Search for supersymmetry with jets, missing transverse momentum and at least one hadronically decaying $\tau$ lepton in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


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Search for supersymmetry with jets, missing transverse momentum and at least one hadronically decaying $\tau$ lepton in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

A search for production of supersymmetric particles in final states containing jets, missing transverse momentum, and at least one hadronically decaying $\tau$ lepton is presented. The data were recorded by the ATLAS experiment in $\sqrt{s} = 7$ TeV proton–proton collisions at the Large Hadron Collider. No excess above the Standard Model background expectation was observed in 2.05 fb$^{-1}$ of data. The results are interpreted in the context of gauge mediated supersymmetry breaking models with $M_{mess} = 250$ TeV. $N_5 = 3$, $\mu > 0$, and $C_{grav} = 1$. The production of supersymmetric particles is excluded at 95% C.L. up to a supersymmetry breaking scale $\Lambda = 30$ TeV, independent of $\tan \beta$, and up to $\Lambda = 43$ TeV for large $\tan \beta$.

1. Introduction

Supersymmetry (SUSY) [1–9] is a well-motivated theoretical concept that introduces a symmetry between bosons and fermions. As a consequence, every Standard Model (SM) particle has a SUSY partner with the same mass and quantum numbers except for the spin which differs by half a unit. Since none of these partners has been observed SUSY must be a broken symmetry if realized in nature. If R-parity is conserved [10–14], SUSY particles can only be produced in pairs and would decay through cascades involving lighter SUSY particles. These decay cascades end in the production of the lightest supersymmetric particle (LSP), which is stable and escapes the detector unseen, giving rise to missing transverse momentum in the detector. SUSY can remedy various shortcomings of the Standard Model, such as the hierarchy problem [14–19], the lack of a dark matter candidate [20,21] and the non-unification of the gauge couplings [22–25]. To achieve this, the masses of at least some SUSY particles must be near the weak scale, and therefore, if weak-scale SUSY is realized in nature, there are good prospects to discover it at the Large Hadron Collider (LHC).

In certain SUSY models, large mixing between left and right sfermions, the partners of the left-handed and right-handed SM fermions, implies that the lightest sfermions belong to the third generation. This leads to a large production rate of $\tau$ leptons from decays of $\tilde{f}$ sleptons and gauginos, the partners of the SM gauge bosons, in SUSY cascade decays. For example, in the context of Gauge Mediated SUSY Breaking (GMSB) [26–31] the lighter of the two $\tilde{\tau}$ sleptons is the next-to-lightest supersymmetric particle (NLSP) for a large part of the parameter space, and the very light gravitino, $\tilde{G}$, is the LSP. Hence $\tilde{\tau}$ sleptons decay to a $\tau$ lepton and a gravitino. While this $\tilde{\tau} \rightarrow \tau G$ process is the dominant source of $\tau$ leptons from SUSY decays in certain regions of GMSB model parameter space, the analysis presented here is sensitive to any process producing $\tau$ leptons in association with jets and missing transverse momentum.

This Letter presents a search for supersymmetry in final states with at least one hadronically decaying $\tau$ lepton, missing transverse momentum and jets with the ATLAS detector at the LHC. The results of the search are interpreted within the GMSB model. Previous experiments at LEP [32–34] have placed constraints on $\tilde{\tau}$ and $\tilde{f}$ masses and on more generic GMSB signatures. Among these the limits from the OPAL experiment [32] were the most stringent, excluding $\tilde{\tau}$ NLSPs with masses below 87.4 GeV. The D0 Collaboration performed a search for squark production in events with hadronically decaying $\tau$ leptons, jets, and missing transverse momentum [35], and the CMS Collaboration performed searches for new physics in same-sign ditau events [36] and multi-lepton events [37] including $\tau$ pairs, but the GMSB model was not specifically considered in any of these results. A search for supersymmetry in final states containing at least two hadronically decaying $\tau$ leptons could provide stringent constraints on the GMSB parameter space.

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2. ATLAS detector

The ATLAS detector [39] is a multipurpose particle physics apparatus with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. The inner tracking detector consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and by high-granularity liquid-argon sampling calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. A muon spectrometer consisting of large superconducting toroids and a system of precision tracking chambers surrounds the calorimeters.

3. Data and simulated samples

The analysis is based on data collected by the ATLAS detector in proton–proton collisions at a center-of-mass energy of 7 TeV between March and August 2011. Application of beam, detector, and data-quality requirements resulted in an integrated luminosity of 2.05 ± 0.08 fb⁻¹ [40,41]. The data were collected using triggers based on one jet with transverse momentum and data-quality requirements resulted in an integrated luminosity in proton–proton collisions at a center-of-mass energy of 7 TeV measured at the raw electromagnetic scale, and missing transverse momentum above 45 GeV.

In GMSB models, the breaking of SUSY is mediated through flavor-blind SM gauge interactions of messenger fields with mass scale $M_{\text{mess}}$, which is small compared to the Planck mass. In addition to $M_{\text{mess}}$, the free parameters in GMSB models are the scale of the SUSY breaking, $\Lambda$, the number of messenger fields, $N_S$, the sign of the Higgsino mixing parameter, sign$(\mu)$, the scale factor for the gravitino mass, $C_{\text{grav}}$, and the ratio of the vacuum expectation values of the two Higgs doublets, tanβ. In this analysis, GMSB models are studied in the $\Lambda$–tanβ plane for fixed $M_{\text{mess}} = 250$ TeV, $N_S = 3$, sign$(\mu) = +1$ and $C_{\text{grav}} = 1$. The chosen set of parameter values restricts the analysis to specific final states relevant for the search with τ leptons and to promptly decaying NLSPs. For $N_S \geq 2$ and large tanβ the lightest τ lepton is the NLSP, $\tilde{\tau}_1$, the NLSP.

Samples of simulated GMSB events are generated with the HERWIG++ [42] generator for ten values of $\Lambda$ in the range $10 \leq \Lambda \leq 85$ TeV and ten values of tanβ in the range $2 \leq \tan\beta \leq 45$, with the SUSY mass spectra generated using SISAJET 7.80 [43]. The MSTW2007 LO* [44] parton distribution functions (PDFs) are used. The production cross sections are calculated with PROSPINO [45–48] to next-to-leading order in the QCD coupling using the next-to-leading-order CTEQ6.6 [49] PDF set. The two samples with $\Lambda = 30$ (40) TeV and $\tan\beta = 20$ (30), which have cross sections of 1.95 (0.41) pb, are used as representative points for the optimization of the event selection.

The dominant background processes in this search are production of $W$ and $Z$ bosons in association with jets ($W +$ jets and $Z +$ jets), top quark pair (tt) and single top quark production. The $W +$ jets and $Z +$ jets production processes are simulated with the ALPGEN [50] generator, using the CTEQ6L1 [51] PDF set, and are normalized to a cross section of 31.4 nb and 9.02 nb [52–54], respectively. The tt, single-top and diboson production processes are generated with MC@NLO [55] and the CTEQ6.6 [49] PDF set, and are normalized using a cross section of 0.165 nb, 0.085 nb [56–58] and 0.071 nb [59,60], respectively. Parton showers and hadronization are simulated with HERWIG and the underlying event is modeled with JIMMY [61]. The programs TAUOLA [62,63] and PHOTOS [64] are used to model the decays of τ leptons and the radiation of photons, respectively. The production of multijet events is simulated with PHOTIA [65], though the multijet background yield in this analysis is estimated using data. All simulated samples are processed through a full simulation of the ATLAS detector [66] based on GEANT4 [67]. To match the pile-up (overlap of several interactions in the same bunch crossing) observed in the data, the generated signal and background events are overlaid with minimum-bias events [68,69] and the resulting events are reweighted so that the distribution of the number of interactions per bunch crossing agrees with the data.

4. Object reconstruction

Jet candidates are reconstructed with the anti-$k_t$ clustering algorithm [70] with radius parameter $R = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as a four-vector with zero mass. Jets are corrected for calorimeter non-compensation, upstream material, and other effects using $p_T$- and $\eta$-dependent correction factors obtained from Monte Carlo simulation and validated with extensive test-beam and collision-data studies [71]. Only jet candidates with $p_T > 30$ GeV, $|\eta| < 2.8$ and a distance $\Delta R > 0.2$ with respect to the nearest identified electron are considered as real hadronic jets, where the distance is defined as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.

The electron and muon identification criteria are identical to those in Ref. [72]. Electrons and muons are only considered if they satisfy $p_T > 20$ GeV and $\Delta R > 0.4$ with respect to the nearest identified jet. The magnitude of the missing transverse momentum, $E_T^{\text{miss}}$, is computed from the vector sum of the transverse momenta of all identified electrons and muons, all jets, and remaining clusters of calorimeter cells with $|\eta| < 4.5$ [73].

Hadreronically decaying τ leptons are reconstructed from jet candidates with $p_T > 10$ GeV and are distinguished from quark- or gluon-initiated jets using a boosted decision tree (BDT) based on eleven discriminating shower-shape and tracking variables [74]. Electrons are further rejected using transition radiation and calorimetric information. An energy calibration factor for hadronically decaying τ leptons is applied as function of $p_T$ and $\eta$. Candidates are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$ and to have one or three associated reconstructed tracks (prongs) with total charge ±1. The τ candidates are required to satisfy a $p_T$-dependent BDT output criterion [74] chosen to give ∼30% (∼50%) signal efficiency for one-prong (three-prong) τ candidates as estimated in $Z(\rightarrow \tau \tau) +$ jets events. The BDT selection has a corresponding background acceptance of ∼0.5% (∼3%), estimated in dijet events, and the different selection criteria reflect different abundances of one- and three-prong jets in background samples.

During a part of the data-taking period, an electronics failure in the liquid-argon calorimeter created a dead region in the second and third layer of the calorimeter, corresponding to approximately 1.4 × 0.2 rad in $\Delta \eta \times \Delta \phi$. A correction is made to the jet energy using energy depositions in cells neighboring the dead region; events having at least one jet, including the leading τ candidate, in this region for which the corrected energy is above 30 GeV are discarded, resulting in a loss of ∼6% of the data sample.
5. Event selection

Events are required to have a reconstructed primary vertex with at least five associated tracks with \( p_T > 500 \) MeV. Events are rejected if they contain identified electrons or muons or if any jet or \( \tau \) candidate is consistent with arising from detector noise or non-collision background [71]. Events are required to contain one or more identified \( \tau \) candidates, at least two jets, one with \( p_T > 30 \) GeV and another with \( p_T > 130 \) GeV, and missing transverse momentum \( E_{\text{T}}^{\text{miss}} > 130 \) GeV. The latter two requirements ensure that the trigger efficiency is above 98% in both data and simulation.

The two jets leading in \( p_T \) are required to be separated in azimuth from the direction of the missing transverse momentum by more than 0.3 rad. This requirement reduces multijet events, which typically have instrumental missing transverse momentum aligned with the leading jets. Multijet events are further suppressed by requiring \( E_{\text{T}}^{\text{miss}}/m_{\text{eff}} > 0.25 \), where the effective mass, \( m_{\text{eff}} \), is defined as the scalar sum of \( E_{\text{T}}^{\text{miss}} \), the \( p_T \) of the two leading jets, and the \( p_T \) of the leading \( \tau \) candidate.

Events are required to have a transverse mass, \( m_T \), above 110 GeV. The transverse mass is defined as

\[
m_T = \sqrt{m_T^2 + 2p_T^{\text{miss}} \cos \Delta\phi(p_T^{\text{miss}}, \vec{p}_T)}.
\]

where \( \Delta\phi(p_T^{\text{miss}}, \vec{p}_T) \) is the azimuthal angle between the \( \tau \) and the direction of the missing transverse momentum. This requirement suppresses backgrounds due to \( W + \) jets and top-quark production. The remaining SM backgrounds are further suppressed by requiring \( m_{\text{eff}} > 600 \) GeV. This is the final selection defining the signal region for the analysis. The \( m_T \) and \( m_{\text{eff}} \) requirements as well as the criteria used for the suppression of multijet events are chosen to maximize the signal significance computed with the Asimov approximation [75].

6. Background estimation

Background processes are divided into three classes which are estimated separately: events with true \( \tau \) leptons from \( t \to b\tau V \) decays (both top-quark-pair and single top quark production) and \( W(\to \tau v) + \) jets events; events with misidentified (‘fake’) \( \tau \) candidates in top, \( W + \) jets, and \( Z + \) jets events; and events with fake \( \tau \) candidates in multijet events. The two fake-\( \tau \) classes are treated separately to account for differences in \( \tau \) misidentification probabilities due to different event topologies and jet composition.

Events with true \( \tau \) leptons are estimated in a control region defined by replacing the requirement on the transverse mass in the final selection with the requirement \( m_T < 70 \) GeV. For events with a correctly reconstructed \( \tau \) lepton and with \( E_{\text{T}}^{\text{miss}} \) entirely due to a single neutrino, \( m_T \) is kinematically bounded from above by the \( W \) mass, within the detector resolution; by requiring \( m_T < 70 \) GeV, more than 90% of the events in the resulting control region are expected to contain true \( \tau \) leptons from top-quark and \( W \) decays. The composition of the event sample in this control region is given in Table 1. Within this control region, the background due to \( Z \) decays is estimated from simulation and the remaining small background due to multijet events is estimated using a procedure similar to that used to estimate the multijet background in the signal region, described below.

Within the \( m_T < 70 \) GeV control region, top-quark and \( W + \) jets yields are estimated individually with a maximum-likelihood fit to the output distribution of a BDT built from four variables: the number of \( b \)-quark jets, the total jet multiplicity, the transverse momentum of the second-leading jet, and the transverse thrust \( T \) of the event, defined as \( T = \max_i (\sum_j \vec{p}_T \cdot \vec{p}_T / \sum_j \vec{p}_T) \), where \( i \) runs over the missing transverse momentum and all jets, excluding the \( \tau \) candidates, with transverse momentum vectors \( \vec{p}_T \), and the transverse thrust axis is given by the unit vector \( \vec{n} \) for which the maximum is attained. Top-quark events have more reconstructed \( b \)-quark jets, a higher jet multiplicity, higher jet momenta, and tend to be more spherical than \( W + \) jets events. Jets containing \( b \) quarks are identified with about 60% efficiency, evaluated with top-quark events, using secondary vertex reconstruction and three-dimensional impact parameters of tracks associated with the jet [76]. The output distribution of this BDT is shown in Fig. 1 along with the results of the fit. The results of the fit are scale factors for \( W + \) jets and top quark backgrounds which reflect differences in cross sections and reconstruction efficiencies between data and simulation. The measured scale factors are 1.22 ± 0.13 for top events and 0.71 ± 0.03 for \( W + \) jets events. These scale factors are applied to simulated event samples in the signal region to derive the final expected true-\( \tau \) yields from background processes.

For the estimation of backgrounds due to fake \( \tau \) candidates in top-quark, \( W + \) jets, and \( Z + \) jets events, a second control sample is defined by selecting events that fulfill the event selection but with modified criteria on \( m_T \) and \( m_{\text{eff}} \): \( m_T > 70 \) GeV and either \( m_T > 110 \) GeV or \( m_{\text{eff}} < 600 \) GeV. Since the \( m_T \) distribution falls rapidly above the \( W \) mass for true-\( \tau \) events, the intermediate \( m_T \) region selected here is relatively enhanced in fake-\( \tau \) events, and the overall composition of this region is expected to be very similar to that of the signal region. Multijet events are expected to make up less than 3% of this sample and are estimated from
simulation. The composition of the fake-τ-enhanced sample in this control region is shown in Table 2. Within this control region, true-τ backgrounds are subtracted using estimates derived from the true-τ-dominated control region. The numbers of events remaining after the true-τ subtraction are used to determine a scale factor, 0.50 ± 0.08, which is then applied to simulated samples of fake-τ events in the signal region to obtain a final background estimate. While this scale factor differs significantly from unity, it is consistent with other ATLAS studies of the performance of τ fake rates in simulation.

Backgrounds due to multijet events are estimated in a third control region in which either $E_T^{\text{miss}}/m_{\text{eff}} < 0.25$ or one of the two leading jets is aligned in azimuth with the missing transverse momentum direction. Within this sample, the probability for jets (which contain very few true τ leptons) to satisfy the τ selection criteria is estimated by applying the selection to randomly chosen jet candidates. This probability is then applied to a complementary sample of multijet events, where the azimuthal separation and $E_T^{\text{miss}}/m_{\text{eff}}$ as well as all other event selection requirements, match those of the signal region, but where the τ candidate is again randomly chosen from among the jet candidates. This provides an estimate of the multijet background yield in the signal region. It is found that the multijet background makes up only a few percent of the total SM background in the signal region.

Possible contamination from SUSY signals has been considered in all three background-estimation control regions and is found to have a negligible effect on the results presented below.

### 7. Systematic uncertainties

Dominant systematic uncertainties on the estimated background yields are due to uncertainties in the jet energy scale (3–8%) [71], jet energy resolution (6–13%) [71], τ energy scale (2–10%) [74], statistical uncertainties in the data control regions (5–15%), and Monte Carlo uncertainties related to the extrapolation from the control regions to the signal region (10–20%). This last term includes statistical uncertainties in the simulation, variations in the in the assumed W+jets/top/Z+jets mixture in the fake-τ control region, and Monte Carlo generator uncertainties (estimated by varying the shower matching, factorization and renormalization scales, α_s, and the amount of initial-state and final-state radiation) [77]. Additional uncertainties on W+jets and top-quark backgrounds are estimated by varying the assumed b-quark identification efficiency within measured uncertainties (4–11%) [76]. Uncertainties on the multijet background yield are estimated by studying correlations between $m_{\text{eff}}$ and the azimuthal separation between the leading two jets and the missing transverse momentum. Additional systematic uncertainties, including those on the pile-up description in the simulation, are considered and found to be negligible.

### 8. Results

Fig. 2 shows the distributions of $E_T^{\text{miss}}$, $p_T^\tau$, and $m_{\text{eff}}$ for data with all selection requirements except for that on $m_{\text{eff}}$, along with the corresponding estimated backgrounds. Backgrounds are taken from simulation and normalized with control regions in data. The solid (red) line with shaded (yellow) error band corresponds to the total SM prediction, while the data points are shown in error bars. The error bands indicate the size of the total (statistical and systematic) uncertainty. The notation GMSB(40,30) stands for the GMSB model with $A = 40 \text{ TeV}$ and $\tan \beta = 30$ and analogously for GMSB(30,20). (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

In addition to the sources described above, systematic uncertainties on the SUSY signal cross section are estimated by varying the factorization and renormalization scales in PROSPINO up and down by a factor of two, by considering variations in $\alpha_s$, and by varying the proton PDFs within their uncertainties. These theoretical uncertainties total typically 8–12% across the relevant region of parameter space. Uncertainties are calculated separately for individual SUSY production processes.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>True τ</th>
<th>Fake τ</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>$53.3 \pm 7.5$</td>
<td>$37.8 \pm 5.8$</td>
<td>$91.1 \pm 9.4$</td>
</tr>
<tr>
<td>W + jets</td>
<td>$80.5 \pm 6.9$</td>
<td>$33.8 \pm 4.1$</td>
<td>$113.8 \pm 8.0$</td>
</tr>
<tr>
<td>Z + jets</td>
<td>$5.1 \pm 1.6$</td>
<td>$41.5 \pm 10.8$</td>
<td>$46.5 \pm 10.5$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$0 \pm 0$</td>
<td>$2.9 \pm 1.0$</td>
<td>$2.9 \pm 1.0$</td>
</tr>
<tr>
<td>Total</td>
<td>$139 \pm 10$</td>
<td>$116 \pm 13$</td>
<td>$254 \pm 17$</td>
</tr>
<tr>
<td>Data</td>
<td>197</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Distributions of $E_T^{\text{miss}}$, $p_T^\tau$, and $m_{\text{eff}}$ for data with all selection requirements except for that on $m_{\text{eff}}$, along with the corresponding estimated backgrounds.
Table 3

<table>
<thead>
<tr>
<th>Top</th>
<th>W + jets</th>
<th>Z + jets</th>
<th>Multijet</th>
<th>( \Sigma_{SM} )</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6 ± 1.4</td>
<td>4.7 ± 1.5</td>
<td>2.4 ± 0.7</td>
<td>0.5 ± 0.6</td>
<td>13.2 ± 4.2</td>
<td>11</td>
</tr>
</tbody>
</table>

Fig. 3. Expected and observed 95% C.L. exclusion limits in the \( M_{\text{mess}} = 250 \) TeV, \( N_\tau = 3, \mu > 0, C_{\text{grav}} = 1 \) slice of GMSB, together with the most stringent previous limits from OPAL [32]. The identity of the NLSP is indicated, with CoNLSP the region where the \( f \) and \( \tilde{e} \) are nearly degenerate.

13.2 ± 4.2 expected, an upper limit of 8.5 on the number of events observed due to non-SM sources is derived at 95% confidence level (C.L.). This limit corresponds to an upper limit on the production of super-symmetric particles can be excluded at 95% C.L. up to \( \Lambda = 30 \) TeV, independent of \( \tan \beta \), and up to \( \Lambda = 43 \) TeV for large values of \( \tan \beta \).

9. Conclusions

In conclusion, this Letter presents a search for supersymmetry in final states containing jets, missing transverse momentum, and at least one \( \tau \) lepton with the ATLAS experiment in \( \sqrt{s} = 7 \) TeV proton–proton collisions at the LHC. This is the first search in these final states at the LHC that includes events with one \( \tau \) lepton. No excess of events is seen beyond the expected Standard Model backgrounds in 2.05 fb\(^{-1}\) of data. Limits are placed on the visible cross section and in the context of GMSB models. The limits obtained extend the results from previous experiments.

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References

26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa, ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (c) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, (d) Department of Modern Physics, Chinese Academy of Science and Technology of China, Anhui, (e) Department of Physics, Nanjing University, Jiangsu, (f) School of Physics, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Aubière Cedex, France
34 Nevis Laboratory, Columbia University, Irvington, NY, United States
35 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
36 (a) INFN Sezione di Genova, (b) Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy
37 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
38 The Henryk Niewodnichanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas, TX, United States
40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham, NC, United States
45 SUPO – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova, (b) Diapartmento 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 Il Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 Il 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 Department of 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 Instituto de Física La Plata, Universidad Nacional de La Plata y CONICET, La Plata, Argentina
70 Physics Department, Lancaster University, Lancaster, United Kingdom
71 (a) INFN Sezione di Lecce, (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
72 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
73 Department of Physics, Josef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
74 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
75 Department of Physics, Royal Holloway University of London, London, United Kingdom
76 Department of Physics and Astronomy, University College London, London, United Kingdom
77 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
78 Fysiska institutionen, Lunds universitet, Lund, Sweden
79 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
80 Institut für Physik, Universität Mainz, Mainz, Germany
81 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
82 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
83 Department of Physics, University of Massachusetts, Amherst, MA, United States
84 Department of Physics, McGill University, Montreal, QC, Canada
85 School of Physics, University of Melbourne, Victoria, Australia
86 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
87 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
88 (a) INFN Sezione di Milano, (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
89 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
90 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
91 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
92 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
93 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
94 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
95 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
96 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
97 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
98 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
99 Nagasaki Institute of Applied Science, Nagasaki, Japan
100 Graduate School of Science, Nagoya University, Nagoya, Japan
101 (a) INFN Sezione di Napoli, (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
102 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
103 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
104 NIKHEF National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
105 Department of Physics, Northern Illinois University, DeKalb, IL, United States
106 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
107 Department of Physics, New York University, New York, NY, United States
108 Ohio State University, Columbus, OH, United States
109 Faculty of Science, Okayama University, Okayama, Japan
110 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
111 Department of Physics, Oklahoma State University, Stillwater, OK, United States
112 Palacky University, KCPTM, Olomouc, Czech Republic
113 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
114 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
115 Graduate School of Science, Osaka University, Osaka, Japan
116 Department of Physics, University of Oslo, Oslo, Norway
117 Department of Physics, Oxford University, Oxford, United Kingdom
118 IN2P3 Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
119 Department of Physics, Pennsylvania State University, University Park, PA, United States
120 Petersburg Nuclear Physics Institute, Gatchina, Russia
121 (a) IFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
123 (a) Laboratory for Instrumentation and Applied Physics, University of Bern, Bern, Switzerland; (b) Dipartimento di Fisica Teorica e del Cosmos and IFN Sezione di Roma, Roma, Italy
124 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
125 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
126 Czech Technical University in Prague, Prague, Czech Republic
127 State Research Center Institute for High Energy Physics, Protvino, Russia
128 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
129 Physics Department, University of Regina, Regina, SK, Canada
130 Ritsumeikan University, Kusatsu, Shiga, Japan
131 (a) IFN Sezione di Roma L; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
132 (a) IFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
133 (a) IFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
134 (a) École des Hautes Études en Sciences Sociales (EHESS), Paris, France; (b) Laboratoire de Physique des Particules de Planck, CNRS/IN2P3, Orsay, France
135 Physics Department, University of Washington, Seattle, WA, United States
136 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
137 Department of Physics, Shinshu University, Nagano, Japan
138 Fachbereich Physik, Universität Siegen, Siegen, Germany
139 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
140 SLAC National Accelerator Laboratory, Stanford, CA, United States
141 (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
142 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
143 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
144 Physics Department, Royal Institute of Technology, Stockholm, Sweden
145 Department of Physics & Astronomy and Chemistry, Stockholm University, Stockholm, Sweden
146 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
147 School of Physics, University of Sydney, Sydney, Australia
148 Institute of Physics, Academia Sinica, Taipei, Taiwan
149 Department of Physics, Technion - Israel Inst. of Technology, Haifa, Israel
150 Raymon and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
151 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
152 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
153 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
154 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
155 Department of Physics, University of Toronto, Toronto, ON, Canada
156 (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
157 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan
158 Science and Technology Center, Tsukuba University, Medford, MA, United States
159 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
160 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
161 (a) IN2P3 Sezione di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambientale, Università di Udine, Udine, Italy
162 Department of Physics, University of Illinois, Urbana, IL, United States
163 Department of Physics and Astronomy, University of Uppsala, Uppala, Sweden
164 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
165 Department of Physics, University of British Columbia, Vancouver, BC, Canada
166 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
167 Waseda University, Tokyo, Japan
168 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
169 Department of Physics, University of Wisconsin, Madison, WI, United States
170 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
171 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
172 Department of Physics, Yale University, New Haven, CT, United States
173 Yerevan Physics Institute, Yerevan, Armenia
174 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France