Measurement of the mass difference between top and anti-top quarks in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV using the ATLAS detector

The ATLAS Collaboration

Abstract

A measurement of the mass difference between top and anti-top quarks is presented. In a 4.7 fb\(^{-1}\) data sample of proton–proton collisions at \( \sqrt{s} = 7 \) TeV recorded with the ATLAS detector at the LHC, events consistent with \( tt \) production and decay into a single charged lepton final state are reconstructed. For each event, the mass difference between the top and anti-top quark candidate is calculated. A two \( b \)-tag requirement is used in order to reduce the background contribution. A maximum likelihood fit to these per-event mass differences yields \( \Delta m \equiv m_t - m_{\bar{t}} = 0.67 \pm 0.61 \text{(stat)} \pm 0.41 \text{(syst)} \) GeV, consistent with CPT invariance.
measurement of the mass difference between top and anti-top quarks in pp collisions at √s = 7 TeV using the ATLAS detector

Abstract

A measurement of the mass difference between top and anti-top quarks is presented. In a 4.7 fb⁻¹ data sample of proton–proton collisions at √s = 7 TeV recorded with the ATLAS detector at the LHC, events consistent with t ¯t production and decay into a single charged lepton final state are reconstructed. For each event, the mass difference between the top and anti-top quark candidate is calculated. A two b-tag requirement is used in order to reduce the background contribution. A maximum likelihood fit to these per-event mass differences yields ∆m ≡ mt − m ¯t = 0.67 ± 0.61(stat) ± 0.41(syst) GeV, consistent with CPT invariance.

1. Introduction

The CPT symmetry [1] required by a locally gauge-invariant quantum field theory dictates that the masses of all particles and their anti-particles be exactly equal. Any deviation from this would have major implications for particle physics, implying a non-local field theory [1]. Searches for CPT violation both in the B meson sector [2, 3, 4, 5] and with K mesons [6, 7, 8] have not yielded any deviations from the Standard Model (SM). The top quark has the unique property of decaying before hadronization, making it the only quark for which a direct measurement of its mass is possible. The CDF Collaboration measured the mass difference between top and anti-top quarks to be ∆m ≡ mt − m ¯t = 3.3 ± 1.4 ± 1.0 GeV [9], approximately 2 standard deviations away from zero. The D0 Collaboration measured ∆m = 0.8 ± 1.8 ± 0.5 GeV [10], in agreement with the SM value. The CMS Collaboration recently measured ∆m = −0.44 ± 0.46 ± 0.27 GeV [11], also in agreement with the SM value. The CDF and D0 analyses used both the top and anti-top quarks within each event to measure ∆m. The CMS measurement, the masses of the top and anti-top quarks with hadronic W boson decays are extracted from two separate samples, split using the lepton charge, and subtracted from one another. In this Letter, the ATLAS Collaboration presents a measurement of this mass difference. The top and anti-top quarks are each taken from the same event, in which a t ¯t pair is produced and decays in the lepton+jets channel.

2. ATLAS detector

ATLAS [12] is a general-purpose particle physics detector with cylindrical geometry covering nearly the entire solid angle around the collision point. Cylindrical coordinates (r, φ) are used in the transverse plane, where φ is the azimuthal angle around the beam pipe. The pseudorapidity is defined as η ≡ −ln tan(θ/2), where θ is the polar angle. The transverse mass (mT) of any two objects is defined as mT ≡ √2E1T E2T (1 − cos ∆φ), where Ei is the object’s transverse energy, defined in the plane transverse to the beam axis.

The inner detector (ID) systems, located closest to the interaction region, are immersed in a 2 T axial magnetic field and provide charged particle tracking in the range |η| < 2.47. The ID systems consist of a high-granularity silicon pixel detector and a silicon microstrip detector, as well as a transition radiation tracker. Located outside the solenoid, electromagnetic calorimetry is provided by barrel and endcap lead/liquid-argon calorimeters, and hadronic calorimetry by the steel/scintillating-tile sampling calorimeters in the central region, and liquid-argon calorimeters in the endcap/forward regions. Comprising separate trigger and high-precision tracking chambers, the muon

---

3CPT is the combination of three symmetries; Charge conjugation (C), Parity (P) and Time reversal (T).
spectrometer measures the deflection of muons in a magnetic field with a field integral from $2\text{–}8\ \text{T}\cdot\text{m}$, generated by one barrel and two endcap superconducting air-core toroids. A three-level trigger system is used to select and record interesting events. The level-1 hardware trigger uses a subset of detector information to reduce the event rate resulting from the peak LHC bunch crossing rate of $20\ \text{MHz}$ in 2011 to a value of at most $65\ \text{kHz}$. The level-1 trigger is followed by two software-based trigger levels, level-2 and the event filter, which together reduce the event rate to a few hundred Hz for permanent storage and offline analysis.

3. Data sample and event selection

This analysis uses $4.7\pm0.2\ \text{fb}^{-1}$ of proton–proton collision data recorded by the ATLAS experiment at $\sqrt{s} = 7\ \text{TeV}$ in 2011. The selected events used in this analysis must contain the signature of a $t\bar{t}$ event decaying in the lepton+jets channel. Exactly one charged lepton is required – either a single electron with $E_{T} > 25\ \text{GeV}$, or a single muon with $p_{T} > 20\ \text{GeV}$, where $p_{T}$ is the object’s transverse momentum, defined in the plane transverse to the beam axis. Energy deposits are selected as electron candidates based on their shower shapes in the electromagnetic calorimeters and on the presence of a good-quality track pointing to them. Electron candidates are required to pass the “tight” quality cuts described in Ref. [13], to fall inside a well-instrumented region of the detector, and to be well isolated from other objects in the event. Muons are required to pass “tight” muon quality cuts [15, 16, 17], to be well measured in both the ID and the muon spectrometer, and to be isolated from other objects in the event. Events with an electron (muon) are required to have been triggered by an electron (muon) trigger with an $E_{T}$ ($p_{T}$) threshold of $20\ (18)\ \text{GeV}$. The selection requirements ensure that triggered events are on the trigger efficiency plateau [15, 19].

Jets are reconstructed in the calorimeter using the anti-$k_{t}$ algorithm [20, 21] with a radius parameter of 0.4, starting from energy deposits grouped into noise-suppressed topological clusters [22, 23]. Jets are required to satisfy $p_{T} > 25\ \text{GeV}$ and $|\eta| < 2.5$. Events with jets arising from problematic regions in the calorimeters, beam backgrounds and cosmic rays are rejected [24]. Additional corrections are applied after the default ATLAS jet energy calibration [24] to restore on average the partonic energies in $t\bar{t}$ events. Jets from the decay of long-lived heavy-flavor hadrons are selected by using a multivariate tagging algorithm (b-tagging) [25–26]. The transverse momentum of neutrinos is inferred from the magnitude of the missing transverse momentum ($E_{T}^{\text{miss}}$) [27].

In addition to the requirement of exactly one charged lepton, the signal selection for this analysis requires four or more jets, at least two of which must be $b$-tagged. The selected lepton is required to match a trigger object that caused the event to be recorded. To suppress backgrounds from multi-jet events, $E_{T}^{\text{miss}}$ must be larger than 30 (20) GeV in the electron (muon) channel. Further reduction of the multi-jet background in the electron channel is achieved by requiring the transverse mass ($m_{T}$) of the lepton and $E_{T}^{\text{miss}}$ to be $>30\ \text{GeV}$. In the muon channel, $E_{T}^{\text{miss}} + m_{T} > 60\ \text{GeV}$ is required.

4. Simulated samples and background estimation

The ATLAS detector simulation [28], based on Geant4 [29], is used to process simulated signal and background events. Simulated minimum bias collisions are overlaid on top of the hard scatter process, and events are reweighted so that the distribution of the average number of interactions (typically 5–20, see Ref. [30]) per bunch crossing matches the distribution observed in data.

Simulated samples of $t\bar{t}$ events are produced using $\text{Pythia}$ v6.425 [31] with $\Delta m$ ranging from $-15\ \text{GeV}$ to $+15\ \text{GeV}$. In total, 15 such samples are used, with decreasing granularity at large $|\Delta m|$. Near $\Delta m = 0$, the granularity is 0.3 GeV. In these samples, the average top quark mass ($m_{t}$) is set to 172.5 GeV. The underlying-event tune used is AUE2B [32], and the parton distribution function (PDF) set is MRST [33]. Despite being a leading order generator, $\text{Pythia}$ is used because it allows generation of events where the masses of the top and anti-top quarks are not equal. Non-zero widths as predicted by the SM for the corresponding top and anti-top quark masses are included in the event generation.

Pseudo-experiments and additional checks for systematic uncertainties are performed with a SM $t\bar{t}$ sample with $\Delta m = 0$ generated using $\text{MC@NLO}$ [34].

\begin{itemize}
  \item In total, 15 signal samples were generated with a $\Delta m$ of $\pm 15, \pm 10, \pm 5, \pm 3, \pm 1, \pm 0.6, \pm 0.3$ and 0 GeV.
\end{itemize}
5. Kinematic fits

In order to measure a quantity sensitive to the mass difference $\Delta m$ between the top and anti-top quarks, the kinematic $\chi^2$ fitter described below is used to reconstruct the $t\bar{t}$ system from the observed lepton, $E_T^{miss}$ and jets. The assignment of the selected jets to the partons from the $t\bar{t}$ decay uses knowledge of the over-constrained $t\bar{t}$ system with the reconstructed top/anti-top quark mass difference ($\Delta m^{fit}$) as a free parameter in each event. In the kinematic fitter, the $p_T$ of the lepton and jets is allowed to fluctuate within uncertainties determined from simulated $t\bar{t}$ events. The average top quark mass is fixed, but the individual $t$ and $\bar{t}$ masses are allowed to fluctuate while being constrained by the predicted top quark width. The masses of the two reconstructed $W$ bosons are also allowed to vary within the $W$ boson width. The fit is applied by examining all jet–parton assignments (from among the five leading jets) consistent with the $b$-jet assignment and minimizing the following $\chi^2$:

$$
\chi^2 = \sum_{i=e,\mu,\tau,4 jets} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_T^{j,\text{fit}} - p_T^{j,\text{meas}})^2}{\sigma_{E_T}} + \sum_{k=jj,E_W} \frac{(m_k^{\text{meas}} - m_W^{(2)})^2}{\sigma_W^2} + \sum_{i=jj,E_W} \frac{(m_{bji}^{\text{meas}} - m_{bji}^{(2)})^2}{\sigma_{\Delta m}^2},
$$

where $p_T^{i,\text{fit}}$ and $p_T^{i,\text{meas}}$ are the fitted and measured $p_T$ of the jets and the charged lepton, and $\sigma_i$ is the uncertainty on those values. The unclustered energy in the calorimeter ($E_T$) is defined as a quantity that includes all energy not associated with the primary lepton or the jets and is used to correct $E_T^{miss}$. The width of the $W$ boson ($\sigma_W$) is set to the PDG value [12], and the top quark width ($\sigma_t$) is set to the value predicted from theory. The top quark mass ($m_t$) is fixed to 172.5 GeV, and the $W$ boson mass ($m_W$) is set to $m_W = 80.42$ GeV. The value of $m_t^{fit}$ is the fitted dijet (lepton–neutrino) mass from the hadronic (leptonic) $W$ boson decay, and $m_{bji}^{fit}$ and $m_{bji}^{meas}$ are the fitted top quark masses with leptonically and hadronically decaying $W$ bosons. The value of the mass difference between the hadronic- and leptonic-side top quarks is a free parameter in the fit. In each event, the single jet–parton assignment with the lowest $\chi^2$ is used, and the fitted value of $\Delta m^{fit}$ is taken as an observable to measure the true $\Delta m$. As seen in Eq. (2), $\Delta m$ is calculated from the product of the lepton charge ($q_\ell$) and the difference between $m_{bji}^{fit}$ and $m_{bji}^{meas}$. Events with $\chi^2 > 10$ for the best jet–parton assignment are considered to be poorly measured or background, and are rejected. The value of this cut is chosen based on studies of simulated signal events, and the efficiency of the $\chi^2$ selection is estimated in simulation to be 55% for $t\bar{t}$ signal events and 31% for background events. Table [1] shows the expected and observed number...
of events after all selection requirements, including the $\chi^2$ cut, are applied.

Distributions of $\Delta m^{\text{fit}}$ are produced for all background samples as well as for a number of simulated $t\bar{t}$ samples generated with different $\Delta m$.

The $\Delta m^{\text{fit}}$ distributions in the signal samples are parameterized in templates by fitting the sum of two Gaussians, where the narrow one corresponds to the correct jet–parton pairing, and the wide one corresponds to an incorrect pairing. The widths of the two Gaussians are quadratic functions of $\Delta m$ (symmetric about $\Delta m = 0$). The means of the two Gaussians are fit to linear functions of $\Delta m$. The relative weight of the two Gaussians is fit to a quadratic function symmetric about $\Delta m = 0$.

Fig. (1) shows the parameterization for five different values of $\Delta m$. The $\Delta m^{\text{fit}}$ distributions for all background samples are combined with relative weights according to the SM prediction, into a single template distribution that is fit with a Gaussian, as shown in Fig. (2). The choice of background parameterization has only a small impact on the fits due to the small background in the double $b$-tag channel. The signal and background templates are used to model the probability density distributions in $\Delta m$.

6. Likelihood fit

An unbinned extended maximum likelihood fit to the distribution of $\Delta m^{\text{fit}}$ is performed to extract $\Delta m$, as well as the expected number of signal ($n_s$) and background ($n_b$) events in the data. Given the data $D$, which contain $N$ values of $\Delta m^{\text{fit}}$, the probability distribution function for signal ($p_s$) and background ($p_b$) are used to write down a likelihood ($L$):

$$L(D|n_s, n_b, \Delta m) = q(N, n_s + n_b) \times \prod_{i=1}^{N} \frac{n_s p_s(\Delta m^{\text{fit},i}|\Delta m) + n_b p_b(\Delta m^{\text{fit},i})}{n_s + n_b}$$

where $q(N, n_s + n_b)$ is the Poisson probability to observe $N$ events given $n_s + n_b$ expected events and the product over $i$ is over the $N$ reconstructed events. The likelihood is maximized over all three parameters ($n_s$, $n_b$, $\Delta m$). Ensembles of pseudo-experiments are run to ensure that the fits are unbiased and return correct statistical uncertainties. The widths of pull distributions are consistent with unity. Due to the use of PYTHIA to generate templates and MC@NLO to run ensemble tests, a 175 MeV offset is applied to all pseudo-experiments (and to the nominal fit result) to return an unbiased measurement, with the statistical uncertainty of 50 MeV on this calibration taken as a systematic uncertainty. The 175 MeV offset is the average difference between the mc@nlo samples with the top and anti-top quark masses reweighted to the distributions in PYTHIA for a given mass difference. When running pseudo-experiments, events are drawn directly from the simulated samples and not from the parameterizations in order to check for any potential bias.

The extended maximum likelihood fit is applied to the full 2011 dataset, yielding the result shown in Fig. (3). The value of 175 MeV quoted above is subtracted from the result to correct for this bias, giving a measured top/anti-top quark mass difference of $m_t - m_{\bar{t}} = 0.67 \pm 0.61(\text{stat})$. The $\chi^2$ per
Systematic Uncertainty & $\Delta(\Delta m) \ [\text{GeV}]$
\hline
$b/b$ decay uncertainties & 0.34 \\
$K^+/K^-$ calorimeter response asymmetry & 0.08 \\
Residual $b$ vs $\bar{b}$ differences & 0.08 \\
b-tagging & 0.08 \\
Mis-tagging as a $b$-quark jet & 0.05 \\
Jet energy scale & 0.04 \\
b-jet energy scale & 0.05 \\
Jet energy resolution & 0.03 \\
Parton shower & 0.08 \\
MC generator & 0.08 \\
ISR/FSR & 0.07 \\
Calibration method & 0.05 \\
Non-\(t\bar{t}\) normalization & 0.04 \\
Non-\(t\bar{t}\) shape & 0.04 \\
Parton distribution function & 0.02 \\
Lepton energy scale asymmetry & < 0.01 \\
Electron reconstruction & 0.02 \\
& identification & 0.04 \\
Muon reconstruction & 0.04 \\
& identification & 0.04 \\
Top mass input & 0.04 \\
Total & 0.41 \\
\hline
Table 2: Systematic uncertainties.

Fig. 2: Parameterized background template.

Fig. 3: Reconstructed top/anti-top quark mass difference with the best maximum likelihood fit for signal and background overlaid.

degree of freedom for Fig. 3 is 1.2.

7. Systematic uncertainties

Due to cancellations from measuring the mass difference and not the individual quark masses, most systematic effects yield small uncertainties on the final measurement. Systematic uncertainties are evaluated by performing pseudo-experiments with pseudo-data that reflect a variation due to the potential source of uncertainty considered, and comparing the extracted $\Delta m$ to the one obtained with default pseudo-data. A list of all systematic uncertainties and their effects on the measurement are summarized in Table 2. The total systematic uncertainty of 0.41 GeV on the measured $\Delta m$ is dominated by the uncertainty from the choice of $b$ fragmentation model, which can induce different detector response to jets from $b$- and $\bar{b}$-quarks in simulation. The various systematic uncertainties are discussed in more detail below.

Systematic uncertainties on $\Delta m$ due to differences in the detector response to jets from $b$- and $b$-quarks are difficult to evaluate with in-situ methods in the $t\bar{t}$ environment due to correlations with $\Delta m$. Based on the evaluation of the jet energy scale uncertainty from single-hadron response measurements, most differences between the jet energy scale uncertainty from single-hadron response measurements, most differences between the calorimeter response to the two types of jets are expected to be small; exceptions are discussed below. One such difference could come from the different responses to positively and negatively charged kaons, which occur at different rates in jets from $b$- and $b$- quarks. The interaction cross sections for $K^+$ and $K^-$ in the calorimeters are different. Such effects are studied by comparing convolutions of the kaon spectra in $b$- and $b$-jets from $t\bar{t}$ events with the expected calorimeter response to kaons simulated with various hadron shower simulation models, as specified in Ref. [43]. The resulting uncertainty is 80 MeV. Uncertainties due to fragmentation and the decay of
b-hadrons can also lead to uncertainties in the particle content and hadron momentum spectra, and thus in the calorimeter response. This uncertainty is evaluated by comparing \textsc{powheg} samples that use \textsc{evtgen} and \textsc{pythia} to decay b-hadrons, and is estimated to be 340 MeV. The \textsc{evtgen} particle decay simulation implements different hadron decay models and up-to-date b-hadron decay tables. An additional 80 MeV is assigned to account for any residual difference in response between jets from b and b quarks due to effects not considered above. Parton shower and additional fragmentation uncertainties are estimated by comparing \textsc{powheg} samples interfaced with \textsc{herwig} to those interfaced with \textsc{pythia}.

Other uncertainties are small compared to those from differences between jets from b- and \overline{b}-quarks. The uncertainty on \( \Delta m \) from the uncertainty on the b-tagging efficiency is measured by varying the b-tag scale factors, which correct simulated efficiencies to those measured in data, within 1\( \sigma \) of their uncertainties. The systematic effects from uncertain light- and b-jet energy scales and resolutions are small, as they affect the top and anti-top quark masses in the same way \[45, 46\]. Generator uncertainties are estimated by comparing pseudo-experiments using \textsc{mc@nlo} and \textsc{powheg}. A systematic uncertainty on the amount of QCD radiation is derived from \textsc{acermc} \( t\bar{t} \) samples that have varying amounts of initial- and final-state radiation \[47\]. Uncertainties from the template parameterization are estimated by varying the parameters within their uncertainties, and are found to be small. The systematic uncertainties due to background shape and rate are estimated by replacing the W+jets background used in pseudo-experiments with the shape from the multi-jet background and by varying the normalization within uncertainties. A small systematic uncertainty due to the parton distribution functions of the proton is evaluated by taking the envelope of the MSTW2008NLO \[48\], NNPDF2.3 \[49\] and CTEQ6.6 \[50\] PDF set uncertainties, following the PDF4LHC recommendations \[51\]. Asymmetries due to lepton energy scales are negligible. A systematic uncertainty on the top quark mass of 40 MeV is estimated by comparing pseudo-experiments where the input average top quark mass is shifted up and down by 1.5 GeV. Other systematic uncertainties considered are those caused by the uncertainty on the lepton identification and reconstruction.

8. Conclusions

The analysis described in this Letter is the first measurement by ATLAS of the mass difference between the top and anti-top quarks using event-by-event quantities in \( t\bar{t} \) events. It is based on 4.7 \( fb^{-1} \) of 7 TeV proton–proton collisions at the LHC. The mass difference, \( \Delta m \), is calculated using a kinematic \( \chi^2 \) fitter. The measured mass difference is \( \Delta m \equiv m_t - m_{\bar{t}} = 0.67 \pm 0.61 \) (stat) \( \pm 0.41 \) (syst) GeV, consistent with the SM expectation of no mass difference.

9. Acknowledgements

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; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CERN, China; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DAE, India; BMBF, DFG and MPG, Germany; INFN, Italy; INFN, Italy; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; NRC and ¯{b}r, Korea; LNSM, Latvian Academy of Sciences, Latvia; MEES, Lithuania; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZS, 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.

References

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) Division of Physics, TOBB University of Economics and Technology, Ankara; (d) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States 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, University of 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 COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, 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, Physics Department, 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, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 INFN Laboratori Nazionali di Frascati, Frascati, Italy
47 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
48 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
49 Physics Department, Southern Methodist University, Dallas TX, United States of America
50 INFN Laboratori Nazionali di Frascati, Frascati, Italy
51 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
52 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
53 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
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 of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Louisiana Tech University, Ruston LA, United States of America
79 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
80 Fysiska institutionen, Lunds universitet, Lund, Sweden
125 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
129 State Research Center Institute for High Energy Physics, Protvino, Russia
130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
131 Physics Department, University of Regina, Regina SK, Canada
132 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l’Énergie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Department of Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (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
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) 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 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
and CNRS/IN2P3, Paris, France

* Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India

ab Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

ac Also at 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

ad Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ae Also at Section de Physique, Université de Genève, Geneva, Switzerland

af Also at Departamento de Física, Universidade de Minho, Braga, Portugal

ag Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

ah Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

ai Also at DESY, Hamburg and Zeuthen, Germany

aj Also at International School for Advanced Studies (SISSA), Trieste, Italy

ak Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

al Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

am Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

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

ao Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

ap Also at Department of Physics, Oxford University, Oxford, United Kingdom

aq Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

ar Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

as Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased