Measurement of Spin Correlation in Top–Antitop Quark Events and Search for Top Squark Pair Production in $pp$ Collisions at $\sqrt{s}=8$ TeV Using the ATLAS Detector

The ATLAS Collaboration

Abstract

A measurement of spin correlation in $t\bar{t}$ production is presented using data collected with the ATLAS detector at the Large Hadron Collider in proton–proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 20.3 fb$^{-1}$. The correlation between the top and antitop quark spins is extracted from dilepton $t\bar{t}$ events by using the difference in azimuthal angle between the two charged leptons in the laboratory frame. In the helicity basis the measured degree of correlation corresponds to $A_{\text{helicity}} = 0.38 \pm 0.04$, in agreement with the Standard Model prediction. A search is performed for pair production of top squarks with masses close to the top quark mass decaying to predominantly right-handed top quarks and a light neutralino, the lightest supersymmetric particle. Top squarks with masses between the top quark mass and 191 GeV are excluded at the 95% confidence level.
Measurement of Spin Correlation in Top–Antitop Quark Events and Search for Top Squark Pair Production in $pp$ Collisions at $\sqrt{s}=8$ TeV Using the ATLAS Detector

The ATLAS Collaboration

A measurement of spin correlation in $t\bar{t}$ production is presented using data collected with the ATLAS detector at the Large Hadron Collider in proton–proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 20.3 fb$^{-1}$. The correlation between the top and antitop quark spins is extracted from dilepton $t\bar{t}$ events by using the difference in azimuthal angle between the two charged leptons in the laboratory frame. In the helicity basis the measured degree of correlation corresponds to $A_{\text{helicity}} = 0.38 \pm 0.04$, in agreement with the Standard Model prediction. A search is performed for pair production of top squarks with masses close to the top quark mass decaying to predominantly right-handed top quarks and a light neutralino, the lightest supersymmetric particle. Top squarks with masses between the top quark mass and 191 GeV are excluded at the 95% confidence level.

Detailed studies of the correlation of the spin of top and antitop quarks in $t\bar{t}$ events produced at hadron colliders are of great interest; they provide important precision tests of the predictions of the Standard Model (SM) and are sensitive to many new physics scenarios [1][6]. The orientations of the top and antitop quark spins are transferred to the decay products and can be measured directly via their angular distributions [3][17–36]. The strength of their correlation has been studied previously by the CDF and D0 collaborations in proton–antiproton scattering at 1.98 TeV [37][40] and by the ATLAS and CMS collaborations in proton–proton scattering at 7 TeV [41][43].

In this Letter the first measurement of $t\bar{t}$ spin correlation in proton–proton collisions at a center-of-mass energy of 8 TeV is presented. Because the polarization analyzing power of the angular distributions of charged leptons from top and antitop quark decays is effectively 100% [44][45], dilepton final states of $ee$, $\mu\mu$ and $e\mu$ are analyzed. An observable very sensitive to $t\bar{t}$ spin correlation is the azimuthal angle $\Delta\phi$ between the charged leptons [34], which is also well measured by the ATLAS detector.

First, the measurement of $\Delta\phi$ is used to extract the spin correlation strength $A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}}$, where $N_{\text{like}}$ ($N_{\text{unlike}}$) is the number of events where the top quark and top antiquark spins are parallel (anti-parallel) with respect to the spin quantization axis. This axis is chosen to be that of the helicity basis, using the direction of flight of the top quark in the center-of-mass frame of the $t\bar{t}$ system. Second, to study a specific model that predicts zero spin correlation, a search for supersymmetric (SUSY) top squark pair production is performed.

At the Large Hadron Collider (LHC), the SUSY partners of the top quark, the top squarks, could be produced in pairs. Models with light top squarks are particularly attractive since they provide a solution to the hierarchy problem [46][49]. In such models, the mass $m_{\tilde{t}_1}$ of the lighter top squark mass eigenstate $\tilde{t}_1$ could be close to the mass of the top quark $m_t$. If the lightest SUSY particle, the neutralino $\tilde{\chi}_1^0$ (or alternatively the gravitino), is light and the top quark mass is only slightly larger than the top quark mass, two-body decays $t_1 \rightarrow t\tilde{\chi}_1^0$, in which the momentum of $\tilde{\chi}_1^0$ is very small can predominate [16]. The masses of all other SUSY particles are assumed to be large. In SUSY models where $\tilde{R}$-parity is conserved, such as the Minimal Supersymmetric Standard Model (MSSM) [52][56], this could lead to $t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$ intermediate states, appearing like SM $t\bar{t}$ production with additional missing transverse momentum carried away by the escaping neutralinos, making traditional searches exploiting kinematic differences as presented in Refs. [57][63] very difficult. $t\bar{t}$ events can be distinguished from SM $t\bar{t}$ events through an increase of the measured $t\bar{t}$ cross section as analyzed in Ref. [64], and since top squarks have zero spin, through measuring angular correlations sensitive to spin correlation, as analyzed in this Letter.

A description of the ATLAS detector can be found elsewhere [65]. This analysis uses proton–proton collision data with a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb$^{-1}$.

Monte Carlo (MC) simulation samples are used to evaluate the contributions, and shapes of distributions of kinematic variables, for signal $t\bar{t}$ events and for background processes not evaluated from complementary data samples. All MC samples are processed with the GEANT4 [66] simulation of the ATLAS detector [67] and are passed through the same analysis chain as data. The simulation includes multiple proton–proton interactions per bunch crossing (pile-up). Events are weighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data.

Samples of $t\bar{t}$ events with SM spin correlation and without spin correlation are generated using MC@NLO v4.06 [68][69] interfaced to HERWIG v6.520 [70] for shower simulation and hadronization. Both samples are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71][72]. The CT10 parton distribution function (PDF) set [73] is used. For the sample with no spin correlation, the parton shower simu-
lation performs isotropic decays of the top quarks whereas the full matrix element is used for the generation of the SM spin-correlation sample. The top quark mass is set to 172.5 GeV \(^{[74]}\). The production of a \(t \bar{t}\) pair in association with a \(Z\) or \(W\) boson is simulated using MADGRAPH 5 \(^{[75]}\) interfaced to PYTHIA v6.426 \(^{[76]}\) and is normalized to the next-to-leading-order (NLO) quantum chromodynamics (QCD) cross sections \(^{[77]}\).

Backgrounds to \(t \bar{t}\) events with same-flavor dilepton final states arise from the Drell–Yan \(Z/\gamma^*\)+jets production process with the \(Z/\gamma^*\) boson decaying into \(e^+e^−, \mu^+\mu^−\) and \(\tau^+\tau^−\), followed by leptonic decays of the \(\tau\) leptons. They are generated using the ALPGEN v2.13 \(^{[77]}\) generator including leading-order (LO) matrix elements with up to five additional partons. The CTEQ6L1 PDF set \(^{[78]}\) is used, and the cross section is normalized to the next-to-next-to-leading-order (NNLO) QCD prediction \(^{[79]}\). Parton showering and fragmentation are modeled by HERWIG, and multiparton interactions are simulated by JIMMY \(^{[80]}\). The “MLM” parton–jet matching scheme \(^{[81]}\) is employed. Correction factors are derived from data in \(Z/\gamma^*\)+jets-dominated control regions and applied to the predicted yields in the signal region, to account for the difference between the simulation prediction and data.

Single top quark background from associated \(Wt\) production is modeled with POWHEG-BOX r2129 \(^{[82–85]}\) interfaced with PYTHIA using the CT10 PDF set \(^{[78]}\) and normalized to the approximate NNLO QCD theoretical cross section \(^{[86]}\). Single-top \(Zt\) and \(WZt\) production is generated by MADGRAPH 5 interfaced with PYTHIA.

The diboson (\(WW\), \(WZ\), \(ZZ\)) backgrounds are modeled using SHERPA v1.4.1 \(^{[87]}\) and are normalized to the theoretical calculation at NLO QCD \(^{[88]}\). The background arising from the misidentified and nonprompt leptons (collectively referred to as “fake leptons") is determined from a combination of MC simulation of \(W+jets\) events using SHERPA, single-top events via \(t\)-channel exchange using MC@NLO+HERWIG, \(tt\) events with single-lepton final states using MC@NLO+HERWIG, and data using a technique known as the matrix method \(^{[89–90]}\).

Top squark pair-production samples are simulated using the HERWIG++ v2.6.1 \(^{[91]}\) generator with the CTEQ6L1 PDFs \(^{[78]}\). The top squarks are assumed to decay exclusively via \(\tilde{t}_1 \rightarrow t\chi_0^0\). The corresponding mixing matrices for the top squarks and for the neutralinos are chosen such that the top quark has a right-handed polarization in 95% of the decays.

Candidate events are selected in the dilepton topology. The analysis requires events selected online by inclusive single-lepton triggers (\(e\) or \(\mu\)). Electron candidates are reconstructed from an isolated electromagnetic calorimeter energy deposit matched to a charged-particle track in the inner detector and must pass “medium identification requirements” \(^{[92]}\). Muon candidates were reconstructed by combining tracks reconstructed in both the inner detector and muon spectrometer \(^{[93]}\). Jets are reconstructed from clusters of adjacent calorimeter cells \(^{[65–94]}\) using the anti-\(k_t\) algorithm \(^{[95–97]}\) with a radius parameter \(R = 0.4\). Jets originating from \(b\)-quarks were identified ('tagged') using a multivariate discriminant employing the long lifetime, high decay multiplicity, hard fragmentation and high mass of \(B\) hadrons \(^{[98–99]}\). The missing transverse momentum \(E_T^{miss}\) is reconstructed as the magnitude of a vector sum of all calorimeter cell energies associated with topological clusters \(^{[100]}\). The following kinematic requirements are made:

- Electron candidates are required to have transverse momentum of \(p_T > 25\) GeV and pseudorapidity \(\eta\) of \(|\eta| < 2.47\), excluding electrons from the transition region between the barrel and end-cap calorimeters defined by \(1.37 < |\eta| < 1.52\). Muon candidates are required to have \(p_T > 25\) GeV and \(|\eta| < 2.5\). Events must have exactly two oppositely charged lepton candidates \((e^+e^−, \mu^+\mu^−, e^±\mu^\mp)\).

- Events must have at least two jets (after having removed the jet closest to the electron, if there are jets within a cone of \(\Delta R = 0.2\) around a selected electron) with \(p_T > 25\) GeV and \(|\eta| < 2.5\). At least one jet must be identified as a \(b\)-jet using a requirement in the multivariate discriminant corresponding to a 70% \(b\)-tagging efficiency.

- Events in the \(e^+e^−\) and \(\mu^+\mu^-\) channels must satisfy \(E_T^{miss} > 30\) GeV to suppress backgrounds from Drell–Yan \(Z/\gamma^*\)+jets and \(W+jets\) events.

- Events in the \(e^+e^−\) and \(\mu^+\mu^-\) channels are required to have \(m_{\ell\ell} > 15\) GeV (where \(\ell\) indicates \(e\) or \(\mu\)) to ensure compatibility with the simulated backgrounds and to remove contributions from \(\Upsilon\) and \(J/\psi\) production. In addition, \(m_{\ell\ell}\) must differ by at least 10 GeV from the \(Z\) boson mass \((m_Z = 91\) GeV\) to further suppress the \(Z/\gamma^*\)+jets background.

- For the \(e^±\mu^\mp\) channel, no \(E_T^{miss}\) or \(m_{\ell\ell}\) requirements are applied. In this case, the remaining background from \(Z/\gamma^*(\rightarrow \tau\tau)+jets\) production is further suppressed by requiring that the scalar sum of the \(p_T\) of all selected jets and leptons is greater than 130 GeV.

The expected numbers of \(t \bar{t}\) signal and background events are compared to data in Table[Fig. 1]. The expected yield for top squark pair production with a top squark mass of 180 GeV and a neutralino mass of 1 GeV is also shown. Figure[Fig. 1] shows the reconstructed \(\Delta\phi\) distribution for the sum of the three dilepton channels. A binned log-
Events/0.1
0
2000
4000
6000
8000
10000
12000
14000
16000
ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>54000 ± 3400</td>
</tr>
<tr>
<td>$Z/\gamma^* + jets$</td>
<td>2800 ± 300</td>
</tr>
<tr>
<td>$tV$ (single top)</td>
<td>2600 ± 180</td>
</tr>
<tr>
<td>$ttV$</td>
<td>80 ± 11</td>
</tr>
<tr>
<td>$WW, WZ, ZZ$</td>
<td>180 ± 65</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>780 ± 780</td>
</tr>
<tr>
<td>Total non-$tt$</td>
<td>6400 ± 860</td>
</tr>
<tr>
<td>Expected</td>
<td>60000 ± 3500</td>
</tr>
<tr>
<td>Observed</td>
<td>60424</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>7100 ± 1100</td>
</tr>
</tbody>
</table>

$(m_{\tilde{t}_1} = 180 \text{ GeV}, m_{\tilde{q}_1} = 1 \text{ GeV})$

**TABLE I.** Observed dilepton yield in data and the expected SUSY and $tt$ signals and background contributions. Systematic uncertainties due to theoretical cross sections and systematic uncertainties evaluated for data-driven backgrounds are included in the uncertainties.

The likelihood fit is used to extract the spin correlation from the $\Delta\phi$ distribution in data. This is done by defining a coefficient $f_{SM}$ that measures the degree of spin correlation relative to the SM prediction. The fit includes a linear superposition of the $\Delta\phi$ distribution from SM $tt$ MC simulation with coefficient $f_{SM}$, and from the $t\bar{t}$ simulation without spin correlation with coefficient $(1 - f_{SM})$. The $e^+e^-, \mu^+\mu^-$ and $e^\pm\mu^\mp$ channels are fitted simultaneously with a common value of $f_{SM}$, leaving the $t\bar{t}$ normalization free with a fixed background normalization. The $t\bar{t}$ normalization obtained by the fit agrees with the theoretical prediction of the production cross section [71] within the uncertainties. Negative values of $f_{SM}$ correspond to an anti-correlation of the top and antitop quark spins. A value of $f_{SM} = 0$ implies that the spins are uncorrelated and values of $f_{SM} > 1$ indicate a degree of $tt$ spin correlation larger than predicted by the SM.

Systematic uncertainties are evaluated by applying the fit procedure to pseudo-experiments created from simulated samples modified to reflect the systematic variations. The fit of $f_{SM}$ is repeated to determine the effect of each systematic uncertainty using the nominal templates. The difference between the means of Gaussian fits to the results from many pseudo-experiments using nominal and modified pseudo-data is taken as the systematic uncertainty on $f_{SM}$ [102].

The various systematic uncertainties are estimated in the same way as in Ref. [42] with the following exceptions: since this analysis employs $b$-tagging, the associated uncertainty is estimated by varying the relative normalizations of simulated $b$-jet, $c$-jet and light-jet samples. The uncertainty due the choice of generator is determined by comparing the default to an alternative $tt$ sample generated with the POWHEG-BOX generator interfaced with PYTHIA.

The uncertainty due to the parton shower and hadronization model is determined by comparing two $tt$ samples generated by ALPGEN, one interfaced with PYTHIA and the other one interfaced with HERWIG. The uncertainty on the amount of initial- and final-state radiation (ISR/FSR) in the simulated $tt$ sample is assessed by comparing ALPGEN events, showered with PYTHIA, with varied amounts of ISR and FSR. As in Ref. [42], the size of the variation is compatible with the recent measurements of additional jet activity in $tt$ events [103]. The $Wt$ normalization is varied within the theoretical uncertainties of the cross-section calculation [86], and the sensitivity to the interference between $Wt$ production and $tt$ production at NLO is studied by comparing the predictions of POWHEG-BOX with the diagram-removal (baseline) and diagram-subtraction schemes [85] [104]. As in Ref. [42], the uncertainty due to the top quark mass is evaluated but not included in the systematic uncertainties, since it would have no significant

**FIG. 1.** Reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels. The prediction for background (blue histogram) plus SM $tt$ production (solid black histogram) and background plus $t\bar{t}$ prediction with no spin correlation (dashed black histogram) is compared to the data and to the result of the fit to the data (red dashed histogram) with the orange band representing the total systematic uncertainty on $f_{SM}$. Both the SM $tt$ and the no spin correlation $t\bar{t}$ predictions are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71] [72] (the theory uncertainty of 7% on this cross section is not displayed). The prediction for $t\bar{t}$ production ($m_{\tilde{t}_1} = 180 \text{ GeV}$ and $m_{\tilde{q}_1} = 1 \text{ GeV}$) normalized to the NLO cross section including next-to-leading-logarithm corrections [101] plus SM $tt$ production plus background is also shown (solid green histogram). The lower plot shows those distributions (except for background only) divided by the SM $tt$ plus background prediction.
impact on the results.

The sizes of the systematic uncertainties in terms of $\Delta f_{SM}$ are listed in Table I. The total systematic uncertainty is calculated by combining all systematic uncertainties in quadrature.

The measured value of $f_{SM}$ for the combined fit is $1.20 \pm 0.05$ (stat) $\pm 0.13$ (syst). This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41, 42], and compares to the best previous measurement using $\Delta \phi$ of $f_{SM} = 1.19 \pm 0.09$ (stat) $\pm 0.18$ (syst) [42]. It also agrees with the SM prediction to within two standard deviations.

This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41, 42] and agrees with the SM prediction to within two standard deviations. An indirect extraction of $A_{helicity}$ can be achieved by assuming that the $t\bar{t}$ sample is composed of top quark pairs as predicted by the SM, but with varying spin correlation. In that case, a change in the fraction $f_{SM}$ leads to a linear change of $A_{helicity}$ (see also Ref. [42]), and a value of the spin correlation strength in the helicity basis $A_{helicity}$ at a center-of-mass energy of 8 TeV is obtained by applying the measured value of $f_{SM}$ as a multiplicative factor to the SM prediction of $A_{helicity}^{SM} = 0.318 \pm 0.005$ [36]. This yields a measured value of $A_{helicity} = 0.38 \pm 0.04$.

The measurement of the variable $\Delta \phi$ is also used to search for top squark pair production with $\tilde{t}_1 \to t \tilde{\chi}_1^0$ decays. The present analysis is sensitive both to changes in the yield and to changes in the shape of the $\Delta \phi$ distribution caused by a potential admixture of $\tilde{t}_1 \tilde{t}_1$ with the SM $t\bar{t}$ sample. An example is shown in Fig. 1, where the effect of $\tilde{t}_1 \tilde{t}_1$ production in addition to SM $t\bar{t}$ production and backgrounds is compared to data. No evidence for $\tilde{t}_1 \tilde{t}_1$ production was found.

Limits are set on the top squark pair-production cross section by fitting each bin of the $\Delta \phi$ distribution to the difference between the data and the SM prediction, varying the top squark signal strength $\mu$. In contrast to the measurement of $f_{SM}$ where the $t\bar{t}$ cross section is varied in the fit, here the $t\bar{t}$ cross section is fixed to its SM value [71]. In addition, a systematic uncertainty of 7% is introduced, composed of factorization and renormalization scale variation, top quark mass uncertainty, PDF uncertainty and uncertainty in the measurement of the beam energy. All other sources of systematic uncertainty are identical to ones in the measurement of $f_{SM}$. All shape-dependent modeling uncertainties on the SUSY signal are found to be negligible. The limits are determined using a profile likelihood ratio in the asymptotic limit [105], using nuisance parameters to account for the theoretical and experimental uncertainties.

![Graphical representation of expected and observed limits at 95% CL on the top squark pair-production cross section as a function of $m_{\tilde{t}_1}$ for pair-produced top squarks $\tilde{t}_1$ decaying with 100% branching ratio via $t \to t \chi_1^0$ to predominantly right-handed top quarks, assuming $m_{\chi_1^0} = 1$ GeV. The black dotted line shows the expected limit with $\pm 1$ (green) and $\pm 2$ (green-yellow) standard deviation contours, taking into account all uncertainties. The red dashed line shows the theoretical cross section with uncertainties. The solid black line gives the observed limit.](att:graph.png)
pair-production cross section at the 95% confidence level (CL) are extracted using the CLs prescription \cite{106} and are shown in Fig. 2. Adopting the convention of reducing the estimated SUSY production cross section by one standard deviation of its theoretical uncertainty (15%, coming from PDFs and QCD scale uncertainties \cite{107}), top squark masses between the top quark mass and 191 GeV are excluded, assuming a 100% branching ratio for $t\bar{t} \rightarrow t\tilde{\chi}_1^0$ and $m_{\tilde{\chi}_1^0} = 1$ GeV. The expected limit is 178 GeV. In the presented range of $m_{\tilde{\chi}_1}$, within the allowed phase space, varying the neutralino mass does not affect the cross-section limits by more than a few percent. If the top quarks are produced with full left-handed polarization, the expected limits change by less than 10% compared to the predominantly right-handed case.

If the $t\bar{t}$ cross-section normalization were arbitrary and not fixed to its theory prediction, the expected cross-section limit would increase by approximately 30%. If, on the other hand, the shape information of $\Delta\phi$ are not used in the fit, the expected cross-section limit would increase by 30-40%.

The constraints on the top squark mass presented here improve previous limits in a region not explored before, to top squark masses larger than limits from Ref. \cite{64} and to top squark masses lower than limits from analyses exploring kinematic distributions as presented in Ref. \cite{61}.

In conclusion, the first measurement of $t\bar{t}$ spin correlation in proton–proton scattering at a center-of-mass energy of 8 TeV at the LHC has been presented using 20.3 fb$^{-1}$ of ATLAS data in the dilepton decay topology. A template fit is performed to the $\Delta\phi$ distribution and the measured value of $f_{SM} = 1.20 \pm 0.05$ (stat) $\pm 0.13$ (syst) is consistent with the SM prediction. This represents the most precise measurement to date. The results have been used to search for pair-produced supersymmetric top squarks decaying to top quarks and light neutralinos. Assuming 100% branching ratio for the decay $t\bar{t} \rightarrow t\tilde{\chi}_1^0$, and the production of predominantly right-handed top quarks, top squark masses between the top quark mass and 191 GeV are excluded at 95% CL, which is an improvement over previous constraints.

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; SSTC, Belarus; CPNP 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, DNSRC 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; RGC, Hong Kong SAR, China; 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 Walsenberg 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.

\begin{thebibliography}{99}
\bibitem{17} M. Beneke \emph{et al.}, \emph{In Geneva 1999, Standard model physics and more at the LHC}, 419-529, arXiv:hep-ph/0003033.
\bibitem{19} V. D. Barger, J. Ohnemus and R. J. Phillips, Int. J. Mod.
\end{thebibliography}

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Istanbul Aydin University, Istanbul; (d) Division of Physics, TOBB University of Economics and Technology, 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 of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
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, 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 of America
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) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, Universität Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJJ), 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 of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Bucharest, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) 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 of America
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; (e) Physics Department, Shanghai Jiao Tong University, Shanghai.
Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
87 Department of Physics, McGill University, Montreal QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
95 Group of Particle Physics, University of Montreal, Montreal QC, Canada
96 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
100 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102 Nagasaki Institute of Applied Science, Nagasaki, Japan
103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
104 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
108 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York NY, United States of America
111 Ohio State University, Columbus OH, United States of America
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
114 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
115 Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
117 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
123 Petersburg Nuclear Physics Institute, Gatchina, Russia
124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
126 (a) Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma; Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre; Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l’Énergie des Sciences Techniques Nucléaires, Rabat; Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Cape Town, Cape Town; Department of Physics, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University; The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto ON, Canada

TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ICTP, Trieste; Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana IL, United States of America

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

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

Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel