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Permalink
https://escholarship.org/uc/item/3bp9t2b4

Journal
Physical Review Letters, 120(16)

ISSN
0031-9007

Authors
Aaboud, M
Aad, G
Abbott, B
et al.

Publication Date
2018-04-20

DOI
10.1103/PhysRevLett.120.161802

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Peer reviewed
Search for High-Mass Resonances Decaying to $\tau\nu$ in $pp$ Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

The ATLAS Collaboration

A search for high-mass resonances decaying to $\tau\nu$ using proton–proton collisions at $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider is presented. Only $\tau$-lepton decays with hadrons in the final state are considered. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb$^{-1}$. No statistically significant excess above the standard model expectation is observed; model-independent upper limits are set on the visible $\tau\nu$ production cross section. Heavy $W'$ bosons with masses less than 3.7 TeV in the sequential standard model and masses less than 2.2–3.8 TeV depending on the coupling in the non-universal $G(221)$ model are excluded at the 95% credibility level.
Heavy charged gauge bosons ($W'$) appear frequently in theories of physics beyond the standard model (SM). They are often assumed to obey lepton universality, such as in the sequential standard model (SSM) [1], which predicts a $W'_{\text{SSM}}$ boson with couplings identical to those of the SM $W$ boson. However, this assumption is not required. In particular, models in which the $W'$ boson couples preferentially to third-generation fermions may be linked to the high mass of the top quark [2–5] or to recent indications of lepton flavor universality violation in $B$ meson decays [6, 7]. An example is the non-universal $G(221)$ model (NU) [4, 5], which exhibits a $SU(2)_l \times SU(2)_h \times U(1)$ gauge symmetry, where $SU(2)_l$ couples to light fermions (first two generations), $SU(2)_h$ couples to heavy fermions (third generation) and $\phi_{\text{NU}}$ is the mixing angle between them. The model predicts $W'_{\text{NU}}$ and $Z'_{\text{NU}}$ bosons which are approximately degenerate in mass and couple only to left-handed fermions. At leading order and neglecting sign, the $W'_{\text{NU}}$ couplings to heavy (light) fermions are scaled by $\cot\phi_{\text{NU}}$ ($\tan\phi_{\text{NU}}$) relative to those of $W'_{\text{SSM}}$. Thus $\cot\phi_{\text{NU}} > 1$ corresponds to enhanced couplings to tau leptons while $\cot\phi_{\text{NU}} = 1$ yields $W'_{\text{NU}}$ couplings identical to those of $W'_{\text{SSM}}$. For $Z'_{\text{NU}}$, the coupling to heavy (light) fermions is given by $g \cot\phi_{\text{NU}}$ ($g \tan\phi_{\text{NU}}$), where $g$ is the SM weak coupling constant. At high values of $\cot\phi_{\text{NU}}$, the branching fraction of $W'_{\text{NU}}$ to a tau lepton ($\tau$) and a neutrino ($\nu$) approaches 26%.

In this Letter, a search for high-mass resonances (0.5–5 TeV) decaying to $\tau\nu$ using proton–proton ($pp$) collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider (LHC) is presented. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of $36.1 \text{ fb}^{-1}$. Only $\tau$ decays with hadrons in the final state are considered; these account for 65% of the total $\tau$ branching fraction. A counting experiment is performed from events that pass a high transverse-mass threshold, optimized separately for each of the signal mass hypotheses.

A direct search for high-mass resonances decaying to $\tau\nu$ has been performed by the CMS Collaboration using $19.7 \text{ fb}^{-1}$ of integrated luminosity at $\sqrt{s} = 8$ TeV [8]. The search excludes $W'_{\text{SSM}}$ with a mass below 2.7 TeV at the 95% credibility level and $W'_{\text{NU}}$ with a mass below 2.7–2.0 TeV for $\cot\phi_{\text{NU}}$ in the range 1.0–5.5. The most stringent limit on $W'_{\text{SSM}}$ from searches in the $e\nu$ and $\mu\nu$ final states is $5.1 \text{ TeV}$ from ATLAS [9] using $36.1 \text{ fb}^{-1}$ of integrated luminosity at $\sqrt{s} = 13$ TeV.

The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry [10, 11]. It consists of an inner detector for charged-particle tracking in the pseudorapidity region $|\eta| < 2.5$, electromagnetic and hadronic calorimeters that provide energy measurements up to $|\eta| = 4.9$, and a muon spectrometer that covers $|\eta| < 2.7$. A two-level trigger system is used to select events [12].

Hadronic $\tau$ decays are composed of a neutrino and a set of visible decay products ($\tau_{\text{had-vis}}$), typically one or three charged pions and up to two neutral pions. The reconstruction of the visible decay products [13] is seeded by jets reconstructed from topological clusters of energy depositions [14] in the calorimeter. The $\tau_{\text{had-vis}}$ candidates must have a transverse momentum $p_T > 50 \text{ GeV}$, $|\eta| < 2.4$ (excluding $1.37 < |\eta| < 1.52$), one or three associated tracks and an electric charge of $\pm 1$. Only the candidate with the highest $p_T$ in each event is selected. Hadronic $\tau$ decays are identified using boosted decision trees that exploit calorimetric shower shape and tracking information [15, 16]. Loose criteria are used, which offer adequate rejection against quark- and gluon-initiated jets. Very loose criteria, with about one quarter of the rejection power, are used to create control regions. An additional dedicated veto is used to reduce the number of electrons misidentified as $\tau_{\text{had-vis}}$. The total efficiency for $\tau_{\text{had-vis}}$ is $\sim 60\%$ at $p_T = 100 \text{ GeV}$ and decreases to $\sim 30\%$ at $p_T = 2 \text{ TeV}$, where the large boost and collimation of the decay products causes inefficiencies in the track reconstruction and association.

Events containing electron or muon candidates are rejected. Electron candidates [17–19] must have $p_T > 20 \text{ GeV}$, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$) and must pass a loose likelihood-based
identification selection. Muon candidates [20] are required to have non-perturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

Table 1: The event generators and other software packages used to generate the matrix-element process and model non-perturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>Matrix Element</th>
<th>Non-perturbative</th>
<th>Refs.</th>
</tr>
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<tbody>
<tr>
<td>W/Z/γ∗</td>
<td>Powheg-Box 2, CT10, PHOTOS+ 3.52</td>
<td>Pythia 8.186, AZNLO, CTEQ6L1, EvtGen 1.2.0</td>
<td>[28–36]</td>
</tr>
<tr>
<td>t¯t</td>
<td>Powheg-Box 2, CT10</td>
<td>Pythia 6.428, P2012, CTEQ6L1, EvtGen 1.2.0</td>
<td>[37–39]</td>
</tr>
<tr>
<td>Single top</td>
<td>Powheg-Box 1, CT10, MadSpin</td>
<td>Pythia 6.428, P2012, CTEQ6L1, EvtGen 1.2.0</td>
<td>[40–43]</td>
</tr>
<tr>
<td>Diboson</td>
<td>Sherpa 2.1.1, CT10</td>
<td>Sherpa 2.1.1</td>
<td>[44–48]</td>
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</table>

Events are selected by triggers that require $E_T^{miss}$ above thresholds of 70, 90 or 110 GeV depending on the data-taking period. To minimize uncertainties in the trigger efficiency, the offline reconstructed $E_T^{miss}$ is required to be at least 150 GeV. At this threshold the trigger efficiency is 80% and increases to more than 98% above 250 GeV. This behavior is determined by the $E_T^{miss}$ resolution of the trigger, which is lower than in the offline reconstruction. The events must satisfy criteria designed to reduce backgrounds from cosmic rays, single-beam-induced events and calorimeter noise [24] and they must contain a loose $\tau$ had-vis candidate. To further suppress single-beam-induced background, the $E_T^{miss}$ must have at least one associated track with $p_T > 10$ GeV. The multijet background is further suppressed by requiring that the $\tau$ had-vis $p_T$ and the $E_T^{miss}$ are balanced: $0.7 < p_T / E_T^{miss} < 1.3$. The azimuthal angle between the $\tau$ had-vis and the missing momentum, $\Delta \phi$, is required to be larger than 2.4. Finally, thresholds ranging from 0.25 TeV to 1.8 TeV in steps of 0.05 TeV are placed on the transverse mass, $m_T$, where $m_T^2 = 2 E_T^{miss} (1 - \cos \Delta \phi)$.

The background is divided into events where the selected $\tau$ had-vis originates from a quark- or gluon-initiated jet (jet background) and those where it does not (non-jet background). The jet background originates primarily from W/Z+jets and multijet production and is estimated using a data-driven technique. The non-jet background is estimated using simulation and originates primarily from $W \rightarrow \tau \nu$ production with additional minor contributions from $W/Z/\gamma^*$, $t\bar{t}$, single top-quark and diboson ($WW$, $WZ$ and $ZZ$) production (collectively called others).

The event generators and other software packages used to produce the simulated samples are summarized in Table 1. The $W/Z/\gamma^*$ sample is artificially enhanced in high-mass events to improve statistical coverage in the scanned mass range. Particle interactions with the ATLAS detector are simulated with Geant4 [25, 26] and contributions from additional $pp$ interactions (pileup) are simulated using Pythia 8.186 and the MSTW2008LO parton distribution function (PDF) set [27]. Finally, the simulated events are processed through the same reconstruction software as the data. Corrections are applied to account for mismodeling of the momentum scales and resolutions of reconstructed objects, the $E_T^{miss}$ reconstruction and identification efficiency, the electron to $\tau$ had-vis misidentification rate and the $E_T^{miss}$ trigger efficiency.

The simulated samples are normalized using the integrated luminosity of the collected dataset and their theoretical cross sections. The $W/Z/\gamma^*$ cross sections are calculated as a function of the boson mass at next-to-next-to-leading order (NNLO) [49] using the CT14NNLO PDF set, including electroweak corrections at next-to-leading order (NLO) [50] using the MRST2004QED PDF set [51]. Uncertainties are taken from Ref. [52] and include variations of the PDF sets, scale, $a_S$, beam energy and electroweak

### Table 1: The event generators and other software packages used to generate the matrix-element process and model non-perturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

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corrections. The variations amount to a ~5% total uncertainty in the $W/Z/\gamma^*$ cross section at low mass, increasing to 34% at 2 TeV. The $t\bar{t}$ and single top-quark production cross sections are calculated to at least NLO with an uncertainty of 3–6% [53–56]. The diboson cross sections are calculated to NLO with an uncertainty of 10% [44, 57].

The simulated samples are affected by uncertainties associated with the generation of the events, the detector simulation and the determination of the integrated luminosity. Uncertainties related to the modeling of the hard scatter, radiation and fragmentation are at most 2% of the total background estimate. Uncertainties in the detector simulation manifest themselves through the efficiency of reconstruction, identification and triggering algorithms, and through particle energy scales and resolutions. The effects of energy uncertainties are propagated to total energy uncertainties are propagated to trigger efficiency is negligible for $p_T < 150$ GeV in accord with studies of high-$p_T$ jets [58]. The uncertainty in the $\tau_{\text{had}}$ energy scale is 2–3%. The probability for electrons to be misidentified as $\tau_{\text{had}}$ measured with a precision of 3–14% [16]. The uncertainty in the $E_T^{\text{miss}}$ trigger efficiency is negligible for $E_T^{\text{miss}} > 300$ GeV and can be as large as 10% for $E_T^{\text{miss}} < 300$ GeV. Uncertainties associated with reconstructed electrons, muons and jets are found to have a very small impact. The uncertainty in the combined 2015+2016 integrated luminosity is 2.1%, derived following a methodology similar to that used in Ref. [59], and has a minor impact. The uncertainty related to the simulation of pileup is ~1%.

The $W'$ signal events are modeled by reweighting the $W$ sample using a leading-order matrix-element calculation. Electroweak corrections for the $W$ cross section and interference between $W$ and $W'$ are not included as they are model dependent. Uncertainties in the $W'$ cross section are estimated in the same way as for $W$ bosons. They are not included in the fitting procedure used to extract experimental cross-section limits, but are instead included when overlaying predicted model cross sections. Uncertainties in the $W'$ acceptance due to PDF, scale, and $\alpha_S$ variations are negligible. In the NU model, the total decay width increases to 35% of the pole mass for large values of $\cot \phi_{\text{NU}}$, which decreases the signal acceptance as more events are produced at low mass. Decays to $WZ$ and $Wh$ are not considered in the calculation of the total $W'_{\text{NU}}$ decay width as their impact is small (< 7%) and model dependent. Values of $\cot \phi_{\text{NU}} > 5.5$ are not considered as the model is non-perturbative in this range.

The jet background contribution is estimated using events in three control regions (CR1, CR2 and CR3). The events must pass the selection for the signal region, except in CR1 and CR3 they must fail loose but pass very loose $\tau_{\text{had}}$ identification and in CR2 and CR3 they must have $E_T^{\text{miss}} < 100$ GeV and the requirement on $p_T^\tau/E_T^{\text{miss}}$ is removed. The low-$E_T^{\text{miss}}$ requirement yields high multijet purity in CR2 and CR3, while the very loose identification preferentially rejects gluon-initiated jets over quark-initiated jets. This produces a similar fraction of quark-initiated jets in all control regions, which ensures minimal correlation between the identification and $E_T^{\text{miss}}$. The estimated jet contribution is defined as: $N_{\text{jet}} = N_{\text{CR1}}/N_{\text{CR2}}/N_{\text{CR3}}$. The non-jet contamination in CR1 (10%), CR2 (3.7%) and CR3 (0.5%) is subtracted using simulation. The transfer factor, $N_{\text{CR2}}/N_{\text{CR3}}$, is parameterized in $\tau_{\text{had}}$ $p_T$ and track multiplicity and is in the range 0.4–0.7 (0.15–0.3) for 1-track (3-track) $\tau_{\text{had}}$. Systematic uncertainties are assigned to account for any residual correlation between the transfer factor and the $E_T^{\text{miss}}$ and $p_T^\tau/E_T^{\text{miss}}$ selection criteria, which would arise if the jet composition was different in CR1 and CR3. They are evaluated by repeating the jet estimate with the following modified control region definitions: (a) altered very loose $\tau_{\text{had}}$ identification criteria, (b) modified $E_T^{\text{miss}}$ and $p_T^\tau/E_T^{\text{miss}}$ selection, and (c) CR2 and CR3 replaced by alternative control regions rich in $W(\rightarrow \mu
u)+$jets events. The corresponding variations define the dominant uncertainty in the jet background contribution, which ranges from 20% at $m_T = 0.2$ TeV to ~200% at $m_T = 2$ TeV, where the
Figure 1 shows the observed $m_T$ distribution of the data after event selection, including the estimated SM background contributions and predictions for $W'_\text{SSM}$ and $W'_\text{NU}$ ($\cot\phi_{\text{NU}} = 5.5$) bosons with masses of 3 TeV. The number of observed events is consistent with the expected SM background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau\nu$. The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Figure 2 as a function of the $m_T$ threshold.

Limits are set at the 95% credibility level (CL) using the Bayesian Analysis Toolkit [60]. Figure 3 shows the model-independent upper limits on the visible $\tau\nu$ production cross section, $\sigma(pp \to \tau\nu + X)A\epsilon$, as a function of the $m_T$ threshold, where $A$ is the fiducial acceptance (including the $m_T$ threshold) and $\epsilon$ is the reconstruction efficiency. Model-specific limits can be derived by evaluating $\sigma$, $A$ and $\epsilon$ for the model in question and checking if the corresponding visible cross section is excluded at any $m_T$ threshold. This
Figure 2: Dominant relative uncertainties in the expected signal and background contributions as a function of the \( m_T \) threshold. For each threshold a \( W'_\text{SSM} \) boson with a mass of approximately 1.7 times the threshold is chosen. \textit{Theory} includes uncertainties in the cross sections used to normalize the simulated samples and uncertainties associated with the modeling provided by the event generators. \textit{Other} is the impact of all other uncertainties added in quadrature.

allows the results to be reinterpreted for a broad range of models, regardless of their \( m_T \) distribution. Good agreement between the generated and reconstructed \( m_T \) distributions is found, indicating that a reliable calculation of the \( m_T \) threshold acceptance can be made at generator level. The reconstruction efficiency depends on \( m_T, \epsilon(m_T [\text{TeV}]) = 0.633 - 0.313m_T + 0.0688m_T^2 - 0.00575m_T^3 \), ranging from 60\% at 0.2 TeV to 7\% at 5 TeV, and must be appropriately integrated out given the \( m_T \) distribution of the model. The relative uncertainty in the parameterized efficiency due to the choice of signal model is \( \sim 10\% \). With these inputs the visible cross sections for \( W'_\text{SSM} \) and \( W'_\text{NU} \) bosons could be reproduced within 10\% using only generator-level information. Data and details to facilitate reinterpretations can be found at Ref. [61].

Limits are also set on benchmark models by selecting the most sensitive \( m_T \) threshold for each \( W' \) mass hypothesis (\( \sim 0.6m_{W'} \) up to a maximum of 1.45 TeV). The chosen threshold is found to have little dependence on the \( W' \) width. Figure 4(a) shows the 95\% CL upper limit on the cross section times branching fraction as a function of \( m_{W'} \) in the SSM. Heavy \( W'_{\text{SSM}} \) bosons with a mass lower than 3.7 TeV are excluded, with an expected exclusion limit of 3.8 TeV. Figure 4(b) shows the excluded region in the parameter space of the non-universal \( G(221) \) model. Heavy \( W'_{\text{NU}} \) bosons with a mass lower than 2.2–3.8 TeV are excluded depending on \( \cot \phi_{\text{NU}} \), thereby probing a significantly larger region of parameter space than previous searches [8]. The \( W'_{\text{NU}} \) limits are typically weaker than the \( W'_{\text{SSM}} \) limits as the increased \( W' \) width yields lower acceptances, while the enhancement in the decay rate cancels with the suppression in the production via first- and second-generation quarks. Limits from the ATLAS ee, \( \mu\mu \) and \( \tau\tau \) searches [58, 62] are also overlaid, showing that the \( \tau\tau \) search is complementary and extends the sensitivity over a large fraction of the parameter space. These results suggest that the \( \tau\nu \) searches should be considered when placing limits on non-universal extended gauge groups, such as those seeking to explain lepton flavor violation in \( B \) meson decays.
Figure 3: The 95% CL upper limit on the visible $\tau\nu$ production cross section as a function of the $m_T$ threshold.

Figure 4: (a) The 95% CL upper limit on the cross section times $\tau\nu$ branching fraction for $W'_{SSM}$. The $W'_{SSM}$ cross section is overlaid where the additional lines represent the total theoretical uncertainty. (b) Excluded region for $W'_{NU}$. The 95% CL limits from the ATLAS $ee$, $\mu\mu$ [62] and $\tau\tau$ [58] searches and indirect limits at 95% CL from fits to electroweak precision measurements (EWPT) [63], lepton flavor violation (LFV) [64], CKM unitarity [65] and the original $Z$-pole data [2] are overlaid.
In summary, a search for $W' \rightarrow \tau \nu$ in 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC is presented. The channel where the $\tau$ decays hadronically is analyzed and no significant excess over the SM expectation is found. Upper limits are set on the visible cross section for $\tau \nu$ production, allowing interpretation in a broad range of models. Sequential standard model $W'_{SSM}$ bosons with masses less than 3.7 TeV are excluded at 95% CL, while non-universal $G(221) W'_{NU}$ bosons with masses less than 2.2–3.8 TeV are excluded depending on the model parameters.

**Acknowledgments**

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; 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 and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [66].

**References**


[11] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2).


The ATLAS Collaboration

E. Valdes Santurio, M. Valente, S. Valentini, A. Valero, L. Valéry,
R.A. Vallance, A. Vallier, J.A. Valls Ferrer, T.R. Van Daalen, W. Van Den Wollenberg,
H. van der Graaf, P. van Gemmeren, J. Van Nieuwkoop, I. van Vulpen, M.C. van Woerden,
M. Vanadia, W. Vandelli, A. Vaniach, P. Vankov, R. Varri, E.W. Varnes,
C. Varni, D. Varol, D. Varouchas, A. Vartapetian, K.E. Varvell, J.G. Vasquez,
G.A. Vasquez, F. Vazeeille, D. Vazquez Furelos, T. Vazquez Schroeder, J. Vetach,
V. Vecchio, L.M. Velocci, F. Veloso, S. Veneziano, A. Ventura,
M. Venturi, N. Venturi, V. Vercesi, M. Verducci, C. Vergis, W. Verkerk,
A.T. Vermeulen, J.C. Vermeulen, M.C. Vetterli, N. Viaux Maira, O. Viazlo,
I. Vickou, T. Vickey, O.E. Vickey Boeri, G.H.A. Viehhauser, S. Viel, L. Vignati,
M. Villa, M. Villaplana Perez, E. Viluchii, G. Vincter, V.B. Vinogradov,
A. Vishwakarma, G. Vittori, I. Vivarelli, S. Vlachos, M. Vogel, P. Vokac, G. Volpi,
S.E. von Buddenbrock, E. von Toerne, J. Vorobel, K. Vorobiev, M. Vos, J.H. Vossebeek,
N. Vranjes, M. Vranjes Milosavljevic, V. Vrbas, M. Vreeswijk, R. Vuillermet,
I. Vukotic, P. Wagner, W. Wagner-Kühn, H. Wahlberg, S. Wahrmund, K. Wakamiya,
J. Walder, R. Walker, W. Walkowiak, V. Wallangen, A.M. Wang, C. Wang, Y. Wang,
F. Wang, H. Wang, H. Wang, J. Wang, J. Wang, Q. Wang, R. Wang, R. Wang,
R. Wang, S.M. Wang, T. Wang, W. Wang, Y. Wang, Y. Wang,
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S. Wenig, N. Werner, M.D. Werner, P. Werner, M. Wessels, T.D. Weston, K. Whalen,
N.L. Whallon, A.M. Wharton, A.S. White, A. White, M.J. White, R. White, D. Whiteson,
B.W. Whitmore, F.J. Wickens, W. Wiedenmann, M. Wiegler, C. Wiglesworth,
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M.W. Wolter, H. Wolters, V.W.S. Wong, N.L. Woods, S.D. Worm, B.K. Wosiek,
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E. Yatsenko, K.H. Yau Watson, J.F. Ye, S. Ye, Y. Ye, I. Yeletskikh, E. Yigitbasi, E. Yıldırım,
K. Yorita, K. Yoshihara, C. Young, C.J.S. Young, J. Yu, J. Yu, J. Xu, Y. Xue, S.P.Y. Yuen,
I. Yusuf, B. Zabiniski, G. Zacharis, R. Zaidan, A.M. Zaitsev, N. Zakharchuk,
J. Zalieckas, S. Zambito, D. Zanzi, C. Zeitzsch, G. Zemaityte, J.C. Zeng, Q. Zeng,
O. Zenin, T. Zeni, D. Zerwas, M. Zgubić, D. Zhang, D. Zhang, H. Zhang, J. Zhang,
R. Zhang, Z. Zhang, Z. Zhang, L. Zhang, L. Zhang, M. Zhang, P. Zhang, P. Zhang,
Z. Zhang, X. Zhang, Y. Zhang, Z. Zhang, Z. Zhang, X. Zhao, Y. Zhao, Z. Zhao,
A. Zibell, D. Ziemińska, I. Zimine, S. Zimmermann, Z. Zinonos, M. Zinser,
M. Ziolkowski, L. Živković, G. Zobernig, A. Zoccoli, K. Zoch, T.G. Zorbas,
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) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy, 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, National and Kapodistrian University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, The University of Texas at Austin, Austin TX, United States of America
12 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
14 Institute of Physics, University of Belgrade, Belgrade, Serbia
15 Department for Physics and Technology, University of Bergen, Bergen, Norway
16 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
17 Department of Physics, Humboldt University, Berlin, Germany
18 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (d) Bosphorus University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston MA, United States of America
25 Department of Physics, Brandeis University, Waltham MA, United States of America
26 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
28 (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (e) University Politehnica Bucharost, Bucharost; (f) West University in Timisoara, Timisoara, Romania
29 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31 Department of Physics, Carleton University, Ottawa ON, Canada
32 CERN, Geneva, Switzerland
33 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
35 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Physics, Nanjing University, Jiangsu; (c) Physics Department, Tsinghua University, Beijing; (d) University of Chinese Academy of Science (UCAS), Beijing, China
36 (a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui; (b) School of Physics, Shandong University, Shandong; (c) School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University; (d) Tsung-Dao Lee Institute, Shanghai, China
37 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
38 Nevis Laboratory, Columbia University, Irvington NY, United States of America
39 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
40 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
41 (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
42 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
43 Physics Department, Southern Methodist University, Dallas TX, United States of America
44 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
45 DESY, Hamburg and Zeuthen, Germany
46 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
47 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
48 Department of Physics, Duke University, Durham NC, United States of America
49 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
50 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
51 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
52 Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
53 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
54 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
55 II. Physikalisches Institut, Justus-Liebig-Universität, Giessen, Germany
56 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
57 LPSC, Université Grenoble Alpes, CNRS-IN2P3, Grenoble INP, Grenoble, France
58 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
59 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
60 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
61 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
62 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
63 Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
64 Department of Physics, Indiana University, Bloomington IN, United States of America
65 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

25
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15 and CIAFF, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli; Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
Department of Physics, University of Coimbra, Coimbra, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
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, Rabat, Morocco
Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université
Mohammed V, Rabat, Morocco
138 Institut de Recherches sur les Lois Fondamentales de l’Univers, DSM/IRFU, CEA Saclay, Gif-sur-Yvette, France
139 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
140 Department of Physics, University of Washington, Seattle WA, United States of America
141 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
142 Department of Physics, Shinshu University, Nagano, Japan
143 Department Physik, Universität Siegen, Siegen, Germany
144 Department of Physics, Simon Fraser University, Burnaby BC, Canada
145 SLAC National Accelerator Laboratory, Stanford CA, United States of America
146 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
147 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
148 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
149 Physics Department, Royal Institute of Technology, Stockholm, Sweden
150 Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
151 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
152 School of Physics, University of Sydney, Sydney, Australia
153 Institute of Physics, Academia Sinica, Taipei, Taiwan
154 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
155 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
156 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
157 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
158 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
159 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
160 Tomsk State University, Tomsk, Russia
161 Department of Physics, University of Toronto, Toronto ON, Canada
162 (a) INFN-TIFPA; (b) University of Trento, Trento, Italy
163 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
164 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
165 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
166 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
167 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
168 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
169 Department of Physics, University of Illinois, Urbana IL, United States of America
170 Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
171 Department of Physics, University of British Columbia, Vancouver BC, Canada

28
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
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
a Also at Department of Physics, King’s College London, London, United Kingdom
b 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 and Astronomy, University of Louisville, Louisville, KY, United States of America
f Also at Department of Physics, California State University, Fresno CA, United States of America
g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
h Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
i Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
j Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
k Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
l Also at Universita di Napoli Parthenope, Napoli, Italy
m Also at Institute of Particle Physics (IPP), Canada
n Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
a Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania
p Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
r Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America
s Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
t Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa
u Also at Louisiana Tech University, Ruston LA, United States of America
v Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
w Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
x Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
y Also at Graduate School of Science, Osaka University, Osaka, Japan
z Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
aa Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
ab Also at Near East University, Nicosia, North Cyprus, Mersin 10, Turkey
ac Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
Also at CERN, Geneva, Switzerland

Also at Georgian Technical University (GTU), Tbilisi, Georgia

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan

Also at Manhattan College, New York NY, United States of America

Also at Hellenic Open University, Patras, Greece

Also at The City College of New York, New York NY, United States of America

Also at Departamento de Fisica Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain

Also at Department of Physics, California State University, Sacramento CA, United States of America

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

Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland

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

Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

Also at School of Physics, Sun Yat-sen University, Guangzhou, China

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

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

Also at National Research Nuclear University MEPhI, Moscow, Russia

Also at Department of Physics, Stanford University, Stanford CA, United States of America

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

Also at Giresun University, Faculty of Engineering, Turkey

Also at Department of Physics, Nanjing University, Jiangsu, China

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

Also at Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

* Deceased