Search for scalar charm quark pair production in pp collisions at $s\sqrt{s}=8$ TeV with the ATLAS Detector

Article (Published Version)


This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/55892/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher’s version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.
Search for Scalar Charm Quark Pair Production in \( pp \) Collisions at \( \sqrt{s} = 8 \text{ TeV} \) with the ATLAS Detector

G. Aad et al. (ATLAS Collaboration)

(Received 6 January 2015; published 22 April 2015)

The results of a dedicated search for pair production of scalar partners of charm quarks are reported. The search is based on an integrated luminosity of 20.3 \( \text{fb}^{-1} \) of \( pp \) collisions at \( \sqrt{s} = 8 \text{ TeV} \) recorded with the ATLAS detector at the LHC. The search is performed using events with large missing transverse momentum and at least two jets, where the two leading jets are each tagged as originating from \( c \) quarks. Events containing isolated electrons or muons are vetoed. In an \( R \)-parity-conserving minimal supersymmetric scenario in which a single scalar-charm state is kinematically accessible, and where it decays exclusively into a charm quark and a neutralino, 95% confidence-level upper limits are obtained in the scalar-charm–neutralino mass plane such that, for neutralino masses below 200 GeV, scalar-charm masses up to 490 GeV are excluded.

DOI: 10.1103/PhysRevLett.114.161801

Supersymmetry (SUSY) [1–9] is a theory that extends the Standard Model (SM) and naturally resolves the hierarchy problem by introducing supersymmetric partners of the known bosons and fermions. In the framework of a generic \( R \)-parity-conserving minimal supersymmetric extension of the SM, the MSSM [10–14], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, providing a possible candidate for dark matter. In a large variety of models, the LSP is the lightest neutralino, \( \tilde{\chi}_1^0 \).

The scalar partners (squarks) of various flavors of quarks may, rather generally, have different masses despite constraints on quark flavor mixing [15]. Recent searches disfavor low-mass top squarks (stops), sbottoms, and gluinos, so direct scalar-charm (\( \tilde{c} \)) pair production could be the only squark production process accessible at the LHC. Searches for \( \tilde{c} \) states provide not only a possible supersymmetry discovery mode but also the potential to probe the flavor structure of the underlying theory.

Since no dedicated search for \( \tilde{c} \) has previously been performed, the best existing lower limits on \( \tilde{c} \) masses are obtained from searches for generic squark and gluino production at the LHC [16,17], and from the reinterpretation of LHC searches [18] for direct pair production of the scalar partner of the top quark followed by decays \( \tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0 \). The top squark searches have a final state similar to that expected for scalar charm quarks, but are optimized for small \( m_t - m_{\tilde{c}_1} \) mass differences, and so have good sensitivity to the scalar charm quark only when \( m_{\tilde{c}_1} \ll m_W \).

In this Letter, a dedicated search for direct \( \tilde{c} \) pair production is presented. The scalar charm quark is assumed to decay dominantly or exclusively via \( \tilde{c} \rightarrow c + \tilde{\chi}_1^0 \). The expected signal is therefore characterized by the presence of two jets originating from the hadronization of the \( c \) quarks, accompanied by missing transverse momentum (\( E_T^{\text{miss}} \)) resulting from the undetected neutralinos.

The ATLAS detector is described in detail elsewhere [19]. This search uses \( pp \) collision data at a center-of-mass energy of 8 TeV recorded during 2012 at the LHC. After the application of beam, detector, and data quality requirements, the data set corresponds to a total integrated luminosity of 20.3 \( \text{fb}^{-1} \) with a 2.8% uncertainty, using the methods of Ref. [20].

The data are selected with a three-level trigger system that required a high transverse momentum (\( p_T \)) jet and \( E_T^{\text{miss}} \) [21]. While events containing charged leptons (electrons or muons) in the search region are vetoed, single-lepton triggers are used for control regions. Events are required to have a reconstructed primary vertex consistent with the beam positions, and to meet basic quality criteria that suppress detector noise and noncollision backgrounds [22]. Jets are reconstructed from three-dimensional topological calorimeter energy clusters by using the anti-\( k_T \) jet algorithm [23,24] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities and for the noncompensating response of the calorimeter by using \( p_T \)– and \( \eta \)-dependent [25] correction factors [26]. The impact of multiple overlapping \( pp \) interactions (pileup) is accounted for using a technique, based on jet areas, that provides an event-by-event and jet-by-jet correction [27]. Only jet candidates with \( p_T > 20 \text{ GeV} \) within \( |\eta| < 2.8 \) are retained.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
Electron candidates are required to have $p_T > 7$ GeV, $|\eta| < 2.47$ and to satisfy “medium” selection criteria [28]. Muon candidates are required to have $p_T > 6$ GeV, $|\eta| < 2.4$ and are identified by matching an extrapolated inner-detector track to one or more track segments in the muon spectrometer [29]. When defining lepton control regions, muons and electrons must meet additional “tight” selection criteria [29,30], and must satisfy track and calorimeter isolation criteria similar to those in Ref. [31].

Following this object reconstruction, overlaps between jet candidates and electrons or muons are resolved. Any jet within a distance $\Delta R = 0.2$ of a medium quality electron candidate is discarded. Any remaining lepton within $\Delta R = 0.4$ of a jet is discarded. Remaining muons must have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively.

The calculation of $E_T^{miss}$ is based on the vector sum of the calibrated $p_T$ of reconstructed jets (with $p_T > 20$ GeV and $|\eta| < 4.5$), electrons, muons and photons, and the calorimeter energy clusters not belonging to these reconstructed objects [32].

Jets containing $c$-flavored hadrons without $b$-flavored parent hadrons are identified using an algorithm, optimized for charm tagging, based on a neural network that exploits both impact parameter and secondary vertex information and with a $B \to D$ decay chain vertex fitter [33]. This algorithm achieves a tagging efficiency of 19% (13%, 0.5%) for $c$-jets ($b$-jets, light-flavor or gluon jets) in $t\bar{t}$ events. The efficiency for tagging $b$-jets is determined from measurements of dileptonic $t\bar{t}$ events [34]. The $c$-jet tagging efficiency and its uncertainty have been calibrated in inclusive jet events over a range of $p_T$ using jets from collision data containing $D^{*}$ mesons [35]. Jets can be $c$-tagged only within the acceptance of the inner detector ($|\eta| < 2.5$), so only such central jets are retained after the above selection.

Events are then required to have $E_T^{miss} > 150$ GeV and one jet with $p_T > 130$ GeV to ensure full trigger efficiency, as well as a second jet with $p_T > 100$ GeV. The two highest-$p_T$ jets are required to be $c$ tagged. The multijet background contribution with large $E_T^{miss}$, caused by mis-measurement of jet energies in the calorimeters or by neutrino production in heavy-quark decays, is suppressed by requiring a minimum azimuthal separation ($\Delta \phi_{min}$) of 0.4 between the $E_T^{miss}$ direction and any of the three leading jets. To reduce the effect of pileup, the third jet is exempted from this requirement if it has $p_T < 50$ GeV, $|\eta| < 2.4$ and less than half of the sum of its track $p_T$ is associated with tracks matched to the primary vertex. In addition, the ratio of $E_T^{miss}$ to the scalar sum of the transverse momenta of the two leading jets is required to be above one-third. Events containing residual electron or muon candidates are vetoed in order to reduce electroweak backgrounds.

After these requirements, the main SM processes contributing to the background are top quark pair and single top production, together referred to as top production, as well as associated production of $W/Z$ bosons with light- and heavy-flavor jets, referred to as $W +$ jets and $Z +$ jets. A selection based on the boost-corrected contransverse mass $m_{CT}$ [36] is employed to further discriminate scalar-charm pair from top production. For two identical decays of heavy particles into two visible particles $v_1$ and $v_2$, and into invisible particles, the contransverse mass [37] is defined as $\{(E_T(v_1) + E_T(v_2))^2 - (p_T(v_1) + p_T(v_2))^2\}^{1/2}$. The boost correction preserves the expected endpoint in the distribution against boosts caused by initial-state radiation. In the case of scalar-charm pair production with $c \to c + \tilde{X}_1^0$, $m_{CT}$ is expected to have an endpoint at $(m_c^2 - m_{\tilde{X}_1^0}^2)/m_c$. For $t\bar{t}$ production, if both $b$-jets are mistagged as $c$-jets, the $m_{CT}$ built using those two jets is expected to have a kinematic endpoint at 135 GeV.

To maximize the sensitivity across the $c\tilde{X}_1^0$ mass plane, three overlapping signal regions (SR) are defined: $m_{CT} > 150, 200$, and 250 GeV. The remaining $t\bar{t}$ background after the $m_{CT}$ requirement mostly comprises events with one true $c$-jet from a $W$ decay and a mistagged $b$-jet from a top quark decay. Events in which a $Z$ boson is produced in association with heavy-flavor jets where the $Z$ boson decays into $\nu\bar{\nu}$ also enter the high-$m_{CT}$ regions. The heavy-flavor jets often originate from a gluon splitting, $g \to c\bar{c}$, which can lead to a small angular separation between the resulting $c$-jets and therefore a small invariant mass $m_{cc}$. The remaining $t\bar{t}$ background is also concentrated at low $m_{cc}$. Consequently, a final requirement selects events for which the invariant mass of the two $c$-tagged jets is larger than 200 GeV.

Simulated-event samples are used to aid the description of the background and to model the SUSY signal. Top quark pair and single top production in the $s$ and $Wt$ channels are simulated with POWHEG-1.0 (r2092) [38], while the $t$ channel single top production is simulated using ACERMC 3.8 [39]. A top quark mass of 172.5 GeV is used. The parton shower, fragmentation, and hadronization are performed with PYTHIA-6.426 [40]. Samples of $W +$ jets, $Z +$ jets, and dibosons ($WW$, $WZ$, $ZZ$) with light and heavy flavor jets are generated with SHERPA 1.4 [41], assuming massive $b/c$ quarks. Samples of $Zt\bar{t}$ and $Wt\bar{t}$ are generated with MADGRAPH-5.1.3.33 [42] interfaced to PYTHIA-6.426. The signal samples are generated for a simplified SUSY model with only a single $\tilde{c}$ state kinematically accessible, and with BR$(\tilde{c} \to c + \tilde{X}_1^0) = 100\%$, using MADGRAPH-5.1.5.11 interfaced to PYTHIA-6.427 for the parton shower, fragmentation, and hadronization. Signal cross sections are calculated to next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithm accuracy (NLO + NLL) [43–45]. The uncertainty on each nominal cross section is defined by an envelope of predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [46]. The Monte Carlo (MC)
samples are processed through a detector simulation [47] based on GEANT4 [48]. The effects of pileup are included in the simulation. Efficiency corrections derived from the data are applied to the simulation to correct for lepton efficiency as well as the tagging and mistagging rates.

The main SM process contributing to the background after all signal region selections is $Z + \text{jets}$, followed by $W + \text{jets}$, top quark pair, and single top production. Most $t\bar{t}$ events contributing are $t\bar{t} \rightarrow b\bar{b}l\bar{l}qqq$ events, in which either a $\tau$ lepton decays hadronically, or an $e$ or $\mu$ is out of the geometric acceptance or not reconstructed or identified. Contributions from multijet, diboson, and associated production of $t\bar{t}$ with $W$, $Z$ are subdominant. Noncollision backgrounds are found to be negligible.

The estimation of the main background processes is carried out by defining a set of three data control regions (CR) that do not overlap with each other or with the signal regions. The CRs are kinematically close to the SRs and each of them is enhanced in one or two of the backgrounds that is dominant in the SRs, while having low expected signal contamination (less than 1%). A statistical model is set up in which the background expectation in the CRs and SRs depends on several parameters of interest: the normalizations of the dominant backgrounds, top ($t\bar{t}$ single top), $Z$ + jets and $W$ + jets, as well as on nuisance parameters including the effect of uncertainties on the jet energy scale (JES) and resolution, calorimeter resolution for energy clusters not associated with any physics objects, energy scale and resolution of electrons and muons, $c$-tagging and mistagging rates, pileup, and luminosity. A profile likelihood fit of the background expectation to the data is performed simultaneously in all CRs [49], and from it the background normalizations are extracted. The normalization factors, which are consistent with unity within uncertainties, are then applied to the MC expectation in the signal regions.

The first control region is populated largely by $t\bar{t}$ and $W + \text{jets}$. It contains events with exactly one isolated electron or muon with $p_T > 50$ GeV. The leading two jets, with $p_T > 130$ and 50 GeV respectively, must be $c$-tagged. To select events containing $W \rightarrow l\nu$, the transverse mass of the $(l, E_{T}^{\text{miss}})$ system is required to be between 40 and 100 GeV. The upper bound reduces possible signal contamination from SUSY models that produce leptons in cascade decays. Finally, it is required that $E_{T}^{\text{miss}} > 100$ GeV and $m_{CT} > 150$ GeV. The second control region is populated by $Z \rightarrow l^+l^-$ events with two opposite-sign, same-flavor leptons, where the minimum $p_T$ requirement is 70 GeV for the leading lepton and 7(6) GeV for the subleading lepton (muon). The transverse momenta of the leptons are added vectorially to the $E_{T}^{\text{miss}}$, to mimic the $Z \rightarrow \nu\bar{\nu}$ decay, and the modulus of the resulting two-vector is required to be larger than 100 GeV. The leading two jets are required to be $c$-tagged and their $p_T$ must each be above 50 GeV. The invariant mass $m_{\ell\ell}$ of the two leptons is required to be between 75 and 105 GeV (Z-mass interval). A third control region, populated almost exclusively by dileptonic $t\bar{t}$ events, contains events with two opposite-sign, different-flavor leptons, where the leading lepton has $p_T > 25$ GeV and the subleading lepton $p_T$ is above 7(6) GeV for electrons (muons). It is required that $E_{T}^{\text{miss}} > 50$ GeV and $m_{\ell\ell} > 50$ GeV. The leading two jets are required to be $c$-tagged and have $p_T > 50$ GeV. In all CRs, events with additional lepton candidates beyond the required number of signal leptons are vetoed using the same lepton requirements used to veto events in the SRs.

The subdominant background contributions from dibosons, $Zt\bar{t}$ and $Wt\bar{t}$ are estimated by MC simulation. Finally, the residual multijet background is estimated using a data-driven technique based on the smearing of jets in a low-$E_{T}^{\text{miss}}$ data sample with jet response functions [50].

The experimental and theoretical uncertainties affecting the main backgrounds are correlated between control and signal regions, and the data observed in control regions constrain the uncertainties on the expected yields in the signal regions. The residual uncertainty due to the theoretical modeling of the top-production background is about 7%. It is evaluated using additional MC samples generated with HERWIG (where initial- and final-state radiation parameters are varied) an alternative fragmentation model (HERWIG), an alternative generator (MC@NLO), and by using diagram subtraction rather than diagram removal to account for the interference between $t\bar{t}$ and single top $W$-channel production [51]. After the fit, the residual uncertainties on the $W + \text{jets}$ and $Z + \text{jets}$ theoretical modeling account for less than 20% of the total uncertainty. The dominant contributions to the residual uncertainty on the total background are from $c$-tagging ($\sim$20%), normalization uncertainties related to the numbers of events in the CRs (10%–20%), and JES ($\sim$10%).

For the SUSY signal processes, theoretical uncertainties on the cross section due to the choice of renormalization and factorization scales and from PDFs are found to be between 14% and 16% for $\tilde{c}$ masses between 100 and 550 GeV. Prior to the fit, the detector-related uncertainties with largest impact on the signal event yields are those for $c$-tagging (typically 15%–30%) and JES (typically 10%–30%).

Table I reports the observed number of events and the SM predictions for each SR. The data are found to be below the SM background expectations, but consistent with them given the uncertainties. Figure 1 shows the measured $m_{CT}$ and $m_{\ell\ell}$ distributions in the $m_{CT} > 150$ GeV region compared to the SM predictions. Monte Carlo estimates are shown after the normalizations extracted from the profile likelihood fit are applied. For illustrative purposes, the distributions expected for the simplified model with $(\tilde{c}, \tilde{\chi}_1^0)$ masses of (400, 200) GeV and (550, 50) GeV are also shown.
Since no significant excesses are observed, the results are translated into 95% confidence-level (C.L.) upper limits on contributions from non-SM processes using the CL_s prescription [52]. Figure 2 shows the observed and expected exclusion limits at 95% C.L. on the $\tilde{c}$-$\chi^0_1$ mass plane, assuming a single accessible $\tilde{c}$ particle with $\text{BR}(\tilde{c} \to c + \chi^0_1) = 100\%$. The SR with the best expected sensitivity at each point in the plot is adopted as the nominal result. In the region where the $c$-tagged analysis of the ATLAS $t \to c + \chi^0_1$ search [18] provides a stronger expected limit, i.e., for $m_{\tilde{c}} - m_{\chi^0} \lesssim m_W$, that result is used. The region excluded by the ATLAS monojet search described in Ref. [18] is shown separately as a grey shaded area. Systematic uncertainties, other than in the $\tilde{c}$ pair-production cross section, are treated as nuisance parameters and correlated when appropriate. For the SUSY scenario considered, the upper limit at 95% C.L. on the scalar-charm mass obtained in the most conservative cross-section hypothesis is 540 GeV for $m_{\tilde{c}} = 0$ (increasing to 555 GeV for the central estimate of the signal cross section). Neutralino masses up to 200 GeV are similarly 

![Image](image1.png)

FIG. 1 (color online). Distributions of $m_{\text{CT}}$ (top) and $m_{\tilde{c}}$ (bottom), and their corresponding SM predictions. Signal region selections ($m_{\text{CT}} > 150 \text{ GeV}$ for the $m_{\tilde{c}}$ distribution) are applied, other than for the variable plotted. Arrows indicate the SR requirements on $m_{\text{CT}}$ and $m_{\tilde{c}}$. In the ratio plots, the grey bands correspond to the combined MC statistical and experimental systematic uncertainty.

![Image](image2.png)

FIG. 2 (color online). Exclusion limits at 95% C.L. in the $\tilde{c}$-$\chi^0_1$ mass plane. The observed (solid red line) and expected (dashed blue line) limits include all uncertainties except for the theoretical signal cross-section uncertainty (PDF and scale). The band around the expected limits show $\pm 1\sigma$ uncertainties. The dotted lines around the observed limits represent the results obtained when moving the nominal signal cross section up or down by the $\pm 1\sigma$ theoretical uncertainty.

### Table I

<table>
<thead>
<tr>
<th>$m_{\text{CT}}$ (GeV)</th>
<th>&gt;150</th>
<th>&gt;200</th>
<th>&gt;250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>7.4 ± 2.7 (7.1)</td>
<td>3.9 ± 1.6 (3.7)</td>
<td>1.6 ± 0.7 (1.5)</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>14 ± 3 (13)</td>
<td>7.7 ± 1.7 (7.0)</td>
<td>4.3 ± 1.2 (3.9)</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>7.2 ± 4.5 (7.4)</td>
<td>4.1 ± 2.6 (4.2)</td>
<td>1.9 ± 1.2 (1.9)</td>
</tr>
<tr>
<td>Multijets</td>
<td>0.3 ± 0.3</td>
<td>0.2 ± 0.2</td>
<td>0.05 ± 0.05</td>
</tr>
<tr>
<td>Others</td>
<td>0.5 ± 0.3</td>
<td>0.4 ± 0.3</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>30±6</strong></td>
<td><strong>16±3</strong></td>
<td><strong>8.2±1.9</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>19</strong></td>
<td><strong>11</strong></td>
<td><strong>4</strong></td>
</tr>
</tbody>
</table>
excluded for \(m_\tilde{c} < 490\) GeV. This significantly extends the results of previous flavor-blind analyses [16,17], which provide no exclusion for \(m_{\tilde{g}} > 160\) GeV, nor for single light squarks with masses above 440 GeV. The signal regions are used to set limits on the effective cross sections \(\sigma_{\text{vis}}\) of any non-SM processes, including the effects of branching ratios, experimental acceptance, and efficiency, neglecting any possible contamination in the control regions. Values of \(\sigma_{\text{vis}}\) larger than 0.44 fb, 0.36 fb, and 0.23 fb are excluded at 95% C.L. for \(m_{\tilde{cT}}\) greater than 150, 200, and 250 GeV respectively.

In summary, this Letter reports results of a search for scalar-charm pair production in 8 TeV pp collisions at the LHC, based on 20.3 fb\(^{-1}\) of ATLAS data. The selected events have large \(E_T^{\text{miss}}\) and two \(c\)-tagged jets. The results are in agreement with SM predictions for backgrounds and translate into 95% C.L. upper limits on scalar-charm and neutralino masses in a simplified model with a single accessible \(c\) state for which the exclusive decay \(\tilde{c} \rightarrow c + \tilde{\chi}_0^0\) is assumed. For neutralino masses below 200 GeV, scalar-charm masses up to 490 GeV are excluded, significantly extending previous limits.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; STFC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DSNRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; Mineco, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[25] ATLAS uses a coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the $z$ axis along the beam pipe. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$, while $\Delta R \equiv (\Delta \eta)^2 + (\Delta \phi)^2)^{1/2}$.
[36] G. Polesello and D. Tovey, Supersymmetric particle mass measurement with the boost-corrected contravertex mass, J. High Energy Phys. 03 (2010) 030.
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

Department of Physics, Bogazici University, Istanbul, Turkey

Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

INFN Sezione di Bologna, Italy

Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston MA, United States of America

Department of Physics, Brandeis University, Waltham MA, United States of America

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil

Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil

Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

National Institute of Physics and Nuclear Engineering, Bucharest, Romania

National Institute for Research and Development of Isotopic and Molecular Technologies, Bucharest, Romania

University Politehnica Bucharest, Bucharest, Romania

West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaiso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Department of Modern Physics, University of Science and Technology of China, Anhui, China

Department of Physics, Nanjing University, Jiangsu, China

School of Physics, Shandong University, Shandong, China

Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China

Physics Department, Tsinghua University, Beijing 100084, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington NY, United States of America

Niels Bohr Institute, University of Copenhagen, København, Denmark

INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

Dipartimento di Fisica, Università della Calabria, Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
60Department of Physics, Hampton University, Hampton VA, United States of America
57Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
56ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
50Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
51Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
60Department of Physics, The University of Hong Kong, Hong Kong, China
60cDepartment of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61Department of Physics, Indiana University, Bloomington IN, United States of America
62Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63University of Iowa, Iowa City IA, United States of America
64Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
64KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66Graduate School of Science, Kobe University, Kobe, Japan
67Faculty of Science, Kyoto University, Kyoto, Japan
68Kyoto University of Education, Kyoto, Japan
69Department of Physics, Kyushu University, Fukuoka, Japan
71Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72Physics Department, Lancaster University, Lancaster, United Kingdom
73INFN Sezione di Lecce, Italy
74Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
77Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
78Department of Physics and Astronomy, University College London, London, United Kingdom
79Louisiana Tech University, Ruston LA, United States of America
80Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
81Fysikum institutionen, Lunds universitet, Lund, Sweden
82Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83Institut für Physik, Universität Mainz, Mainz, Germany
84School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86Department of Physics, University of Massachusetts, Amherst MA, United States of America
87Department of Physics, McGill University, Montreal QC, Canada
88School of Physics, University of Melbourne, Victoria, Australia
89Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91INFN Sezione di Milano, Italy
92B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
95Group of Particle Physics, University of Montreal, Montreal QC, Canada
96P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
97Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98National Research Nuclear University MEPhI, Moscow, Russia
99D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
100Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102Nagasaki Institute of Applied Science, Nagasaki, Japan
103Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
104INFN Sezione di Napoli, Italy
105Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
106Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
108Department of Physics, Northern Illinois University, DeKalb IL, United States of America
147b The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 TRIUMF, Vancouver BC, Canada
161 Department of Physics and Astronomy, York University, Toronto ON, Canada
162 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
163 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
166 ICTP, Trieste, Italy
167 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
168 Department of Physics, University of Illinois, Urbana IL, United States of America
169 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
170 Department of Physics and Astronomy, Tokyo Metropolitan University, Tokyo, Japan
171 Department of Physics, University of Victoria, Victoria BC, Canada
172 Waseda University, Tokyo, Japan
173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
174 Department of Physics, University of Wisconsin, Madison WI, United States of America
175 Fachrichtung Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
177 Department of Physics, Yale University, New Haven CT, United States of America
178 Yerevan Physics Institute, Yerevan, Armenia
179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
c Also at Novosibirsk State University, Novosibirsk, Russia.
d Also at TRIUMF, Vancouver BC, Canada.
e Also at Department of Physics, California State University, Fresno CA, United States of America.
f Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
g Also at Tomsk State University, Tomsk, Russia.
h Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
i Also at Università di Napoli Parthenope, Napoli, Italy.
j Also at Institute of Particle Physics (IPP), Canada.
k Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
l Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
n Also at Louisiana Tech University, Ruston LA, United States of America.
o Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
p Also at Department of Physics, National Tsing Hua University, Taiwan.
q Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.
r Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
s Also at CERN, Geneva, Switzerland.
t Also at Georgian Technical University (GTU), Tbilisi, Georgia.