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The ATLAS Collaboration

**Abstract**

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# Search for Quantum Black Hole Production in High-Invariant-Mass Lepton+Jet Final States Using $pp$ Collisions at $\sqrt{s} = 8$ TeV and the ATLAS Detector

The ATLAS Collaboration

This Letter presents a search for quantum black-hole production using  $20.3 \text{ fb}^{-1}$  of data collected with the ATLAS detector in  $pp$  collisions at the LHC at  $\sqrt{s} = 8$  TeV. The quantum black holes are assumed to decay into a final state characterized by a lepton (electron or muon) and a jet. In either channel, no event with a lepton-jet invariant mass of 3.5 TeV or more is observed, consistent with the expected background. Limits are set on the product of cross sections and branching fractions for the lepton+jet final states of quantum black holes produced in a search region for invariant masses above 1 TeV. The combined 95% confidence level upper limit on this product for quantum black holes with threshold mass above 3.5 TeV is 0.18 fb. This limit constrains the threshold quantum black-hole mass to be above 5.3 TeV in the model considered.

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Quantum black holes (QBHs) [1, 2] are predicted in low-scale quantum gravity theories that offer solutions to the mass hierarchy problem of the Standard Model (SM) by lowering the scale of quantum gravity ( $M_D$ ) from the Planck scale ( $\sim 10^{16}$  TeV) to a value of about 1 TeV. In models with large extra dimensions such as the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [3–5], only the gravitational field is allowed to penetrate the  $n$  extra dimensions, while all SM fields are localized in the usual four-dimensional space-time. QBHs with masses near  $M_D$ , postulated to conserve total angular momentum, color and electric charge, may decay to two particles [2, 6]. The behavior of QBHs is distinct from semi-classical black holes that decay via Hawking radiation to a large number of objects [7]. Searches for semi-classical black holes typically require three or more objects [8, 9].

The quantum approximations used in the modeling of black hole production are valid when black-hole masses are above a minimal threshold mass,  $M_{\text{th}}$ , which is taken to be equivalent to the QBH inverse gravitational radius. If the QBHs investigated in this Letter are accessible at the Large Hadron Collider (LHC) [10], they can produce lepton+jet final states [2, 6] motivating this first dedicated search for high-invariant-mass final states with a single electron ( $e$ ) or a single muon ( $\mu$ ), and at least one jet. Two-particle QBH decays to a final state consisting of a lepton and a quark-jet violate lepton and baryon number conservation, producing a distinctive signal for physics beyond the SM. Previous searches for QBHs relied on signatures such as dijet mass distributions [11, 12], generic multiobject configurations [9] and photon+jet final states [13].

The largest QBH cross section for the final states considered is predicted for the collision of two  $u$ -quarks ( $\sigma_{uu}$ ), which produces charge  $+4/3$  objects with equal branching fractions (BFs) of  $\text{BF}_{uu} = 11\%$  to each lepton+jet final state. The next largest cross sections are for charge  $+1/3$  ( $ud$ ) and  $-2/3$  ( $dd$ ) QBHs with lepton+jet BFs of  $\text{BF}_{ud} = 5.7\%$  and  $\text{BF}_{dd} = 6.7\%$  [6]. Processes with initial states having antiquarks and heavier sea-

quarks are suppressed by at least a factor of 100 and can be neglected. The QBH cross section is a steeply declining function of  $M_{\text{th}}$ , and has  $\Sigma\sigma_{\text{qq}} \times \text{BF}_{\text{qq}} \approx 8.6 \times 10^5$  fb,  $8.9 \times 10^2$  fb and 0.75 fb for  $M_{\text{th}}$  of 1 TeV, 3 TeV and 5 TeV, respectively [14].

The ATLAS detector [15] includes an inner tracker, covering a pseudorapidity [16] range  $|\eta| < 2.5$ , surrounded by a superconducting solenoid providing a 2 T central field. A liquid-argon (LAr) electromagnetic (EM) sampling calorimeter ( $|\eta| < 3.2$ ), a scintillator-tile hadronic calorimeter ( $|\eta| < 1.7$ ), a LAr hadronic calorimeter ( $1.4 < |\eta| < 3.2$ ), and a LAr forward calorimeter ( $3.1 < |\eta| < 4.9$ ) provide the energy measurements. The muon spectrometer consists of tracking chambers covering  $|\eta| < 2.7$ , and trigger chambers covering  $|\eta| < 2.4$ , in a magnetic field produced by a system of air-core toroids. Events considered in this analysis are required to have one high-transverse-momentum (high- $p_T$ ) lepton ( $e/\mu$ ) that passes requirements of the three-level trigger system [17]. The thresholds applied at the third trigger level are 60 GeV and 36 GeV for electrons and muons, respectively. The analysis is based on the complete 2012 data set of  $pp$  collisions taken at a center-of-mass energy of  $\sqrt{s} = 8$  TeV by the ATLAS detector at the LHC, corresponding to an integrated luminosity of  $20.3 \pm 0.6 \text{ fb}^{-1}$  [18] after data-quality requirements.

The event selection is designed to be efficient for generic lepton+jet final states and is based on leading-order simulated-signal QBH events obtained from the QBH1.04 generator [14], followed by parton showering and hadronization using PYTHIA8.165 [19]. The signal generator uses the MSTW2008LO [20] set of leading-order parton distribution functions (PDFs) with the AU2 underlying-event tune [21]. This Letter assumes the ADD model with  $M_{\text{th}} = M_D$ ,  $n = 6$ , and the QCD factorization scale for the PDFs set to the inverse gravitational radius [14]. Samples with  $M_{\text{th}}$  from 1 TeV to 6 TeV, in steps of 0.5 TeV, are generated for both channels.

Events with a high- $p_T$  lepton and one or more jets can also arise from electroweak (EW) processes includ-

ing vector-boson production with additional jets; diboson ( $WW, WZ, ZZ$ ), top-quark pair ( $t\bar{t}$ ) and single top-quark ( $t$  or  $\bar{t}$ ) production; and multijet processes including non-prompt leptons from semileptonic hadron decays and jets misidentified as leptons.

The EW background in the signal region (SR) is estimated using Monte Carlo (MC) samples normalized to data in control regions. All MC simulated samples are produced using the ATLAS detector simulation [22] based on GEANT4 [23]. The simulated events are reconstructed in the same manner as the data. The  $t\bar{t}$  and single-top-quark events are simulated with MC@NLO4.06 [24] and AcerMC3.8 [25], respectively; the production of  $W$ +jets and  $Z$ +jets is simulated using ALPGEN2.14 [26]; and diboson production is simulated with SHERPA1.4.1 [27]. The leading-order CTEQ6L1 PDFs [28] are used for ALPGEN and AcerMC samples while the next-to-leading-order CT10 PDFs [29] are used for the SHERPA and MC@NLO samples. The generators for all samples except dibosons are interfaced to HERWIG6.520 [30, 31] for parton showering and hadronization and to JIMMY4.31 [32] for the underlying-event model. The results of higher-order calculations are used to adjust the relative fractions of the simulated events as in Refs. [33, 34]. Additional inelastic  $pp$  interactions, termed pileup, are included in the event simulation so as to match the distribution in the data (on average 21 interactions per bunch crossing).

Electron candidates are identified as localized depositions of energy in the EM calorimeter with  $p_{T_e} > 130$  GeV and  $|\eta| < 2.47$ , excluding the barrel-endcap transition region,  $1.37 < |\eta| < 1.52$ , and matched to a track reconstructed in the tracking detectors. Background from jets is reduced by requiring that the shower profiles are consistent with those of electrons [35]. Isolated electrons are selected by requiring the transverse energy deposited in a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  centered on the electron cluster, excluding the energy of the electron cluster itself, to be less than  $0.0055 \times p_{T_e} + 3.5$  GeV after corrections for energy due to pileup and energy leakage from the electron cluster into the cone. This criterion provides nearly constant selection efficiency for signal events over the entire  $p_{T_e}$  range explored and for all the pileup conditions.

Muon candidates are required to be detected in at least three layers of the muon spectrometer and to have  $p_{T_\mu} > 130$  GeV and  $|\eta| < 2.4$ . Possible background from cosmic rays is reduced by requiring the transverse and longitudinal distances of closest approach to the interaction point to be smaller than 0.2 mm and 1.0 mm, respectively. Signal muons are required to be isolated such that  $\sum p_T < 0.05 \times p_{T_\mu}$ , where  $\sum p_T$  is the sum of the  $p_T$  of the other tracks in a cone of radius  $\Delta R = 0.3$  around the direction of the muon.

Jets are constructed from three-dimensional noise-suppressed clusters of calorimeter cells using the anti- $k_t$

algorithm with a radius parameter of 0.4 [36, 37]. Jet energies are corrected for losses in material in front of the active calorimeter layers, detector inhomogeneities, the non-compensating nature of the calorimeter, and pileup. Jet energies are calibrated using MC simulation and the combination of several in-situ techniques applied to data [38–40]. All jets are required to have  $p_{T_j} > 50$  GeV and  $|\eta| < 2.5$ . In addition, the most energetic jet is required to have  $p_{T_j} > 130$  GeV.

The missing transverse momentum (with magnitude  $E_T^{\text{miss}}$ ), used only in the background estimation, is calculated as the negative of the vectorial sum of calibrated clustered energy deposits in the calorimeters, and is corrected for the momenta of any reconstructed muons [41].

In the electron (muon) channel, events are required to have exactly one electron (muon). Multijet background can be reduced, with minimal loss in signal efficiency, by requiring the average value of  $\eta$  for the lepton and leading jet to satisfy  $|\langle\eta\rangle| < 1.25$  and the difference between the lepton and leading jet  $\eta$  to satisfy  $|\Delta\eta| < 1.5$ . The signal lepton and jet are mostly back-to-back in  $\phi$  and are required to satisfy  $|\Delta\phi| > \pi/2$ .

The invariant mass ( $m_{\text{inv}}$ ) is calculated from the lepton and highest- $p_T$  jet. The SR is defined by a lower bound on  $m_{\text{inv}}$ ,  $m_{\text{min}}$ , that accounts for experimental resolution. In the electron channel  $m_{\text{min}} = 0.9M_{\text{th}}$  is used. In the muon channel, the requirement is loosened at high invariant mass, as muon resolution has a term quadratic in  $p_{T_\mu}$ , resulting in  $m_{\text{min}} = [0.95 - 0.05M_{\text{th}}/1\text{TeV}] M_{\text{th}}$ . A low-invariant-mass control region (LIMCR) is defined with  $m_{\text{inv}}$  between 400 GeV and 900 GeV, which has a negligible contamination from a potential signal ( $< 2\%$ ) for the lowest  $M_{\text{th}}$  considered.

The acceptance of the event selection is about 65%, based on generator-level quantities and calculated by imposing selection criteria that apply directly to phase space (lepton/jet  $\eta$ , lepton/jet  $p_T$ ,  $\Delta\eta$ ,  $\Delta\phi$ ,  $\langle\eta\rangle$ , and  $m_{\text{inv}}$ ). All other selection criteria, which in general correspond to event and object quality requirements, are used to calculate the experimental efficiency based on the events included in the acceptance. The experimental efficiency falls from 89(59)% to 81(50)% for masses from 1 TeV to 6 TeV in the electron (muon) channel. The experimental efficiency in the muon channel is lower than that in the electron channel because more stringent requirements are applied to ensure the best possible resolution on  $m_{\text{inv}}$ . The cumulative signal efficiency is the product of the acceptance and experimental efficiency.

In the electron channel, the multijet background is characterized by small values of  $E_T^{\text{miss}}$ , while EW background events can have large  $E_T^{\text{miss}}$  due to the production of high-momentum neutrinos. The discriminating power of  $E_T^{\text{miss}}$  is used to determine the normalization of the two backgrounds to the data in the LIMCR. The multijet template is taken from data in which electron candidates pass relaxed identification criteria but fail the normal

identification selection, and the EW template is taken from MC simulation where electron candidates pass the normal selection. The templates are fit to the  $E_T^{\text{miss}}$  distribution in the interval  $[0, 150]$  GeV in five separate detector-motivated regions of  $\eta$ , to determine normalization factors for both the multijet and EW backgrounds.

To extrapolate both the multijet and EW background to the SR, functions of the form  $p_1 x^{p_2+p_3 \ln(x)} (1-x)^{p_4}$  (with  $x = m_{\text{inv}}/\sqrt{s}$  and fit parameters  $p_1-p_4$ ) [42] are used and the contributions are scaled by the corresponding normalization factor derived in the LIMCR. A simple power-law fit, with  $p_3$  and  $p_4$  fixed to zero, adequately describes both data and simulation. This is used as the baseline, while  $p_3$  and  $p_4$  are allowed to vary as part of the evaluation of the systematic uncertainty.

In the muon channel, the multijet and EW backgrounds can be discriminated on the basis of the transverse impact parameter ( $d_0$ ) distribution of the muon since multijet background is dominated by jets containing charm and bottom hadrons decaying to muons while EW backgrounds are dominated by prompt muons. The template for the EW background is selected using  $Z$ -boson decays to two muons while the template for multijet background is taken from muons that fail the isolation requirement. Both templates are taken from data. The templates are fit to the  $d_0$  distribution in the interval  $[-0.1, +0.1]$  mm to determine the normalization factors. The fraction of multijet background,  $0.046 \pm 0.005$ , is neglected when extrapolating the background in SR. The procedure for extrapolating the EW background to the SR is the same as for the electron channel.

The background estimate in the SR, shown in Fig. 1, was not compared to data until the final fit method and parameters were fixed. The hatched area in Fig. 1 shows the total uncertainty in the background estimate, which is dominated by the systematic uncertainties. In extracting the limits, the fits described above are used to extrapolate the background into the high invariant-mass region.

The systematic uncertainties on the background are evaluated as a function of  $m_{\text{inv}}$ , and are dominated by uncertainties on the fits used to extrapolate the background to the highest  $m_{\text{inv}}$ , uncertainties on PDFs, and the choice of MC generator. Systematic uncertainties due to the choice of fitting functions are evaluated by fitting the  $m_{\text{inv}}$  spectrum with parameters  $p_3$  and  $p_4$  free and taking the difference between these fits and the fits with  $p_3$  and  $p_4$  fixed to zero. Additionally, SHERPA samples are used instead of ALPGEN and the fits are repeated. The uncertainty in the PDFs is estimated using a set of 44 PDF eigenvectors for CTEQ6.6 [43]. For each of the 44 sets, the background fits are repeated and the extrapolated backgrounds are estimated. To estimate the uncertainty in the multijet background in the electron channel, an alternative selection of background-enriched data events, based on photons, is used. The systematic uncer-

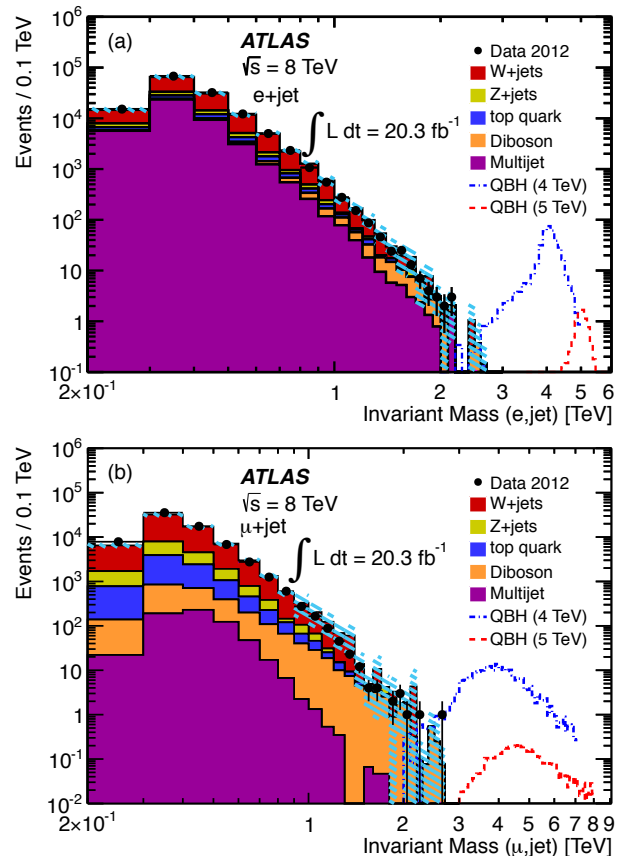


FIG. 1. Distribution of the invariant mass of the lepton and highest- $p_T$  jet in (a) the electron+jet channel and (b) the muon+jet channel, for data (points with error bars) and for SM backgrounds (solid histograms). Overlaid are two examples of QBH signals. The sum of the uncertainties due to the finite MC sample size and from various sources of systematic uncertainty is shown by the hatched area. To extract the upper limit on the lepton+jet cross section, a fit to the invariant-mass distribution is performed, replacing the uncertainties due to MC sample size by the statistical uncertainties on the fit parameters.

tainties from the simulation of the detector response are associated with the jet and electron energy scales and resolutions, the muon momentum scale and resolution, and the trigger requirement. The combined uncertainty in the background prediction ranges from 16% (1 TeV) to 100% (6 TeV) for the electron channel and from 50% (1 TeV) to 170% (6 TeV) for the muon channel. Background systematic uncertainties for  $M_{\text{th}} = 5$  TeV are given in Table I.

Uncertainties on the signal efficiency in each of the mass bins are associated with the requirements on  $\Delta\eta$ ,  $\Delta\phi$ ,  $\langle\eta\rangle$ ,  $m_{\text{inv}}$ , and isolation. In addition, uncertainties on the detector simulation, mentioned above for the background, as well as the uncertainty in luminosity are taken into account. The combined uncertainty in the signal efficiency from these sources ranges from 3.5% at 1 TeV to

TABLE I. Breakdown of relative systematic uncertainties on the SM background for the threshold mass  $M_{\text{th}} = 5$  TeV. The uncertainties are added in quadrature to obtain the total uncertainty.

Source	Electron+jet		Muon+jet	
	%		%	
Lepton reconstruction, scale and resolution	+2	-1	+30	-7
Jet reconstruction, scale and resolution	+31	-15	+5	-5
Multijet modeling	+27	-27	-	-
PDF	+52	-33	+100	-69
Fit	+77	-77	+130	-71
Total	+100	-89	+170	-100

TABLE II. Numbers of expected background (Exp.) and observed (Obs.) events, along with the cumulative signal efficiencies (Eff.), with uncertainties including both the statistical and systematic components for various values of  $M_{\text{th}}$ . Numbers of events are integrated above  $m_{\text{inv}}$  requirement for the given  $M_{\text{th}}$ .

$M_{\text{th}}$	Electron+jet			Muon+jet		
	Obs.	Exp.	Eff.	Obs.	Exp.	Eff.
TeV	%			%		
1.0	1200	$1210^{+230}_{-220}$	$57 \pm 4$	620	$550 \pm 280$	$38 \pm 4$
1.5	100	$110 \pm 40$	$57 \pm 4$	49	$65^{+45}_{-40}$	$36 \pm 4$
2.0	12	$19^{+13}_{-12}$	$56 \pm 4$	8	$14^{+16}_{-14}$	$36 \pm 4$
2.5	0	$5.3^{+4.5}_{-3.9}$	$55 \pm 4$	3	$5^{+6}_{-5}$	$34 \pm 4$
3.0	0	$1.8^{+1.8}_{-1.6}$	$54 \pm 4$	1	$2.1^{+2.9}_{-2.1}$	$34 \pm 4$
3.5	0	$0.76^{+0.79}_{-0.67}$	$54 \pm 4$	0	$1.0^{+1.6}_{-1.0}$	$33 \pm 4$
4.0	0	$0.35^{+0.38}_{-0.34}$	$53 \pm 4$	0	$0.57^{+0.94}_{-0.57}$	$33 \pm 5$
5.0	0	$0.09^{+0.10}_{-0.09}$	$52 \pm 4$	0	$0.24^{+0.39}_{-0.24}$	$32 \pm 5$
6.0	0	$0.03^{+0.04}_{-0.03}$	$52 \pm 4$	0	$0.13^{+0.22}_{-0.13}$	$32 \pm 6$

3.9% at 6 TeV for the electron channel and from 3.6% at 1 TeV to 5.6% at 6 TeV for the muon channel. The cumulative efficiency, shown in Table II, is taken from the signal MC simulation for charge  $+4/3$  QBHs. The differences in the efficiency between the charge  $+4/3$  state and the other charged states are much smaller than the uncertainties mentioned above and are neglected. The effect of the 0.65% uncertainty in the LHC beam energy [44] is to change the QBH production cross section. Since the QBH cross section is nearly constant in  $M_{\text{th}}/\sqrt{s}$  this is effectively an uncertainty in  $M_{\text{th}}$  and has a negligible effect on the limits.

The observed numbers of events and the expected backgrounds, shown in Table II, are in agreement within the total uncertainty. There is no evidence for any excess. Upper limits on  $\Sigma\sigma_{\text{qq}} \times \text{BF}_{\text{qq}}$  for the produc-

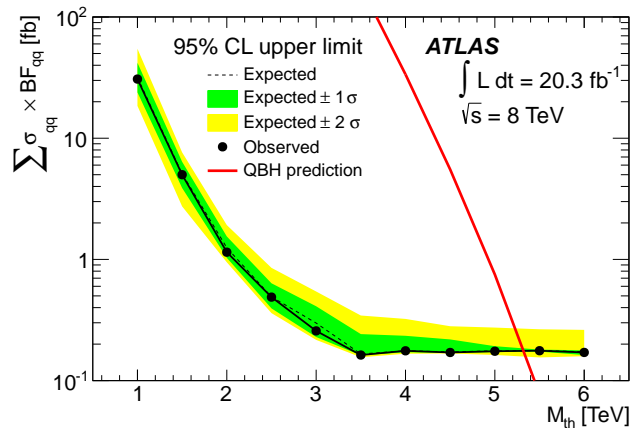


FIG. 2. The combined 95% C.L. upper limits on  $\Sigma\sigma_{\text{qq}} \times \text{BF}_{\text{qq}}$  for QBHs decaying to a lepton and jet, as a function of  $M_{\text{th}}$ , assuming  $M_{\text{D}} = M_{\text{th}}$  and  $n = 6$  ADD extra dimensions. The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. Also shown are the  $\pm 1\sigma$  and  $\pm 2\sigma$  bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The predicted cross section for QBHs is shown as the solid curve.

tion of QBHs above  $M_{\text{th}}$  are determined in the interval 1–6 TeV assuming lepton universality and using the CLs method [45, 46], which is designed to give conservative limits in cases where the observed background fluctuates below the expected values. The statistical combination of the channels employs a likelihood function constructed as the product of Poisson probability terms describing the total number of events observed in each channel. Systematic uncertainties are incorporated as nuisance parameters into the likelihood through their effect on the mean of the Poisson functions and through convolution with their assumed Gaussian distributions. Correlations between channels are taken into account.

Figure 2 shows the 95% confidence level (C.L.) combined lepton+jet upper limit on the cross section times branching fraction for the production of QBHs as a function of  $M_{\text{th}}$ . Above 3.5 TeV, the limit is 0.18 fb. For the  $n = 6$  QBH model assumed in this Letter, the 95% C.L. lower limit on  $M_{\text{th}}$  is 5.3 TeV. For  $n = 2$ , and all other model assumptions the same, the 95% C.L. lower limit on  $M_{\text{th}}$  is 4.7 TeV. Treating the channels separately, the 95% C.L. upper limit on the electron (muon)+jet  $\Sigma\sigma_{\text{qq}} \times \text{BF}_{\text{qq}}$  above 3.5 TeV is 0.27 (0.49) fb, and the  $n = 6$  lower limit on  $M_{\text{th}}$  is 5.2 (5.1) TeV.

In conclusion, a first search for two body lepton+jet final states with large invariant mass has been performed using  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions recorded at  $\sqrt{s} = 8$  TeV with the ATLAS detector at the LHC. In the invariant-mass region above 1 TeV the observed events are consistent with data-driven extrapolated backgrounds from the low-invariant-mass control region. Above 3.5 TeV the ex-

pected background drops below one event and the 95% C.L. upper limit on the electron (muon)+jet  $\Sigma\sigma_{qq} \times \text{BF}_{qq}$  is 0.27 (0.49) fb. Assuming lepton universality, the 95% C.L. upper limit on the sum of the product of QBH lepton+jet production cross sections and branching fractions is 0.18 fb.

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G. Aad<sup>48</sup>, T. Abajyan<sup>21</sup>, B. Abbott<sup>112</sup>, J. Abdallah<sup>152</sup>, S. Abdel Khalek<sup>116</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>106</sup>, B. Abi<sup>113</sup>, M. Abolins<sup>89</sup>, O.S. AbouZeid<sup>159</sup>, H. Abramowicz<sup>154</sup>, H. Abreu<sup>137</sup>, Y. Abulaiti<sup>147a,147b</sup>, B.S. Acharya<sup>165a,165b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, T.N. Addy<sup>56</sup>, J. Adelman<sup>177</sup>, S. Adomeit<sup>99</sup>, T. Adye<sup>130</sup>, S. Aefsky<sup>23</sup>, T. Agatonovic-Jovin<sup>13b</sup>, J.A. Aguilar-Saavedra<sup>125b,b</sup>, M. Agustoni<sup>17</sup>, S.P. Ahlen<sup>22</sup>, A. Ahmad<sup>149</sup>, F. Ahmadov<sup>64,c</sup>, G. Aielli<sup>134a,134b</sup>, T.P.A. Åkesson<sup>80</sup>, G. Akimoto<sup>156</sup>, A.V. Akimov<sup>95</sup>, M.A. Alam<sup>76</sup>, J. Albert<sup>170</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>70</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>64</sup>, C. Alexa<sup>26a</sup>, G. Alexander<sup>154</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>165a,165c</sup>, G. Alimonti<sup>90a</sup>, L. Alio<sup>84</sup>, J. Alison<sup>31</sup>, B.M.M. Allbrooke<sup>18</sup>, L.J. Allison<sup>71</sup>, P.P. Allport<sup>73</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>83</sup>, A. Aloisio<sup>103a,103b</sup>, R. Alon<sup>173</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>70</sup>, A. Altheimer<sup>35</sup>, B. Alvarez Gonzalez<sup>89</sup>, M.G. Alviggi<sup>103a,103b</sup>, K. Amako<sup>65</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, V.V. Ammosov<sup>129,\*</sup>, S.P. Amor Dos Santos<sup>125a</sup>, A. Amorim<sup>125a,d</sup>, S. Amoroso<sup>48</sup>, N. Amram<sup>154</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>30</sup>, L.S. Ancu<sup>17</sup>, N. Andari<sup>30</sup>, T. Andeen<sup>35</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>58a</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>90a,90b</sup>, V. Andrei<sup>58a</sup>, X.S. Anduaga<sup>70</sup>, S. Angelidakis<sup>9</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>108</sup>, N. Anjos<sup>125a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>9</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>97</sup>, J. Antos<sup>145b</sup>, F. Anulli<sup>133a</sup>, M. Aoki<sup>65</sup>, L. Aperio Bella<sup>18</sup>, R. Apolle<sup>119,e</sup>, G. Arabidze<sup>89</sup>, I. Aracena<sup>144</sup>, Y. Arai<sup>65</sup>, A.T.H. Arce<sup>45</sup>, J-F. Arguin<sup>94</sup>, S. Argyropoulos<sup>42</sup>, E. Arik<sup>19a,\*</sup>, M. Arik<sup>19a</sup>, A.J. Armbruster<sup>88</sup>, O. Arnaez<sup>82</sup>, V. Arnal<sup>81</sup>, O. Arslan<sup>21</sup>, A. Artamonov<sup>96</sup>, G. Artoni<sup>23</sup>, S. Asai<sup>156</sup>, N. Asbah<sup>94</sup>, S. Ask<sup>28</sup>, B. Åsman<sup>147a,147b</sup>, L. Asquith<sup>6</sup>, K. 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Baranov<sup>95</sup>, T. Barber<sup>48</sup>, E.L. Barberio<sup>87</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>84</sup>, T. Barillari<sup>100</sup>, M. Barisonzi<sup>176</sup>, T. Barklow<sup>144</sup>, N. Barlow<sup>28</sup>, B.M. Barnett<sup>130</sup>, R.M. Barnett<sup>15</sup>, A. Baroncelli<sup>135a</sup>, G. Barone<sup>49</sup>, A.J. Barr<sup>119</sup>, F. Barreiro<sup>81</sup>, J. Barreiro Guimarães da Costa<sup>57</sup>, R. Bartoldus<sup>144</sup>, A.E. Barton<sup>71</sup>, P. Bartos<sup>145a</sup>, V. Bartsch<sup>150</sup>, A. Bassalat<sup>116</sup>, A. Basye<sup>166</sup>, R.L. Bates<sup>53</sup>, L. Batkova<sup>145a</sup>, J.R. Batley<sup>28</sup>, M. Battistin<sup>30</sup>, F. Bauer<sup>137</sup>, H.S. Bawa<sup>144,g</sup>, T. Beau<sup>79</sup>, P.H. Beauchemin<sup>162</sup>, R. Beccherle<sup>123a,123b</sup>, P. Bechtel<sup>21</sup>, H.P. Beck<sup>17</sup>, K. Becker<sup>176</sup>, S. Becker<sup>99</sup>, M. Beckingham<sup>139</sup>, A.J. Beddall<sup>19c</sup>, A. 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Bruckman de Renstrom<sup>39</sup>, D. Bruncko<sup>145b</sup>, R. Bruneliere<sup>48</sup>, S. Brunet<sup>60</sup>, A. Bruni<sup>20a</sup>, G. Bruni<sup>20a</sup>, M. Bruschi<sup>20a</sup>, L. Bryngemark<sup>80</sup>, T. Buanes<sup>14</sup>, Q. Buat<sup>55</sup>, F. Bucci<sup>49</sup>, P. Buchholz<sup>142</sup>, R.M. Buckingham<sup>119</sup>, A.G. Buckley<sup>46</sup>, S.I. Buda<sup>26a</sup>, I.A. Budagov<sup>64</sup>, B. Budick<sup>109</sup>, F. Buehrer<sup>48</sup>, L. Bugge<sup>118</sup>, M.K. Bugge<sup>118</sup>, O. Bulekov<sup>97</sup>, A.C. Bundock<sup>73</sup>, M. Bunse<sup>43</sup>, H. Burckhart<sup>30</sup>, S. Burdin<sup>73</sup>, B. Burghgrave<sup>107</sup>, S. Burke<sup>130</sup>, I. Burmeister<sup>43</sup>, E. Busato<sup>34</sup>, V. Büscher<sup>82</sup>, P. Bussey<sup>53</sup>, C.P. Buszello<sup>167</sup>, B. Butler<sup>57</sup>, J.M. Butler<sup>22</sup>, A.I. Butt<sup>3</sup>, C.M. Buttar<sup>53</sup>,



J.M. Butterworth<sup>77</sup>, W. Buttinger<sup>28</sup>, A. Buzatu<sup>53</sup>, M. Byszewski<sup>10</sup>, S. Cabrera Urbán<sup>168</sup>, D. Caforio<sup>20a,20b</sup>, O. Cakir<sup>4a</sup>, P. Calafiura<sup>15</sup>, G. Calderini<sup>79</sup>, P. Calfayan<sup>99</sup>, R. Calkins<sup>107</sup>, L.P. Caloba<sup>24a</sup>, R. Caloi<sup>133a,133b</sup>, D. Calvet<sup>34</sup>, S. Calvet<sup>34</sup>, R. Camacho Toro<sup>49</sup>, P. Camarri<sup>134a,134b</sup>, D. Cameron<sup>118</sup>, L.M. Caminada<sup>15</sup>, R. Caminal Armadans<sup>12</sup>, S. Campana<sup>30</sup>, M. Campanelli<sup>77</sup>, A. Campoverde<sup>149</sup>, V. Canale<sup>103a,103b</sup>, F. Canelli<sup>31</sup>, A. Canepa<sup>160a</sup>, J. Cantero<sup>81</sup>, R. Cantrill<sup>76</sup>, T. Cao<sup>40</sup>, M.D.M. Capeans Garrido<sup>30</sup>, I. Caprini<sup>26a</sup>, M. Caprini<sup>26a</sup>, M. Capua<sup>37a,37b</sup>, R. Caputo<sup>82</sup>, R. Cardarelli<sup>134a</sup>, T. Carli<sup>30</sup>, G. 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Chakraborty<sup>107</sup>, I. Chalupkova<sup>128</sup>, K. Chan<sup>3</sup>, P. Chang<sup>166</sup>, B. Chapleau<sup>86</sup>, J.D. Chapman<sup>28</sup>, D. Charfeddine<sup>116</sup>, D.G. Charlton<sup>18</sup>, V. Chavda<sup>83</sup>, C.A. Chavez Barajas<sup>30</sup>, S. Cheatham<sup>86</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>160a</sup>, G.A. Chelkov<sup>64</sup>, M.A. Chelstowska<sup>88</sup>, C. Chen<sup>63</sup>, H. Chen<sup>25</sup>, K. Chen<sup>149</sup>, L. Chen<sup>33d,j</sup>, S. Chen<sup>33c</sup>, X. Chen<sup>146c</sup>, Y. Chen<sup>35</sup>, H.C. Cheng<sup>88</sup>, Y. Cheng<sup>31</sup>, A. Cheplakov<sup>64</sup>, R. Cherkaoui El Moursli<sup>136e</sup>, V. Chernyatin<sup>25,\*</sup>, E. Cheu<sup>7</sup>, L. Chevalier<sup>137</sup>, V. Chiarella<sup>47</sup>, G. Chiefari<sup>103a,103b</sup>, J.T. Childers<sup>30</sup>, A. Chilingarov<sup>71</sup>, G. Chiodini<sup>72a</sup>, A.S. Chisholm<sup>18</sup>, R.T. Chislett<sup>77</sup>, A. Chitan<sup>26a</sup>, M.V. 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Wildauer<sup>100</sup>, M.A. Wildt<sup>42,ao</sup>, H.G. Wilkens<sup>30</sup>, J.Z. Will<sup>99</sup>, H.H. Williams<sup>121</sup>, S. Williams<sup>28</sup>, S. Willocq<sup>85</sup>, J.A. Wilson<sup>18</sup>, A. Wilson<sup>88</sup>, I. Wingerter-Seez<sup>5</sup>, S. Winkelmann<sup>48</sup>, F. Winklmeier<sup>115</sup>, M. Wittgen<sup>144</sup>, T. Wittig<sup>43</sup>, J. Wittkowski<sup>99</sup>, S.J. Wollstadt<sup>82</sup>, M.W. Wolter<sup>39</sup>, H. Wolters<sup>125a,i</sup>, B.K. Wosiek<sup>39</sup>, J. Wotschack<sup>30</sup>, M.J. Woudstra<sup>83</sup>, K.W. Wozniak<sup>39</sup>, K. Wraight<sup>53</sup>, M. Wright<sup>53</sup>, S.L. Wu<sup>174</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>88</sup>, E. Wulf<sup>35</sup>, T.R. Wyatt<sup>83</sup>, B.M. Wynne<sup>46</sup>, S. Xella<sup>36</sup>, M. Xiao<sup>137</sup>, D. Xu<sup>33a</sup>, L. Xu<sup>33b,ap</sup>, B. Yabsley<sup>151</sup>, S. Yacoub<sup>146b,aq</sup>, M. Yamada<sup>65</sup>, H. Yamaguchi<sup>156</sup>, Y. Yamaguchi<sup>156</sup>, A. Yamamoto<sup>65</sup>, K. Yamamoto<sup>63</sup>, S. Yamamoto<sup>156</sup>, T. Yamamura<sup>156</sup>, T. Yamanaka<sup>156</sup>, K. Yamauchi<sup>102</sup>, Y. Yamazaki<sup>66</sup>, Z. Yan<sup>22</sup>, H. Yang<sup>33e</sup>, H. Yang<sup>174</sup>, U.K. Yang<sup>83</sup>, Y. Yang<sup>110</sup>, S. Yanush<sup>92</sup>, L. Yao<sup>33a</sup>, Y. Yasu<sup>65</sup>, E. Yatsenko<sup>42</sup>, K.H. Yau Wong<sup>21</sup>, J. Ye<sup>40</sup>, S. Ye<sup>25</sup>, A.L. Yen<sup>57</sup>, E. Yildirim<sup>42</sup>, M. Yilmaz<sup>4b</sup>, R. Yoosofmiya<sup>124</sup>, K. Yorita<sup>172</sup>, R. Yoshida<sup>6</sup>, K. Yoshihara<sup>156</sup>, C. Young<sup>144</sup>, C.J.S. Young<sup>30</sup>, S. Youssef<sup>22</sup>, D.R. Yu<sup>15</sup>, J. Yu<sup>8</sup>, J.M. Yu<sup>88</sup>, J. Yu<sup>113</sup>, L. Yuan<sup>66</sup>, A. Yurkewicz<sup>107</sup>, B. Zabinski<sup>39</sup>, R. Zaidan<sup>62</sup>, A.M. Zaitsev<sup>129,ac</sup>, A. Zaman<sup>149</sup>, S. Zambito<sup>23</sup>, L. Zanello<sup>133a,133b</sup>, D. Zanzi<sup>100</sup>, A. Zaytsev<sup>25</sup>, C. Zeitnitz<sup>176</sup>, M. Zeman<sup>127</sup>, A. Zemla<sup>38a</sup>, K. Zengel<sup>23</sup>, O. Zenin<sup>129</sup>, T. Ženiš<sup>145a</sup>, D. Zerwas<sup>116</sup>, G. Zevi della Porta<sup>57</sup>, D. Zhang<sup>88</sup>, H. Zhang<sup>89</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>152</sup>, X. Zhang<sup>33d</sup>, Z. Zhang<sup>116</sup>, Z. Zhao<sup>33b</sup>, A. Zhemchugov<sup>64</sup>, J. Zhong<sup>119</sup>, B. Zhou<sup>88</sup>, L. Zhou<sup>35</sup>, N. Zhou<sup>164</sup>, C.G. Zhu<sup>33d</sup>, H. Zhu<sup>33a</sup>, J. Zhu<sup>88</sup>, Y. Zhu<sup>33b</sup>, X. Zhuang<sup>33a</sup>, A. Zibell<sup>99</sup>, D. Ziemska<sup>60</sup>, N.I. Zimin<sup>64</sup>, C. Zimmermann<sup>82</sup>, R. Zimmermann<sup>21</sup>, S. Zimmermann<sup>21</sup>, S. Zimmermann<sup>48</sup>, Z. Zinonos<sup>54</sup>, M. Ziolkowski<sup>142</sup>, R. Zitoun<sup>5</sup>, L. Živković<sup>35</sup>, G. Zobernig<sup>174</sup>, A. Zoccoli<sup>20a,20b</sup>, M. zur Nedden<sup>16</sup>, G. Zurzolo<sup>103a,103b</sup>, V. Zutshi<sup>107</sup>, L. Zwalinski<sup>30</sup>.

<sup>1</sup> School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4</sup> (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

<sup>5</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

<sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>12</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

<sup>13</sup> (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

<sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

<sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

- <sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics, Dogus University, Istanbul;
- <sup>(c)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- <sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>22</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>23</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>24</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>26</sup> <sup>(a)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(b)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(c)</sup> University Politehnica Bucharest, Bucharest; <sup>(d)</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>32</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Physics Department, Shanghai Jiao Tong University, Shanghai, China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America
- <sup>36</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>37</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>38</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>39</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- <sup>40</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America
- <sup>41</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- <sup>42</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>45</sup> Department of Physics, Duke University, Durham NC, United States of America
- <sup>46</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>50</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>51</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- <sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States of America
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- <sup>58</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> 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 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> 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
- 81 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 82 Institut für Physik, Universität Mainz, Mainz, Germany
- 83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 85 Department of Physics, University of Massachusetts, Amherst MA, United States of America
- 86 Department of Physics, McGill University, Montreal QC, Canada
- 87 School of Physics, University of Melbourne, Victoria, Australia
- 88 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- 89 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- 90 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- 92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- 93 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- 94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- 98 D.V.Skobeltzyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 101 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 103 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 109 Department of Physics, New York University, New York NY, United States of America
- 110 Ohio State University, Columbus OH, United States of America
- 111 Faculty of Science, Okayama University, Okayama, Japan
- 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of

## America

- 113 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- 114 Palacký University, RCPTM, Olomouc, Czech Republic
- 115 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- 116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- 117 Graduate School of Science, Osaka University, Osaka, Japan
- 118 Department of Physics, University of Oslo, Oslo, Norway
- 119 Department of Physics, Oxford University, Oxford, United Kingdom
- 120 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 121 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- 122 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 123 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- 125 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal; <sup>(b)</sup> Departamento de Física Teórica 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 <sup>(a)</sup> INFN Sezione di Roma I; <sup>(b)</sup> Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 134 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 135 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 136 <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Énergie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> 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 Énergies Alternatives), Gif-sur-Yvette, France
- 138 Santa Cruz Institute for Particle 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 <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 146 <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 147 <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> 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 <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- 161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- 162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- 163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- 165 <sup>(a)</sup> INFN Gruppo Collegato di Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 166 Department of Physics, University of Illinois, Urbana IL, United States of America
- 167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 168 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
- 169 Department of Physics, University of British Columbia, Vancouver BC, Canada
- 170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- 171 Department of Physics, University of Warwick, Coventry, United Kingdom
- 172 Waseda University, Tokyo, Japan
- 173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- 174 Department of Physics, University of Wisconsin, Madison WI, United States of America
- 175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- 176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- 177 Department of Physics, Yale University, New Haven CT, United States of America
- 178 Yerevan Physics Institute, Yerevan, Armenia
- 179 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom
- <sup>b</sup> Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- <sup>c</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>d</sup> Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- <sup>e</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>f</sup> Also at TRIUMF, Vancouver BC, Canada
- <sup>g</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- <sup>h</sup> Also at Novosibirsk State University, Novosibirsk, Russia
- <sup>i</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- <sup>j</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>l</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>m</sup> Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- <sup>n</sup> Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>o</sup> Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- <sup>p</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
- <sup>q</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>r</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- <sup>s</sup> Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- <sup>t</sup> Also at CERN, Geneva, Switzerland
- <sup>u</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- <sup>v</sup> Also at Manhattan College, New York NY, United States of America
- <sup>w</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>x</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- <sup>y</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>z</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>aa</sup> 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 Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ad* Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ae* Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
- af* Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ag* Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ah* Also at DESY, Hamburg and Zeuthen, Germany
- ai* Also at International School for Advanced Studies (SISSA), Trieste, Italy
- aj* Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ak* Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- al* Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- am* Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- an* Also at Department of Physics, Oxford University, Oxford, United Kingdom
- ao* Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ap* Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- aq* Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- \* Deceased