Search for a Structure in the B-s(0) π(±) Invariant Mass Spectrum with the ATLAS Experiment

Aaboud, M.; Aad, G.; Abbott, B.; Abdinov, O.; Abeloos, B; Abidi, S.H.; Abouzeid, Ossama Sherif Alexander; Abraham, NL; Abramowicz, H.; Abreu, H.; Abulaiti, Y.; Acharya, B.S.; Adachi, S.; Adamczyk, L.; Adelman, J ; Adersberger, M.; Adye, T.; Affolder, A. A.; Afik, Y.; Agheorghiesei, C.; Aguilar-Saavedra, J. A.; Ahlen, S. P.; Ahmadov, F.; Dam, Mogens; Hansen, Jørn Dines; Hansen, Jørgen Beck; Xella, Stefania; Hansen, Peter Henrik; Petersen, Troels Christian; Alonso Diaz, Alejandro; Monk, James William; Wiglesworth, Graig; Galster, Gorm Aske Gram Krohn; Stark, Simon Holm; Bajic, Milena; Besjes, Geert-Jan; Thiele, Fabian Alexander Jürgen; de Almeida Dias, Flavia

Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.120.202007

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Search for a Structure in the $B^0_s \pi^\pm$ Invariant Mass Spectrum with the ATLAS Experiment

M. Aaboud et al. (ATLAS Collaboration)

A search for narrow structure, $X(5568)$, reported by the D0 Collaboration in the decay sequence $X \rightarrow B^0_s \pi^\pm$, $B^0_s \rightarrow J/\psi \phi$, 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 $B^0_s$ mesons, $\rho_X$, were determined at 95% confidence level. The results are $N(X) < 382$ and $\rho_X < 0.015$ for $B^0_s$ 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 $B^0_s \pi^\pm$ resonances in the mass range 5550 to 5700 MeV.

DOI: 10.1103/PhysRevLett.120.202007

The D0 Collaboration reported evidence of a narrow structure, $X(5568)$, in the decay $X \rightarrow B^0_s \pi^\pm$ with $B^0_s \rightarrow J/\psi \phi$ 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) $^{\pm 0.9}_{-1.9}$ (syst) and $\Gamma = 21.9 \pm 6.4$ (stat) $^{\pm 5.0}_{-2.5}$ (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 $B^0_s$ meson for a transverse momentum range $10 < p_T(B^0_s) < 30$ 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 $X \rightarrow B^0_s \pi^\pm$, $B^0_s \rightarrow \mu^+\mu^-D^*_s^0$, $D^*_s^0 \rightarrow \phi\pi^\pm$, which is consistent with their previous measurement [1]. However, searches for $X(5568)$ in decays to $B^0_s \pi^\pm$, $B^0_s \rightarrow J/\psi \phi$ 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, $p_T(B^0_s) > 10$ GeV], $\rho_X < 0.011$ [CMS, $p_T(B^0_s) > 10$ GeV] and $\rho_X < 0.010$ [CMS, $p_T(B^0_s) > 15$ 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 ($B^0_s$ refers to both the $B^0_s$ and $\bar{B}^0_s$ mesons). The $B^0_s$ mesons are reconstructed in their decays to $J/\psi\mu^+\mu^-$ via $K^+K^-$, respectively. 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 $B^0_s \rightarrow J/\psi \phi$ and $1 \times 10^6$ $B^0_s \pi^\pm$ 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 $B^0_s \pi^\pm$ resonance was generated using the Breit-Wigner (BW) parametrization appropriate for an S-wave two-body decay near threshold.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP3.
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 

$$\Gamma(m(B_s^{0}\pi^\pm), \Gamma_X) = m^2(B_s^{0}\pi^\pm) + m_X^2 + m_X \Gamma(m(B_s^{0}\pi^\pm), \Gamma_X).$$

The mass-dependent width is described in detail in Ref. [18]. Candidates for $B_s^{0}\pi^\pm$ are 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]. 

Candiates 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 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 $\chi^2$/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 $\chi^2$/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 $m_{\text{fit}}(B_s^{0}) = 5366.6 \pm 0.1 \text{ (stat) MeV}$, in agreement with the world average value $5366.89 \pm 0.19$ 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 $m(J/\psi KK\pi^\pm) - m(J/\psi KK) + m_{\text{fit}}(B_s^{0})$, 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:

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

where $m_{\text{thr}} = m_{\text{fit}}(B_s^{0}) + m_{\Delta}$ 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 $F_{sig}(m(B^0_s\pi^\pm))$ 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

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

where $N(X)$ is the number of signal events and $N_{can}$ 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 introduce 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

$$\rho_X \equiv \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow B^0_s\pi^\pm)}{\sigma(pp \rightarrow B^0_s + \text{anything})} = \frac{N(X)}{N(B^0_s)} \times \frac{1}{\epsilon_{rel}(X)}, \quad (4)$$

where $\sigma$ represents the production cross section for each of the particles, within the ATLAS acceptance, and the relative efficiency $\epsilon_{rel}(X) = e(X)/e(B^0_s)$ 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.

![Figure 2](https://example.com/figure2.png)

**FIG. 2.** Results of the fit to the $B^0_s\pi^\pm$ mass distribution for candidates with $p_T(B^0_s) > 10$ GeV (left) and $p_T(B^0_s) > 15$ GeV (right). The bottom panels show the difference between each data point and the fit divided by the statistical uncertainty of that point.

<table>
<thead>
<tr>
<th>$N(B^0_s)/10^3$</th>
<th>$p_T(B^0_s) &gt; 10$ GeV</th>
<th>$52.75 \pm 0.28$</th>
<th>$43.46 \pm 0.24$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B^0_s) &gt; 15$ GeV</td>
<td>60 \pm 140</td>
<td>-30 \pm 150</td>
<td></td>
</tr>
</tbody>
</table>

$N(X)$

| $p_T(B^0_s) > 10$ GeV | 0.53 \pm 0.09 |
| $p_T(B^0_s) > 15$ GeV | 0.60 \pm 0.10 |

$\epsilon_{rel}(X)$

TABLE I. Yields of $B^0_s$ and $X(5568)$ candidates obtained from the fits to the $B^0_s$ and $B^0_s\pi^\pm$ candidate mass distributions, with statistical uncertainties. The values given for $N(B^0_s)$ are those inside the $B^0_s$ signal window. The reported values for $X(5568)$ are obtained from the fits with signal mass and width parameters fixed to those reported by the D0 Collaboration. The relative efficiencies $e_{rel}(X)$ and their uncertainties are described in the text.
efficiency of the companion pion, including the soft pion acceptance.

The relative efficiency, $e^{rel}(X)$, was determined using MC simulation of events containing $X \to B^0_s \pi^\pm$ and $B^0_s$ decays. In the ratio, the acceptance of the $B^0_s$ decay cancels, so the value to be determined is the pion reconstruction efficiency for $B^0_s \pi^\pm$ events in which the $B^0_s$ meson satisfies acceptance, reconstruction, and selection criteria. Based on MC events, $e^{rel}(X)$ is determined as a function of $p_T(B^0_s)$ and of $m(B^0_s \pi^\pm)$. Using an MC-based function, the acceptance is determined individually for each $B^0_s \pi^\pm$ candidate, based on its measured values of $p_T(B^0_s)$ and $m(B^0_s \pi^\pm)$. The acceptance ratio, $e^{rel}(X)$, is calculated as an average over the events included in the $m(B^0_s \pi^\pm)$ 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 $e^{rel}(X)$ 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 $B^0_s \pi^\pm$ 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 CLs frequentist method [21]. To establish the limit on the number of $B^0_s \pi^\pm$ signal events, the PDF models for signal and background, defined respectively by Eqs. (1) and (2), are used as inputs to the CLs 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 $B^0_s \pi^\pm$ 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. To extract the upper limits on $\rho_X$ additional systematic uncertainties are included. The calculation of $\rho_X$ also depends on the precision of extracting the number of $B^0_s$ signal events and the relative efficiency $e^{rel}(X)$. To include these uncertainties, the central values and the uncertainties of the number of $B^0_s$ signal events and $e^{rel}(X)$ are used to construct Gaussian constraints, which are included as additional inputs to the CLs 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 $B^0_s \pi^\pm$ 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 $B^0_s \pi^\pm$ mass tested, $e^{rel}(X)$ is calculated using the same method as for $X(5568)$. The values of $e^{rel}(X)$ 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 the $B^0_s \pi^\pm$ 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.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhi, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; ARRS and MIZ, 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, USA. 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; and the 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. [22].

[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.
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, Louisiana, USA
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 Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics and Astronomy, The University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Italy
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, Quebec, Canada
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, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
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, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
The Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
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, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
INFN Sezione di Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
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
Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal
Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
{Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, 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
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
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

\(^a\)Deceased.
\(^b\)Also at Department of Physics, King’s College London, London, United Kingdom.
\(^c\)Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
\(^d\)Also at Novosibirsk State University, Novosibirsk, Russia.
\(^e\)Also at TRIUMF, Vancouver, British Columbia, Canada.
\(^f\)Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
\(^g\)Also at Physics Department, An-Najah National University, Nablus, Palestine.
\(^h\)Also at Department of Physics, California State University, Fresno, CA, USA.
\(^i\)Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
\(^j\)Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
\(^k\)Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
\(^l\)Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\(^m\)Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
\(^n\)Also at Università di Napoli Parthenope, Napoli, Italy.
\(^o\)Also at Institute of Particle Physics (IPP), Canada.
\(^p\)Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
\(^q\)Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
\(^r\)Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
\(^s\)Also at Borough of Manhattan Community College, City University of New York, New York City, NY, USA.
\(^t\)Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
\(^u\)Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
\(^v\)Also at Louisiana Tech University, Ruston, LA, USA.
\(^w\)Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
\(^x\)Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
\(^y\)Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
\(^z\)Also at Graduate School of Science, Osaka University, Osaka, Japan.
\(^aa\)Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
\(^bb\)Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
\(^cc\)Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
\(^dd\)Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
\(^ee\)Also at CERN, Geneva, Switzerland.
\(^ff\)Also at Georgian Technical University (GTU), Tbilisi, Georgia.
\(^gg\)Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
\(^hh\)Also at Manhattan College, New York, NY, USA.
\(^ii\)Also at The City College of New York, New York, NY, USA.
\(^jj\)Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal.
\(^kk\)Also at Department of Physics, California State University, Sacramento, CA, USA.
\(^ll\)Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
\(^mm\)Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.
\(^nn\)Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
\(^oo\)Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
\(^pp\)Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
\(^qq\)Also at Faculty of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia.
\(^rr\)Also at National Research Nuclear University MEPhI, Moscow, Russia.
\(^ss\)Also at Department of Physics, Stanford University, Stanford, CA, USA.
\(^tt\)Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
