivalent masses are automatically excluded. (For interpretation of the references to colour, the reader is referred to the web version of this Letter.)

2. In SR-SSjveto, the leptons have the same charge, resulting in a generally different background composition, and the presence of an additional component: "charge-flip". The background components in this region are: fake leptons (estimated using the described matrix method), dibosons (estimated using MC events) and charge-flip. This mis-identification of charge arises when an electron in an event undergoes hard bremsstrahlung with subsequent photon conversion. The probability of an electron undergoing a flip is measured from Z events in data using a likelihood technique [71], and in MC simulation. This probability, evaluated as a function of electron rapidity and p_{T}, is applied to $t\bar{t} \to e^{\pm}\ell^{\mp}$, $Z+$jets and diboson MC events to evaluate the number of $e^{\pm}e^{\pm}$ and $e^{\pm}\mu^{\pm}$ events resulting from the charge-flip mechanism. The probability of misidentifying the charge of a muon is negligible. The possible double counting of charge-flip events in the matrix method for SR-SSjveto is not significant.

7. Systematic uncertainties

In this analysis systematic uncertainties arise in the estimates of the background in the signal regions, as well as on the estimate of the SUSY signal itself. The primary sources of systematic uncertainty are the jet energy scale (JES) [61] calibration, the jet energy resolution (JER) [72], choice of MC generator and lepton efficiencies and momentum measurements. Additional statistical uncertainties arise from limited numbers of MC and data events in the control and signal regions, and a 3.9% luminosity uncertainty [73,74] for normalising MC events to cross-sections.

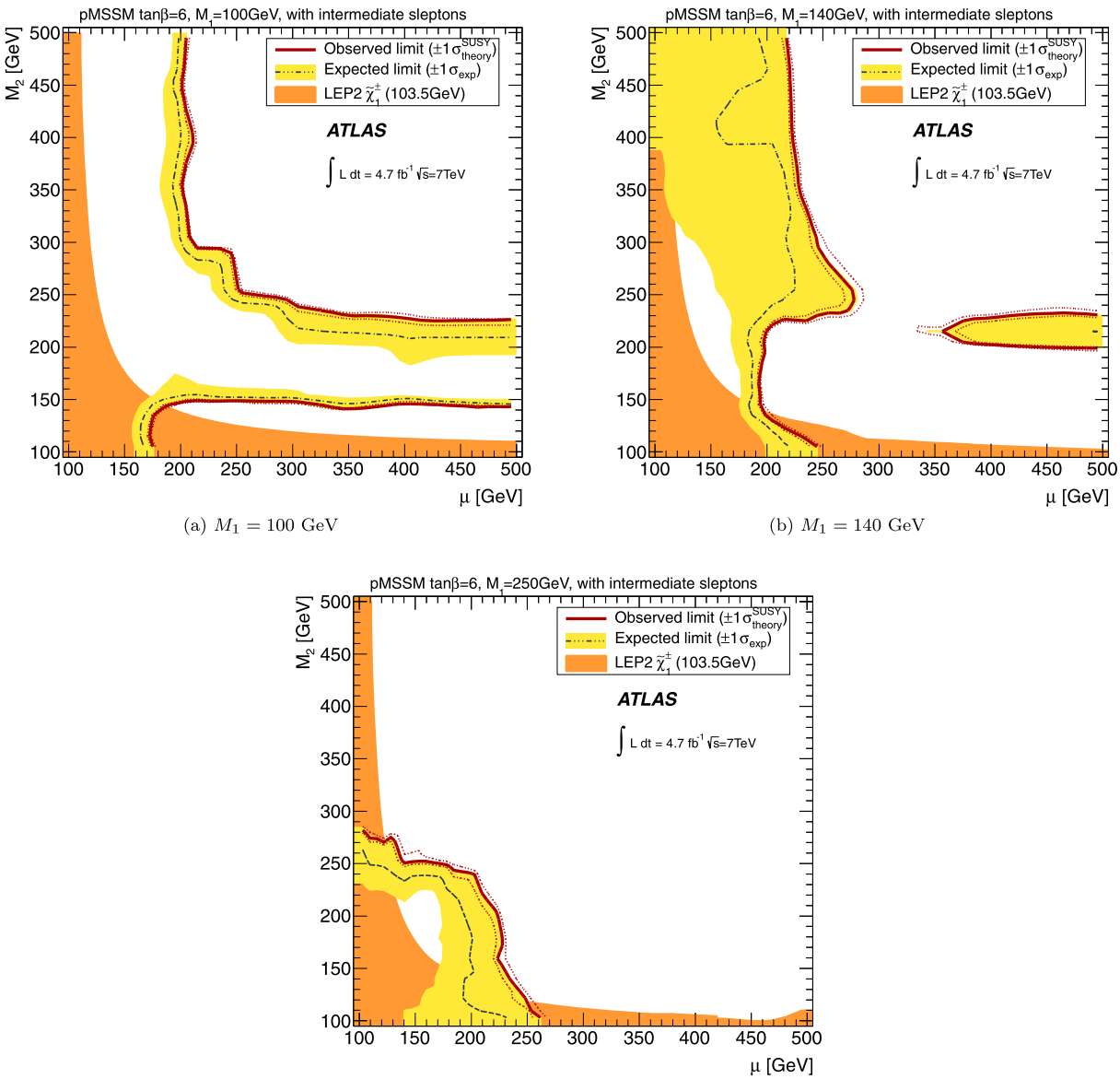
The JES has been determined from a combination of test-beam, simulation and in-situ measurements from 2011 pp collision data. Uncertainties on the lepton identification, momentum/energy scale and resolution are estimated from samples of $Z \to l^+l^-$, $J/\psi \to l^+l^-$ and $W^{\pm} \to \ell^{\mp}\nu$ decays [75,76]. The uncertainties on the jet and lepton energies are propagated to $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$; an additional uncertainty on $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from energy deposits not associated to any reconstructed objects is also included [77]. Uncertainties on the b-tagging efficiency are derived from data samples containing muons associated to jets [64] using the method described in Ref. [78]. Included are uncertainties in the mis-tag rate from charm [79], and light flavour tagging [80].

Theory and MC modelling uncertainties are evaluated for $t\bar{t}$ using the prescriptions described in Ref. [81] (choice of generator, and ISR/FSR). For dibosons they are evaluated by varying the choice of generator. Theoretical uncertainties on the $Z/\gamma^* +$jets background from varying the PDF and renormalisation scales are also included.

When evaluating the fake lepton component in each region the dominant uncertainties arise from the dependency of the efficiencies on $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$, differences between efficiencies obtained using OS and SS events and uncertainties in the relative normalisations of the different components. An additional uncertainty is applied based on differences observed in the fake efficiencies measured from data to validate the MC efficiencies if different validation regions are chosen.

The relative sizes of these sources of systematic uncertainty are detailed in Table 4. In SR-m_{T2}, the jet and lepton energy scales and resolutions are the most significant uncertainties. In SR-OSjveto and SR-2jets, where $t\bar{t}$ and WW are the most significant SM backgrounds (accounting for approximately 80–85% of the SM contribution), the uncertainties in the MC modelling dominate. In SR-SSjveto, because of the significant fake component, the error on the fake estimate from the sources described becomes the only significant source of uncertainty.

In the SUSY mass planes, the theoretical uncertainty on each of the signal cross-sections is included. These arise from considering the cross-section envelope defined using the 68% CL ranges of the `CTEQ6.6` and `MSTW 2008 NLO` PDF sets, and independent variations of the factorisation and renormalisation scales (see Section 3). Further uncertainties on the numbers of predicted signal events arise from the various experimental uncertainties.



(a) $M_1 = 100$ GeV (b) $M_1 = 140$ GeV

(c) $M_1 = 250$ GeV

Fig. 3. 95% CL exclusion limits in the μ–M_2 mass plane of the pMSSM for (a) $M_1 = 100$ GeV, (b) $M_1 = 140$ GeV and (c) $M_1 = 250$ GeV. The dashed and solid lines show the 95% $\mathrm{CL_s}$ expected and observed limits, respectively, including all uncertainties except for the theoretical signal cross-section uncertainty (PDF and scale). The solid band around the expected limit shows the $\pm 1\sigma$ result where all uncertainties, except those on the signal cross-sections, are considered. The $\pm 1\sigma$ lines around the observed limit represent the results obtained when moving the nominal signal cross-section up or down by the $\pm 1\sigma$ theoretical uncertainty.

8. Results and interpretation

Fig. 1 illustrates the level of agreement in each signal region, prior to the application of the final requirement on $E_{\mathrm{T}}^{\mathrm{miss,rel.}}$ and m_{T2}, between the data and the SM prediction. For each signal region two illustrative model points are also presented.

Table 5 compares the observations in data in each flavour channel and in each signal region with the evaluated background contributions. Good agreement is observed across all channels and in each signal region. The absence of evidence for SUSY weak production allows limits to be set on the visible cross-section for non-SM physics in each signal region, $\sigma_{\mathrm{vis}} = \sigma \times \varepsilon \times A$, for which this analysis has acceptance A and efficiency ε. These are calculated using the modified frequentist $\mathrm{CL_s}$ prescription [82] by comparing the number of observed events in data with the SM expectation using the profile likelihood ratio as test statistic. All systematic uncertainties and their correlations are taken into account via nuisance parameters.

The direct slepton pair production 95% CL exclusion region is shown in Fig. 2(a) in the neutralino–slepton mass plane, using the results of SR-m_{T2} in the SF channel. Shown are the 95% $\mathrm{CL_s}$ expected (dashed black) and observed limits (solid red) obtained by including all uncertainties except the theoretical signal cross-section uncertainty. The solid yellow band indicates the impact of the experimental uncertainties on the expected limits whereas the dashed red lines around the observed limit show the changes in the observed limit as the nominal signal cross-sections are scaled up and down by the 1σ theoretical uncertainties. A common value for left-handed electron and left-handed smuon mass between 85 and 195 GeV is excluded when the lightest neutralino has a mass of 20 GeV. The sensitivity decreases as the value of $m_{\tilde{\ell}}$–$m_{\tilde{\chi}_1^0}$ decreases and gives rise to end-points in the m_{T2} distribution at

lower mass, nearer to the end-points of the SM backgrounds. For a 60 GeV neutralino only sleptons with masses between 135 and 180 GeV are excluded.

The direct $\tilde{\chi}_1^{\pm}$ pair production limits are set for the simplified model, in the scenario of wino-like charginos decaying into the lightest neutralino via an intermediate on-shell charged slepton. The best expected limits are obtained by using for each signal point the signal region that provides the best expected p-value. The resulting limit for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production is illustrated in Fig. 2(b). Chargino masses between 110 and 340 GeV are excluded at 95% CL for a 10 GeV neutralino. The best sensitivity is provided by SR-m_{T2}. Previous gaugino searches at the Tevatron and the LHC [29–32] focused on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ associated production. The present result provides a new mass limit on $\tilde{\chi}_1^{\pm}$ independently of the mass of the $\tilde{\chi}_2^0$.

The signal regions are combined in Fig. 3 to derive exclusion limits in the pMSSM μ–M_2 plane for $\tan\beta = 6$, by selecting for each signal point the signal region which provides the best expected p-value. Figs. 3(a)–3(c) show respectively the exclusion limits for $M_1 = 100, 140, 250$ GeV. The present result significantly extends previous limits in the pMSSM μ–M_2 plane. The model independent limits in Table 5 provide additional constraints on other gaugino production channels discussed previously in this Letter. In particular, SR-2jets provides sensitivity to models where one gaugino produced in association with $\tilde{\chi}_2^0$ decays hadronically. The best sensitivity to models where final states containing $\geqslant 3$ leptons dominate would come from a statistical combination of the results set in SR-2jets, SR-OSjveto and SR-SSjveto, and results of searches for three or more leptons [32].

9. Summary

This Letter has presented a dedicated search for $\tilde{\ell}^{\pm}$ and $\tilde{\chi}_1^{\pm}$ pair production in final states with two leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$. In scenarios where sleptons decay directly into the lightest neutralino and a charged lepton, left-handed slepton masses between 85 and 195 GeV for a 20 GeV neutralino are excluded at 95% confidence. In the scenario of chargino pair production, with wino-like charginos decaying into the lightest neutralino via an intermediate on-shell charged slepton, chargino masses between 110 and 340 GeV are excluded at 95% CL for a neutralino of 10 GeV. New limits in the pMSSM μ–M_2 plane are provided for $\tan\beta = 6$. Signal regions targeting several gaugino production and decay modes into two-lepton final states have also been used to set limits on the visible cross-section.

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Schwienhorst [88], R. Schwierz [44], J. Schwindling [136], T. Schwindt [21], M. Schwoerer [5], G. Sciolla [23], W.G. Scott [129], J. Searcy [114], G. Sedov [42], E. Sedykh [121], S.C. Seidel [103], A. Seiden [137], F. Seifert [44], J.M. Seixas [24a], G. Sekhniaidze [102a], S.J. Sekula [40], K.E. Selbach [46], D.M. Seliverstov [121], B. Sellden [146a], G. Sellers [73], M. Seman [144b], N. Semprini-Cesari [20a,20b], C. Serfon [98], L. Serin [115], L. Serkin [54], R. Seuster [99], H. Severini [111], A. Sfyrla [30], E. Shabalina [54], M. Shamim [114], L.Y. Shan [33a], J.T. Shank [22], Q.T. Shao [86], M. Shapiro [15], P.B. Shatalov [95], K. Shaw [164a,164c], D. Sherman [176], P. Sherwood [77], S. Shimizu [101], M. Shimojima [100], T. Shin [56], M. Shiyakova [64], A. Shmeleva [94], M.J. Shochet [31], D. Short [118], S. Shrestha [63], E. Shulga [96], M.A. Shupe [7], P. Sicho [125], A. Sidoti [132a], F. Siegert [48], Dj. Sijacki [13a], O. Silbert [172], J. Silva [124a], Y. Silver [153], D. Silverstein [143], S.B. Silverstein [146a], V. Simak [127], O. Simard [136], Lj. Simic [13a], S. Simion [115], E. Simioni [81], B. Simmons [77], R. Simoniello [89a,89b], M. Simonyan [36], P. Sinervo [158], N.B. Sinev [114], V. Sipica [141], G. Siragusa [174], A. Sircar [25], A.N. Sisakyan [64,*], S.Yu. Sivoklokov [97], J. Sjölin [146a,146b], T.B. Sjursen [14], L.A. Skinnari [15], H.P. Skottowe [57], K. Skovpen [107], P. Skubic [111], M. Slater [18], T. Slavicek [127], K. Sliwa [161], V. Smakhtin [172], B.H. Smart [46], L. Smestad [117], S.Yu. Smirnov [96], Y. Smirnov [96], L.N. Smirnova [97], O. Smirnova [79], B.C. Smith [57], D. Smith [143], K.M. Smith [53], M. Smizanska [71], K. Smolek [127], A.A. Snesarev [94], S.W. Snow [82], J. Snow [111], S. Snyder [25], R. Sobie [169,k], J. Sodomka [127], A. Soffer [153], C.A. Solans [167], M. Solar [127], J. Solc [127], E.Yu. Soldatov [96], U. Soldevila [167], E. Solfaroli Camillocci [132a,132b], A.A. Solodkov [128], O.V. Solovyanov [128], V. Solovyev [121], N. Soni [1], V. Sopko [127], B. Sopko [127], M. Sosebee [8], R. Soualah [164a,164c], A. Soukharev [107], S. Spagnolo [72a,72b], F. Spanò [76], R. Spighi [20a], G. Spigo [30], R. Spiwoks [30], M. Spousta [126,ah], T. Spreitzer [158], B. Spurlock [8], R.D. St. Denis [53], J. Stahlman [120], R. Stamen [58a], E. Stanecka [39], R.W. Stanek [6], C. Stanescu [134a], M. Stanescu-Bellu [42], M.M. Stanitzki [42], S. Stapnes [117], E.A. Starchenko [128], J. Stark [55], P. Staroba [125], P. Starovoitov [42], R. Staszewski [39], A. Staude [98], P. Stavina [144a,*], G. Steele [53], P. Steinbach [44], P. Steinberg [25], I. Stekl [127], B. Stelzer [142], H.J. Stelzer [88], O. Stelzer-Chilton [159a], H. Stenzel [52], S. Stern [99], G.A. Stewart [30], J.A. Stillings [21], M.C. Stockton [85], K. Stoerig [48], G. Stoicea [26a], S. Stonjek [99], P. Strachota [126], A.R. Stradling [8], A. Straessner [44], J. Strandberg [147], S. Strandberg [146a,146b], A. Strandlie [117], M. Strang [109], E. Strauss [143], M. Strauss [111], P. Strizenec [144b], R. Ströhmer [174], D.M. Strom [114], J.A. Strong [76,*], R. Stroynowski [40], J. Strube [129], B. Stugu [14], I. Stumer [25,*], J. Stupak [148], P. Sturm [175], N.A. Styles [42], D.A. Soh [151,w], D. Su [143], HS. Subramania [3], A. Succurro [12], Y. Sugaya [116], C. Suhr [106], M. Suk [126], V.V. Sulin [94], S. Sultansoy [4d], T. Sumida [67], X. Sun [55], J.E. Sundermann [48], K. Suruliz [139], G. Susinno [37a,37b], M.R. Sutton [149], Y. Suzuki [65], Y. Suzuki [66], M. Svatos [125], S. Swedish [168], I. Sykora [144a], T. Sykora [126], J. Sánchez [167], D. Ta [105], K. Tackmann [42], A. Taffard [163], R. Tafirout [159a], N. Taiblum [153], Y. Takahashi [101], H. Takai [25], R. Takashima [68], H. Takeda [66], T. Takeshita [140], Y. Takubo [65], M. Talby [83], A. Talyshev [107,f], M.C. Tamsett [25], K.G. Tan [86], J. Tanaka [155], R. Tanaka [115], S. Tanaka [131], S. Tanaka [65], A.J. Tanasijczuk [142], K. Tani [66], N. Tannoury [83], S. Tapprogge [81], D. Tardif [158], S. Tarem [152], F. Tarrade [29], G.F. Tartarelli [89a], P. Tas [126], M. Tasevsky [125], E. Tassi [37a,37b], M. Tatarkhanov [15], Y. Tayalati [135d], C. Taylor [77], F.E. Taylor [92],

G.N. Taylor [86], W. Taylor [159b], M. Teinturier [115], F.A. Teischinger [30], M. Teixeira Dias Castanheira [75], P. Teixeira-Dias [76], K.K. Temming [48], H. Ten Kate [30], P.K. Teng [151], S. Terada [65], K. Terashi [155], J. Terron [80], M. Testa [47], R.J. Teuscher [158,k], J. Therhaag [21], T. Theveneaux-Pelzer [78], S. Thoma [48], J.P. Thomas [18], E.N. Thompson [35], P.D. Thompson [18], P.D. Thompson [158], A.S. Thompson [53], L.A. Thomsen [36], E. Thomson [120], M. Thomson [28], W.M. Thong [86], R.P. Thun [87], F. Tian [35], M.J. Tibbetts [15], T. Tic [125], V.O. Tikhomirov [94], Y.A. Tikhonov [107,f], S. Timoshenko [96], P. Tipton [176], S. Tisserant [83], T. Todorov [5], S. Todorova-Nova [161], B. Toggerson [163], J. Tojo [69], S. Tokár [144a], K. Tokushuku [65], K. Tollefson [88], M. Tomoto [101], L. Tompkins [31], K. Toms [103], A. Tonoyan [14], C. Topfel [17], N.D. Topilin [64], I. Torchiani [30], E. Torrence [114], H. Torres [78], E. Torró Pastor [167], J. Toth [83,ad], F. Touchard [83], D.R. Tovey [139], T. Trefzger [174], L. Tremblet [30], A. Tricoli [30], I.M. Trigger [159a], S. Trincaz-Duvoid [78], M.F. Tripiana [70], N. Triplett [25], W. Trischuk [158], B. Trocmé [55], C. Troncon [89a], M. Trottier-McDonald [142], M. Trzebinski [39], A. Trzupek [39], C. Tsarouchas [30], J.C-L. Tseng [118], M. Tsiakiris [105], P.V. Tsiareshka [90], D. Tsionou [5,ai], G. Tsipolitis [10], S. Tsiskaridze [12], V. Tsiskaridze [48], E.G. Tskhadadze [51a], I.I. Tsukerman [95], V. Tsulaia [15], J.-W. Tsung [21], S. Tsuno [65], D. Tsybychev [148], A. Tua [139], A. Tudorache [26a], V. Tudorache [26a], J.M. Tuggle [31], M. Turala [39], D. Turecek [127], I. Turk Cakir [4e], E. Turlay [105], R. Turra [89a,89b], P.M. Tuts [35], A. Tykhonov [74], M. Tylmad [146a,146b], M. Tyndel [129], G. Tzanakos [9], K. Uchida [21], I. Ueda [155], R. Ueno [29], M. Ugland [14], M. Uhlenbrock [21], M. Uhrmacher [54], F. Ukegawa [160], G. Unal [30], A. Undrus [25], G. 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M. Yilmaz [4c], R. Yoosoofmiya [123], K. Yorita [171], R. Yoshida [6], C. Young [143], C.J. Young [118], S. Youssef [22], D. Yu [25], J. Yu [8], J. Yu [112], L. Yuan [66], A. Yurkewicz [106], M. Byszewski [30], B. Zabinski [39], R. Zaidan [62], A.M. Zaitsev [128], Z. Zajacova [30], L. Zanello [132a,132b], D. Zanzi [99], A. Zaytsev [25], C. Zeitnitz [175], M. Zeman [125], A. Zemla [39], C. Zendler [21], O. Zenin [128], T. Ženiš [144a], Z. Zinonos [122a,122b], S. Zenz [15], D. Zerwas [115], G. Zevi della Porta [57], Z. Zhan [33d], D. Zhang [33b,ak], H. Zhang [88], J. Zhang [6], X. Zhang [33d], Z. Zhang [115], L. Zhao [108], T. Zhao [138], Z. Zhao [33b], A. Zhemchugov [64], J. Zhong [118], B. Zhou [87], N. Zhou [163], Y. Zhou [151], C.G. Zhu [33d], H. Zhu [42], J. Zhu [87], Y. Zhu [33b], X. Zhuang [98], V. Zhuravlov [99], D. Zieminska [60], N.I. Zimin [64], R. Zimmermann [21], S. Zimmermann [21], S. Zimmermann [48], M. Ziolkowski [141], R. Zitoun [5], L. Živković [35], V.V. Zmouchko [128,*], G. Zobernig [173], A. Zoccoli [20a,20b], M. zur Nedden [16], V. Zutshi [106], L. Zwalinski [30]

[1] *School of Chemistry and Physics, University of Adelaide, Adelaide, Australia*
[2] *Physics Department, SUNY Albany, Albany, NY, United States*
[3] *Department of Physics, University of Alberta, Edmonton, AB, Canada*
[4] [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Department of Physics, Dumlupinar University, Kutahya;* [(c)] *Department of Physics, Gazi University, Ankara;* [(d)] *Division of Physics, TOBB University of Economics and Technology, Ankara;* [(e)] *Turkish Atomic Energy Authority, Ankara, Turkey*
[5] *LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[6] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States*
[7] *Department of Physics, University of Arizona, Tucson, AZ, United States*
[8] *Department of Physics, The University of Texas at Arlington, Arlington, TX, United States*
[9] *Physics Department, University of Athens, Athens, Greece*
[10] *Physics Department, National Technical University of Athens, Zografou, Greece*
[11] *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[12] *Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
[13] [(a)] *Institute of Physics, University of Belgrade, Belgrade;* [(b)] *Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[14] *Department for Physics and Technology, University of Bergen, Bergen, Norway*
[15] *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States*
[16] *Department of Physics, Humboldt University, Berlin, Germany*
[17] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[18] *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[19] [(a)] *Department of Physics, Bogazici University, Istanbul;* [(b)] *Division of Physics, Dogus University, Istanbul;* [(c)] *Department of Physics Engineering, Gaziantep University, Gaziantep;* [(d)] *Department of Physics, Istanbul Technical University, Istanbul, Turkey*
[20] [(a)] *INFN Sezione di Bologna;* [(b)] *Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[21] *Physikalisches Institut, University of Bonn, Bonn, Germany*
[22] *Department of Physics, Boston University, Boston, MA, United States*
[23] *Department of Physics, Brandeis University, Waltham, MA, United States*
[24] [(a)] *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* [(b)] *Federal University of Juiz de Fora (UFJF), Juiz de Fora;* [(c)] *Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;* [(d)] *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25] *Physics Department, Brookhaven National Laboratory, Upton, NY, United States*
[26] [(a)] *National Institute of Physics and Nuclear Engineering, Bucharest;* [(b)] *University Politehnica Bucharest, Bucharest ;* [(c)] *West University in Timisoara, Timisoara, Romania*
[27] *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[28] *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[29] *Department of Physics, Carleton University, Ottawa, ON, Canada*
[30] *CERN, Geneva, Switzerland*
[31] *Enrico Fermi Institute, University of Chicago, Chicago, IL, United States*
[32] [(a)] *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* [(b)] *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33] [(a)] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* [(b)] *Department of Modern Physics, University of Science and Technology of China, Anhui;* [(c)] *Department of Physics, Nanjing University, Jiangsu;* [(d)] *School of Physics, Shandong University, Shandong, China*
[34] *Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35] *Nevis Laboratory, Columbia University, Irvington, NY, United States*
[36] *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37] [(a)] *INFN Gruppo Collegato di Cosenza;* [(b)] *Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy*
[38] *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[39] *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[40] *Physics Department, Southern Methodist University, Dallas, TX, United States*
[41] *Physics Department, University of Texas at Dallas, Richardson, TX, United States*
[42] *DESY, Hamburg and Zeuthen, Germany*
[43] *Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[44] *Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
[45] *Department of Physics, Duke University, Durham, NC, United States*
[46] *SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[47] *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48] *Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
[49] *Section de Physique, Université de Genève, Geneva, Switzerland*
[50] [(a)] *INFN Sezione di Genova;* [(b)] *Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51] [(a)] *E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi;* [(b)] *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[52] *II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[53] *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54] *II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
[55] *Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France*
[56] *Department of Physics, Hampton University, Hampton, VA, United States*
[57] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States*
[58] [(a)] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [(b)] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [(c)] *ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
[59] *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[60] *Department of Physics, Indiana University, Bloomington, IN, United States*

[61] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62] University of Iowa, Iowa City, IA, United States
[63] Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
[64] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66] Graduate School of Science, Kobe University, Kobe, Japan
[67] Faculty of Science, Kyoto University, Kyoto, Japan
[68] Kyoto University of Education, Kyoto, Japan
[69] Department of Physics, Kyushu University, Fukuoka, Japan
[70] Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79] Fysiska institutionen, Lunds universitet, Lund, Sweden
[80] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[81] Institut für Physik, Universität Mainz, Mainz, Germany
[82] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[83] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[84] Department of Physics, University of Massachusetts, Amherst, MA, United States
[85] Department of Physics, McGill University, Montreal, QC, Canada
[86] School of Physics, University of Melbourne, Victoria, Australia
[87] Department of Physics, The University of Michigan, Ann Arbor, MI, United States
[88] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
[89] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy
[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[91] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
[92] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
[93] Group of Particle Physics, University of Montreal, Montreal, QC, Canada
[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[95] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[96] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[97] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[98] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[99] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[100] Nagasaki Institute of Applied Science, Nagasaki, Japan
[101] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[102] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[103] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
[104] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[105] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[106] Department of Physics, Northern Illinois University, DeKalb, IL, United States
[107] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[108] Department of Physics, New York University, New York, NY, United States
[109] Ohio State University, Columbus, OH, United States
[110] Faculty of Science, Okayama University, Okayama, Japan
[111] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
[112] Department of Physics, Oklahoma State University, Stillwater, OK, United States
[113] Palacký University, RCPTM, Olomouc, Czech Republic
[114] Center for High Energy Physics, University of Oregon, Eugene, OR, United States
[115] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[116] Graduate School of Science, Osaka University, Osaka, Japan
[117] Department of Physics, University of Oslo, Oslo, Norway
[118] Department of Physics, Oxford University, Oxford, United Kingdom
[119] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[120] Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
[121] Petersburg Nuclear Physics Institute, Gatchina, Russia
[122] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
[124] [(a)] Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; [(b)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[127] Czech Technical University in Prague, Praha, Czech Republic
[128] State Research Center Institute for High Energy Physics, Protvino, Russia
[129] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[130] Physics Department, University of Regina, Regina, SK, Canada
[131] Ritsumeikan University, Kusatsu, Shiga, Japan
[132] [(a)] INFN Sezione di Roma I; [(b)] Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[135] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; [(b)] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; [(d)] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)] Faculté des Sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France

[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
[138] Department of Physics, University of Washington, Seattle, WA, United States
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby, BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford, CA, United States
[144] [(a)] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] [(a)] Department of Physics, University of Johannesburg, Johannesburg; [(b)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] [(a)] Department of Physics, Stockholm University ; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto, ON, Canada
[159] [(a)] TRIUMF, Vancouver, BC; [(b)] Department of Physics and Astronomy, York University, Toronto, ON, Canada
[160] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[161] Department of Physics and Astronomy, Tufts University, Medford, MA, United States
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
[164] [(a)] INFN Gruppo Collegato di Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana, IL, United States
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver, BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
[170] Department of Physics, University of Warwick, Coventry, United Kingdom
[171] Waseda University, Tokyo, Japan
[172] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[173] Department of Physics, University of Wisconsin, Madison, WI, United States
[174] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[175] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[176] Department of Physics, Yale University, New Haven, CT, United States
[177] Yerevan Physics Institute, Yerevan, Armenia
[178] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[c] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[d] Also at TRIUMF, Vancouver, BC, Canada.
[e] Also at Department of Physics, California State University, Fresno, CA, United States.
[f] Also at Novosibirsk State University, Novosibirsk, Russia.
[g] Also at Fermilab, Batavia, IL, United States.
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[i] Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
[j] Also at Università di Napoli Parthenope, Napoli, Italy.
[k] Also at Institute of Particle Physics (IPP), Canada.
[l] Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[m] Also at Louisiana Tech University, Ruston, LA, United States.
[n] Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
[o] Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
[p] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[q] Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
[r] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[s] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[t] Also at Manhattan College, New York, NY, United States.
[u] Also at School of Physics, Shandong University, Shandong, China.
[v] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[w] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[x] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[y] Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
[z] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[aa] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[ab] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[ac] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[ad] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ae] Also at California Institute of Technology, Pasadena, CA, United States.
[af] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

[ag] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
[ah] Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.
[ai] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[aj] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[ak] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[al] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[am] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
[*] Deceased.