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Aaboud, M.; The ATLAS Collaboration

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Search for a Structure in the $B_s^0\pi^\pm$ Invariant Mass Spectrum with the ATLAS Experiment

M. Aaboud et al.*
(ATLAS Collaboration)

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A search for the narrow structure, $X(5568)$, reported by the D0 Collaboration in the decay sequence $X \rightarrow B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$, is presented. The analysis is based on a data sample recorded with the ATLAS detector at the LHC corresponding to 4.9 fb$^{-1}$ of $pp$ collisions at 7 TeV and 19.5 fb$^{-1}$ at 8 TeV. No significant signal was found. Upper limits on the number of signal events, with properties corresponding to those reported by D0, and on the $X$ production rate relative to $B_s^0$ mesons, $\rho_X$, were determined at 95% confidence level. The results are $N(X) < 382$ and $\rho_X < 0.015$ for $B_s^0$ mesons with transverse momenta above 10 GeV, and $N(X) < 356$ and $\rho_X < 0.016$ for transverse momenta above 15 GeV. Limits are also set for potential $B_s^0\pi^\pm$ resonances in the mass range 5550 to 5700 MeV.

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The D0 Collaboration reported evidence of a narrow structure, $X(5568)$, in the decay $X \rightarrow B_s^0\pi^\pm$ with $B_s^0 \rightarrow J/\psi\phi$ in proton-antiproton collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV at the Tevatron collider [1]. The structure was interpreted as a tetraquark with four different quark flavors: $b$, $s$, $u$, and $d$. The mass and natural width of this state were fitted to be $m = 5567.8 \pm 2.9$ (stat) $^{+0.9}_{-1.9}$ (syst) MeV and $\Gamma = 21.9 \pm 6.4$ (stat) $^{+5.0}_{-2.5}$ (syst) MeV, respectively, and the signal significance is 5.1$\sigma$. The ratio $\rho_X$ of the yield of $X(5568)$ to the yield of the $B_s^0$ meson for a transverse momentum range 10 < $p_T(B_s^0)$ < 30 GeV was measured to be 0.086 $\pm$ 0.019 (stat) $\pm$ 0.014 (syst). The result initiated a discussion of the nature of the new state and prospects for observation of other tetraquark hadrons [2–6]. Recently, the D0 Collaboration reported further evidence for the resonance $X(5568)$ [7] in the decay sequence $X \rightarrow B_s^0\pi^\pm$, $B_s^0 \rightarrow \mu^+\mu^-D_s^\pm$, $D_s^\pm \rightarrow \phi\pi^\mp$, which is consistent with their previous measurement [1]. However, searches for $X(5568)$ in decays to $B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$ performed by the LHCb [8] and CMS [9] Collaborations in proton-proton ($pp$) collisions at the LHC and by the CDF Collaboration [10] at the Tevatron, revealed no signal. The upper limits $\rho_X < 0.024$ [LHCb, $p_T(B_s^0) > 10$ GeV], $\rho_X < 0.011$ [CMS, $p_T(B_s^0) > 10$ GeV] and $\rho_X < 0.010$ [CMS, $p_T(B_s^0) > 15$ GeV] at 95% confidence level (C.L.) were determined within the acceptances of the LHCb and CMS experiments. CDF set an upper limit $\rho_X < 0.067$ at 95% C.L. within a kinematic range similar to that of D0 [1].

In this Letter, a search for the $X(5568)$ state by the ATLAS experiment at the LHC is presented ($B_s^0$ refers to both the $B_s^0$ and $B_s^0$ mesons). The $B_s^0$ mesons are reconstructed in their decays to $J/\psi\mu^+\mu^-$ or $K^+K^-$ or $\pi^+\pi^0\pi^0$ or $\pi^+\pi^-\pi^0\pi^0$, with $L$ in the range 10 < $L$ < 30 GeV, and $p_T(B_s^0) > 20$ GeV, and $\rho_X < 0.050$ at 95% confidence level (C.L.) within the acceptance of the detector. The analysis is based on a data sample recorded with the ATLAS detector at the LHC corresponding to 19.5 fb$^{-1}$ of $pp$ collisions at 8 TeV.

The ATLAS detector [11] covers nearly the entire solid angle around the collision point with layers of tracking detectors, calorimeters, and muon chambers. The muon and tracking systems are of particular importance in the reconstruction of $B$ mesons. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids with eight coils each, a system of tracking chambers, and detectors for triggering. To study the detector response, to estimate backgrounds, and to model systematic effects, 12 $\times$ 10$^6$ Monte Carlo (MC) simulated $B_s^0 \rightarrow J/\psi\phi$ and 1 $\times$ 10$^6$ $B_s^0\pi^\pm$ events were generated using Pythia 8.183 [12,13] tuned with ATLAS data [14]. Multiple overlaid proton-proton collisions (pileup) were simulated with Pythia soft QCD processes. The detector response was simulated using the ATLAS simulation framework [15] based on GEANT4 [16]. The MC events were weighted to reproduce the same pileup and trigger conditions as in the data. As in the D0 analysis [1], the $B_s^0\pi^\pm$ resonance was generated using the Breit-Wigner (BW) parametrization appropriate for an $S$-wave two-body decay near threshold.

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\[ F_{BW}(m(B_s^0\pi^\pm), m_X, \Gamma_X) = \frac{m(B_s^0\pi^\pm)m_X\Gamma(m(B_s^0\pi^\pm), \Gamma_X)}{(m_X^2 - m^2(B_s^0\pi^\pm))^2 + m_X^2\Gamma^2(m(B_s^0\pi^\pm), \Gamma_X)}, \]

where \( m(B_s^0\pi^\pm) \) is the invariant mass of the \( B_s^0\pi^\pm \) candidate and \( m_X \) and \( \Gamma_X \) are the mass and the natural width of the resonance. The mass-dependent width is \( \Gamma(m(B_s^0\pi^\pm), \Gamma_X) = \Gamma_X \times q_1/q_0 \), where \( q_1 \) and \( q_0 \) are the magnitudes of the three-vector momenta of the \( B_s^0 \) meson in the rest frame of the \( B_s^0\pi^\pm \) system at the invariant masses equal to \( m(B_s^0\pi^\pm) \) and \( m_X \), respectively. The mass and the width were set to \( m_X = 5567.8 \) MeV and \( \Gamma_X = 21.9 \) MeV, as reported in Ref. [1]. The events were selected by the dimuon triggers [17] based on identification of a \( J/\psi \rightarrow \mu^+\mu^- \) decay, with \( p_T \) thresholds of either 4 or 6 GeV, with both symmetric, (4, 4) or (6, 6) GeV, and asymmetric, (4, 6) GeV, combinations. In addition, each event must contain at least one reconstructed primary vertex (PV), formed from at least six ID tracks. The selection of \( J/\psi \) and \( \phi \rightarrow K^+K^- \) candidates is identical to the one described in detail in Ref. [18]. Candidates for \( B_s^0 \rightarrow J/\psi\phi \) decays are selected by fitting the tracks for each combination of \( J/\psi \rightarrow \mu^+\mu^- \) and \( \phi \rightarrow K^+K^- \) to a common vertex. The fit is further constrained by fixing the invariant mass of the two muon tracks to the \( J/\psi \) mass [19].

A quadruplet of tracks is accepted for further analysis if the vertex fit has a \( \chi^2/\text{d.o.f.} < 3 \). For each \( B_s^0 \) meson candidate the proper decay time \( t \) is extracted using the method described in Ref. [18]. Events with \( t > 0.2 \) ps are selected to reduce the background from the events with a \( J/\psi \) produced directly in the \( pp \) collision. If there is more than one accepted \( B_s^0 \) candidate in the event, the candidate with the lowest \( \chi^2/\text{d.o.f.} \) of the vertex fit is selected. For the selected events the average number of proton-proton interactions per bunch crossing is 21, necessitating a choice of the best candidate for the PV at which the \( B_s^0 \) meson is produced. The variable used is the three-dimensional impact parameter \( d_0 \), which is calculated as the distance between the line extrapolated from the reconstructed \( B_s^0 \) meson vertex in the direction of the \( B_s^0 \) momentum, and each PV candidate. The chosen PV is the one with the smallest \( d_0 \). Using MC simulation it was shown that the fraction of \( B_s^0 \) candidates that are assigned the wrong PV is less than 1% [18] and that the corresponding effect on the results is negligible. Finally, a requirement that the \( B_s^0 \) transverse momentum is greater than 10 GeV is applied. Figure 1 shows the reconstructed \( J/\psi K^+K^- \) mass distribution and the result of an extended unbinned maximum-likelihood fit in the range (5150–5650) MeV, in which the signal is modeled by a sum of two Gaussian distributions and an exponential function is used to model the combinatorial background. The observed signal width is consistent with MC simulation. The fitted \( B_s^0 \) mass is \( m_{\text{fit}}(B_s^0) = 5366.6 \pm 0.1 \) (stat) MeV, in agreement with the world average value 5366.89 ± 0.19 MeV [19]. For further investigation, only candidates with a reconstructed mass in the signal region 5346.6–5386.6 MeV are included, which gives \( N(B_s^0) = 52750 \pm 280 \) (stat) candidates.

The \( B_s^0\pi^\pm \) candidates are constructed by combining each of the tracks forming the selected PV with the selected \( B_s^0 \) candidate. Tracks that were already used to reconstruct the \( B_s^0 \) candidate and tracks identified as leptons (\( e \) or \( \mu \)) are excluded, as well as tracks with transverse momentum \( p_T < 500 \) MeV. This \( p_T \) selection was chosen to maximize the ratio of the \( B_s^0\pi^\pm \) signal to the background, based on MC simulation. Assigning the pion mass hypothesis to the tracks that pass these selection criteria, the mass \( m(B_s^0\pi^\pm) \) is calculated as \( m(J/\psi K^-\pi^+) - m(J/\psi K^-) + m_{\text{fit}}(B_s^0) \), where \( m_{\text{fit}}(B_s^0) = 5366.6 \) MeV. On average there are 1.8 \( B_s^0\pi^\pm \) candidates in each selected event and all are retained for the analysis. A systematic study has shown that the effect on the results due to multiple candidates is negligible.

The mass distribution of \( B_s^0\pi^\pm \) candidates is fitted using an extended unbinned maximum-likelihood method. The probability density function (PDF) for the background component is defined as a threshold function:

\[ F_{\text{bck}}(m(B_s^0\pi^\pm)) = \frac{(m(B_s^0\pi^\pm) - m_{\text{thr}})^a}{n} \times \exp\left(\sum_{i=1}^{4} p_i \left(\frac{m(B_s^0\pi^\pm) - m_{\text{thr}}}{n}\right)^i\right), \]

where \( m_{\text{thr}} = m_{\text{fit}}(B_s^0) + m_x \) and \( n \), \( a \), and \( p_i \) are free parameters of the fit. The background PDF was tested using
events with no real $B^0_s\pi^\pm$ candidates from two categories. The first background sample contains data events where $B^0_s\pi^\pm$ candidates are formed using “fake” $B^0_s$ mesons from the mass sidebands, shown in Fig. 1 by red shaded bands, defined as $5150 < m(J/\psi K^+ K^-) < 5210$ MeV and $5510 < m(J/\psi K^+ K^-) < 5650$ MeV. The second background sample is modeled using MC events containing only $B^0_s$ mesons not originating from the $B^0_s\pi^\pm$ signal, tuned to reproduce the $B^0_s$ transverse momentum distribution in data. In these events the $B^0_s$ meson is combined with each of the tracks originating from the selected PV. The first sample is normalized to the fitted number of $B^0_s$ background events in the $B^0_s$ mass signal region 5346.6–5386.6 MeV, while the second sample is normalized to the fitted number of $B^0_s$ signal events in the same region. The sum of these two distributions is consistent with the distribution of the data. The function in Eq. (2) describes both background distributions as well as their sum within uncertainties. The signal PDF $F_{\text{sig}}(m(B^0_s\pi^\pm))$ is defined as a convolution of an S-wave Breit-Wigner PDF, defined in Eq. (1), and the detector resolution represented by a Gaussian function with a width that is calculated individually for each $B^0_s\pi^\pm$ candidate from the tracking and vertexing error matrices. Using MC and data samples, it has been verified that the per candidate mass resolutions are the same for the $B^0_s\pi^\pm$ signal and for the background events passing the selection criteria. The average resolution for the $B^0_s\pi^\pm$ signal, with the mass and width corresponding to those of the structure reported by the D0 Collaboration ($m_X = 5567.8$ MeV and $\Gamma_X = 21.9$ MeV), is 3.2 MeV. The full probability function used is

$$F(m(B^0_s\pi^\pm)) = N(X) F_{\text{sig}}(m(B^0_s\pi^\pm))$$

$$+ [N_{\text{can}} - N(X)] F_{\text{bck}}(m(B^0_s\pi^\pm)), \quad (3)$$

where $N(X)$ is the number of signal events and $N_{\text{can}}$ is the number of all selected $B^0_s\pi^\pm$ candidates. The signal mass and width are fixed to the central values reported by the D0 Collaboration. Following other experiments, fits are performed for two subsets of $B^0_s\pi^\pm$ candidates, first with $p_T(B^0_s) > 10$ GeV and second with $p_T(B^0_s) > 15$ GeV. The results of the fits are shown in Fig. 2 and summarized in Table I. No significant $X(5568)$ signal is observed. Additional selections such as cuts on the angle between the momenta of the $B^0_s$ and $\pi^\pm$ candidates were investigated and did not produce evidence of a signal. These were found to improve the peaking background so are not included in the analysis. The yields $N(X)$ and $N(B^0_s)$ obtained from the fits are used to evaluate the $X$ production rate relative to $B^0_s$, within the ATLAS acceptance, using the formula

$$\rho_X = \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow B^0_s\pi^\pm)}{\sigma(pp \rightarrow B^0_s + \text{anything})}$$

$$= \frac{N(X)}{N(B^0_s)} \times \frac{1}{e^{\text{rel}}(X)}, \quad (4)$$

where $\sigma$ represents the production cross section for each of the particles, within the ATLAS acceptance, and the relative efficiency $e^{\text{rel}}(X) = e(X)/e(B^0_s)$ is the selection efficiency for the state $X$, decaying to $B^0_s\pi^\pm$, relative to that for the $B^0_s$ meson and accounts for the reconstruction and selection efficiency $e^{\text{rel}}(X)$ and their uncertainties are described in the text.

<table>
<thead>
<tr>
<th>$N(B^0_s)/10^3$</th>
<th>$p_T(B^0_s) &gt; 10$ GeV</th>
<th>$p_T(B^0_s) &gt; 15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B^0_s) &gt; 10$ GeV</td>
<td>52.75 ± 0.28</td>
<td>43.46 ± 0.24</td>
</tr>
<tr>
<td>$p_T(B^0_s) &gt; 15$ GeV</td>
<td></td>
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</tbody>
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<tr>
<th>$N(X)$</th>
<th>$p_T(B^0_s) &gt; 10$ GeV</th>
<th>$p_T(B^0_s) &gt; 15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B^0_s) &gt; 10$ GeV</td>
<td>60 ± 140</td>
<td></td>
</tr>
<tr>
<td>$p_T(B^0_s) &gt; 15$ GeV</td>
<td></td>
<td>-30 ± 150</td>
</tr>
</tbody>
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<tr>
<th>$e^{\text{rel}}(X)$</th>
<th>$p_T(B^0_s) &gt; 10$ GeV</th>
<th>$p_T(B^0_s) &gt; 15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B^0_s) &gt; 10$ GeV</td>
<td>0.53 ± 0.09</td>
<td>0.60 ± 0.10</td>
</tr>
</tbody>
</table>
efficiency of the companion pion, including the soft pion acceptance.

The relative efficiency, \( e_{\text{rel}}(X) \), was determined using MC simulation of events containing \( X \to B^0_s \pi^+ \) and \( B^0 \) decays. In the ratio, the acceptance of the \( B^0 \) decay cancels, so the value to be determined is the pion reconstruction efficiency for \( B^0_s \pi^+ \) events in which the \( B^0_s \) meson satisfies acceptance, reconstruction, and selection criteria. Based on MC events, \( e_{\text{rel}}(X) \) is determined as a function of \( p_T(B^0_s) \) and of \( m(B^0_s \pi^+) \). Using an MC-based function, the acceptance is determined individually for each \( B^0_s \pi^+ \) candidate, based on its measured values of \( p_T(B^0_s) \) and \( m(B^0_s \pi^+) \). The acceptance ratio, \( e_{\text{rel}}(X) \), is calculated as an average over the events included in the \( m(B^0_s \pi^+) \) interval within which the search for a resonance is performed. The width of this interval is defined by a BW function convolved with the mass resolution function, with the start and end points of the range chosen to include 99% of the signal events. The uncertainty of \( e_{\text{rel}}(X) \) is calculated by varying the fitted parameters of the MC-based function used to describe the acceptance as a function of \( p_T(B^0_s) \) within their uncertainties. Small variations of this function due to the pseudorapidity of the \( B^0_s \) were investigated and are included in the systematic uncertainties. The error also includes the uncertainty in the number of data events used in the average and the statistical uncertainty in the \( p_T(B^0_s) \) distribution of these events. The error in the pion reconstruction efficiency, arising from uncertainties in the amount of ID material, is found to have a negligible effect on \( \rho_X \).

As no significant signal is observed, corresponding to the properties of the \( X(5568) \) as reported by Ref. [1], upper limits are determined for the number of \( B^0_s \pi^+ \) signal events, \( N(X) \), and for the relative production rate, \( \rho_X \). These are calculated using the asymptotic approximation from the profile likelihood formalism [20] based on the CL_{s} frequentist method [21]. To establish the limit on the number of \( B^0_s \pi^+ \) signal events, the PDF models for signal and background, defined respectively by Eqs. (1) and (2), are used as inputs to the CL_{s} method. Without systematic uncertainties, the extracted upper limits at 95% C.L. are \( N(X) < 264 \) for \( p_T(B^0_s) > 10 \) GeV and \( N(X) < 213 \) for \( p_T(B^0_s) > 15 \) GeV. Systematic uncertainties affecting these limits are included in the determination of \( N(X) \). To obtain results that can be compared to the state \( X(5568) \) reported by the D0 Collaboration, systematic uncertainties are assigned by varying the values of \( m_X \) and \( \Gamma_X \) independently within Gaussian constraints, with uncertainties equal to those quoted in Ref. [1]. The default model of the \( X \) resonance, which is assumed to be spinless, is changed to a BW \( P \)-wave resonance. To include the systematic uncertainty due to the modeling of the background, the default PDF of Eq. (2) is replaced by a seventh-order Chebyshev polynomial, allowing more free parameters in the fit. For the detector resolution, the default per-candidate mass resolution model is replaced by the sum of three Gaussian functions with a common mean. The parameters used are determined from the \( B^0_s \pi^+ \) MC sample. Using these alternative models, upper limits that include systematic uncertainties are extracted, leading to values \( N(X) < 382 \) for \( p_T(B^0_s) > 10 \) GeV and \( N(X) < 356 \) for \( p_T(B^0_s) > 15 \) GeV. Each \( B^0_s \pi^+ \) signal event and \( e_{\text{rel}}(X) \) are used to construct Gaussian constraints, which are included as additional inputs to the CL_{s} method. Both the statistical and systematic uncertainties are included after being summed in quadrature. For the \( B^0_s \) signal, the default fit model of two Gaussian functions is changed to a triple Gaussian function and the change in the result is taken as a systematic uncertainty. The uncertainty due to the proper decay time requirement \( t > 0.2 \) ps was estimated by varying it within the time resolution and found to be negligible. The resulting upper limits at 95% C.L. are \( \rho_X < 0.015 \) for \( p_T(B^0_s) > 10 \) GeV and \( \rho_X < 0.016 \) for \( p_T(B^0_s) > 15 \) GeV. A hypothesis test is performed for the presence of a \( B^0_s \pi^+ \) peak for every 5 MeV step in its mass from 5550 to 5700 MeV, assuming a resonant state as described by Eq. (1), with a BW width of 21.9 MeV [1] and \( p_T(B^0_s) > 10 \) GeV. For each \( B^0_s \pi^+ \) mass tested, \( e_{\text{rel}}(X) \) is calculated using the same method as for \( X(5568) \). The values of \( e_{\text{rel}}(X) \) vary from 0.50 to 0.55 in the search interval. The upper limit of \( \rho_X \) at 95% C.L. is determined for each tested mass.
mass. The same systematic uncertainties as in the determination of $\rho_X$ for the state $X(5568)$ are included, with the exception of the $X(5568)$ mass uncertainty. The median expected upper limit at 95% C.L. as a function of $p_T^X$ mass is also determined with $\pm 1\sigma$ and $\pm 2\sigma$ error bands. The results are shown in Fig. 3.

In conclusion, a search for a new state $X(5568)$ decaying to $B^0_s \pi^\pm$, with properties as reported by the D0 Collaboration, was performed by the ATLAS experiment at the LHC, using 4.9 fb$^{-1}$ of $pp$ collision data at 7 TeV and 19.5 fb$^{-1}$ at 8 TeV. No significant signal was found. Within the acceptance in which this analysis is performed, upper limits on the number of signal events, $N(X)$, and on the $X$ production rate relative to $B^0_s$ mesons, were determined at 95% C.L., resulting in $N(X) < 382$ and $\rho_X < 0.015$ for $p_T(B^0_s) > 10$ GeV, and $N(X) < 356$ and $\rho_X < 0.016$ for $p_T(B^0_s) > 15$ GeV. Limits are also set for potential $B^0_s \pi^\pm$ resonances in the mass range from 5550 to 5700 MeV. Across the full range, the upper limit set on $\rho_X$ at 95% C.L. varies between 0.010 and 0.018, and does not exceed the $\pm 1\sigma$ error band from the expected limit.

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[18] ATLAS Collaboration, Measurement of the $CP$-violating phase $\phi_t$ and the $B^0_s$ meson decay width difference with $B^0_s \rightarrow J/\psi\phi$ decays in ATLAS, J. High Energy Phys. 08 (2016) 147.


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1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4Department of Physics, Ankara University, Ankara, Turkey
5Istanbul Aydin University, Istanbul, Turkey
6Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
7LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
8High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
9Department of Physics, University of Arizona, Tucson, Arizona, USA
10Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
11Department of Physics, National and Kapodistrian University of Athens, Athens, Greece
12Institute of Physics, National Technical University of Athens, Zografou, Greece
13Department of Physics, The University of Texas at Austin, Austin, Texas, USA
14Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
15Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
16Department for Physics and Technology, University of Bergen, Bergen, Norway
17Department of Physics, Humboldt University, Berlin, Germany
18Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20Department of Physics, Bogazici University, Istanbul, Turkey
21Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
22Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
23Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
24Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
25INFN Sezione di Bologna, Italy
26Department of Physics, Bogazici University, Istanbul, Turkey
27Department of Physics, Boston University, Boston, Massachusetts, USA
28Department of Physics, Brandeis University, Waltham, Massachusetts, USA
29Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
30Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
31Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
32Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
33Physics Department, Brookhaven National Laboratory, Upton, New York, USA
34Transilvania University of Brasov, Brasov, Romania
35Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
36Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
37National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
38University Politehnica Bucharest, Bucharest, Romania
39West University in Timisoara, Timisoara, Romania
40Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
41Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
42Department of Physics, Carleton University, Ottawa, Ontario, Canada
43CERN, Geneva, Switzerland
44Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
45Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
46Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
47Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

202007-14
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, China

Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China

Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, New York, USA

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

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

Dipartimento di Fisica, Università della Calabria, Rende, Italy

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

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

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

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

Department of Physics, Duke University, Durham, North Carolina, USA

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

INFN e Laboratori Nazionali di Frascati, Frascati, Italy

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

Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

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

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

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

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

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

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

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

Department of Physics, The University of Hong Kong, Hong Kong, China

Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

Department of Physics, Indiana University, Bloomington, Indiana, USA

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City, Iowa, USA

Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

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

INFN Sezione di Lecce, Italy

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
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.