






























































































# Search for $B_s^0 \rightarrow \ell^\mp \tau^\pm$ with the semi-leptonic tagging method at Belle



## The Belle collaboration

<https://belle.kek.jp/>

L. Nayak , S. Nishida , A. Giri , I. Adachi , H. Aihara , D.M. Asner ,  
 H. Atmacan , V. Aulchenko , T. Aushev , R. Ayad , V. Babu ,  
 S. Bahinipati , S. Banerjee , M. Bauer , P. Behera , K. Belous , J. Bennett ,  
 M. Bessner , B. Bhuyan , D. Biswas , D. Bodrov , J. Borah , A. Bozek ,  
 M. Bračko , P. Branchini , T.E. Browder , A. Budano , M. Campajola ,  
 D. Červenkov , M.-C. Chang , B.G. Cheon , K. Chilikin , H.E. Cho ,  
 K. Cho , S.-K. Choi , Y. Choi , S. Choudhury , D. Cinabro , J. Cochran ,  
 S. Das , N. Dash , G. De Nardo , G. De Pietro , R. Dhamija , F. Di Capua ,  
 J. Dingfelder , Z. Doležal , T.V. Dong , D. Dossett , S. Dubey ,  
 D. Epifanov , T. Ferber , D. Ferlewicz , B.G. Fulsom , R. Garg , V. Gaur ,  
 P. Goldenzweig , E. Graziani , T. Gu , Y. Guan , S. Halder , T. Hara ,  
 K. Hayasaka , H. Hayashii , M.T. Hedges , D. Herrmann , W.-S. Hou ,  
 C.-L. Hsu , T. Iijima , K. Inami , G. Inguglia , N. Ipsita , A. Ishikawa ,  
 R. Itoh , M. Iwasaki , W.W. Jacobs , E.-J. Jang , S. Jia , Y. Jin ,  
 K.K. Joo , A.B. Kaliyar , T. Kawasaki , C. Kiesling , C.H. Kim , D.Y. Kim ,  
 K.-H. Kim , Y.-K. Kim , K. Kinoshita , P. Kodyš , T. Konno , A. Korobov ,  
 S. Korpar , E. Kovalenko , P. Križan , P. Krokovny , T. Kuhr , M. Kumar ,  
 R. Kumar , K. Kumara , A. Kuzmin , Y.-J. Kwon , S.C. Lee , J. Li ,  
 L.K. Li , Y. Li , J. Libby , K. Lieret , Y.-R. Lin , D. Liventsev , T. Luo ,  
 Y. Ma , M. Masuda , T. Matsuda , S.K. Maurya , F. Meier , M. Merola ,  
 F. Metzner , K. Miyabayashi , R. Mizuk , G.B. Mohanty , I. Nakamura ,  
 M. Nakao , Z. Natkaniec , A. Natochii , N.K. Nisar , S. Ogawa , H. Ono ,  
 P. Oskina , P. Pakhlov , G. Pakhlova , T. Pang , S. Pardi , J. Park ,  
 S.-H. Park , A. Passeri , S. Paul , T.K. Pedlar , R. Pestotnik , L.E. Piilonen ,  
 T. Podobnik , E. Prencipe , M.T. Prim , A. Rostomyan , N. Rout 

G. Russo , S. Sandilya , A. Sangal , L. Santelj , V. Savinov , G. Schnell ,  
C. Schwanda , A.J. Schwartz , Y. Seino , K. Senyo , M.E. Sevier ,  
M. Shapkin , C. Sharma , J.-G. Shiu , A. Sibidanov , E. Solovieva ,  
M. Starič , M. Sumihama , T. Sumiyoshi , M. Takizawa , K. Tanida ,  
F. Tenchini , K. Trabelsi , M. Uchida , Y. Unno , K. Uno , S. Uno ,  
P. Urquijo , S.E. Vahsen , G. Varner , K.E. Varvell , A. Vinokurova ,  
D. Wang , M.-Z. Wang , S. Watanuki , E. Won , B.D. Yabsley , W. Yan ,  
J. Yelton , Y. Yook , C.Z. Yuan , L. Yuan , Y. Yusa , Y. Zhai ,  
Z.P. Zhang , V. Zhilich  and V. Zhukova 

*E-mail:* [lopamudra.nayakcda@gmail.com](mailto:lopamudra.nayakcda@gmail.com)

ABSTRACT: We present a search for the lepton-flavor-violating decays  $B_s^0 \rightarrow \ell^\mp \tau^\pm$ , where  $\ell = e, \mu$ , using the full data sample of  $121 \text{ fb}^{-1}$  collected at the  $\Upsilon(5S)$  resonance with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider. We use  $B_s^0 \bar{B}_s^0$  events in which one  $B_s^0$  meson is reconstructed in a semileptonic decay mode and the other in the signal mode. We find no evidence for  $B_s^0 \rightarrow \ell^\mp \tau^\pm$  decays and set upper limits on their branching fractions at 90% confidence level as  $\mathcal{B}(B_s^0 \rightarrow e^\mp \tau^\pm) < 14 \times 10^{-4}$  and  $\mathcal{B}(B_s^0 \rightarrow \mu^\mp \tau^\pm) < 7.3 \times 10^{-4}$ . Our result represents the first upper limit on the  $B_s^0 \rightarrow e^\mp \tau^\pm$  decay rate.

KEYWORDS: B Physics,  $e^+e^-$  Experiments, Flavour Physics

ARXIV EPRINT: [2301.10989](https://arxiv.org/abs/2301.10989)

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Data sample and Belle detector</b>	<b>1</b>
<b>3</b>	<b>Event selection and analysis overview</b>	<b>2</b>
<b>4</b>	<b>Systematic uncertainties</b>	<b>6</b>
<b>5</b>	<b>Results and summary</b>	<b>8</b>

---

## 1 Introduction

The lepton-flavor-violating (LFV) decays  $B_s^0 \rightarrow \ell^\mp \tau^\pm$ , where  $\ell = e, \mu$ , are forbidden in the standard model (SM). Such decays can occur via neutrino mixing by loop and box diagrams [1], but the predicted decay rates are far below current experimental capabilities. Thus, any observations at current experiments would constitute an unambiguous signature of new physics (NP). Recent results indicating possible lepton flavor universality violation in  $B$  meson decay have been discussed in refs. [2, 3], where many NP models are proposed to explain it. Such models allow significantly enhanced LFV decay rates that may be detectable with current facilities. For example, the models containing a heavy neutral gauge boson ( $Z'$ ) could lead to an enhanced  $B_s^0 \rightarrow \mu^- \tau^+$  branching fraction, up to  $10^{-8}$  when only left- or right-handed couplings to quarks are considered, or of order  $10^{-6}$  [4], if both are allowed. In models with either scalar or vector leptoquarks, the prediction for the branching fraction of  $B_s^0 \rightarrow \ell^- \tau^+$  can be as large as  $10^{-5}$  [5–7], depending on the assumed leptoquark mass. It is imperative to search for signals of physics beyond the SM in all possible avenues, and since the expected branching fraction of  $B_s^0 \rightarrow e^- \tau^+$  may differ from  $B_s^0 \rightarrow \mu^- \tau^+$  depending on models, it is important to search for both decay modes to obtain additional information regarding the NP. To date, no experimental results for  $B_s^0 \rightarrow e^\mp \tau^\pm$  have been reported while an upper limit  $\mathcal{B}(B_s^0 \rightarrow \mu^\mp \tau^\pm) < 3.4 \times 10^{-5}$  at 90% confidence level (C.L.) [8] has been reported by LHCb.

In this paper, we report a search for  $B_s^0 \rightarrow \ell^\mp \tau^\pm$  decays using  $121 \text{ fb}^{-1}$  of data collected by the Belle experiment at the KEKB asymmetric-energy  $e^+e^-$  collider [9, 10]. The data were collected at an  $e^+e^-$  center-of-mass (c.m.) energy corresponding to the  $\Upsilon(5S)$  resonance mass.

## 2 Data sample and Belle detector

The Belle detector is a large-solid-angle magnetic spectrometer comprising a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov

counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and a CsI(Tl) crystal electromagnetic calorimeter (ECL). All these components are located inside a superconducting solenoid providing a magnetic field of 1.5 T. An iron flux return located outside the solenoid coil is instrumented with resistive plate chambers to detect  $K_L^0$  mesons and muons (KLM). A more detailed description of the detector and its layout and performance can be found in refs. [11, 12].

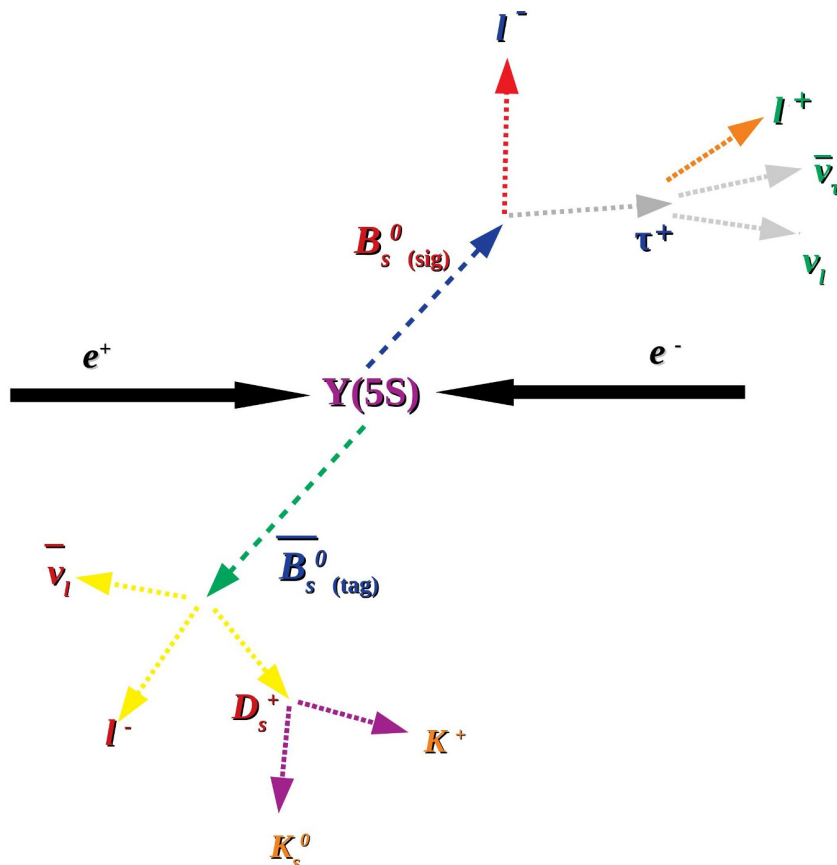
We study the properties of signal events, identify sources of background, and optimize selection criteria using Monte Carlo (MC) simulated events. These samples are generated using EvtGen [13]. The detector response is simulated using the Geant3 framework [14]. We simulate 20 million  $B_s^0 \rightarrow \ell^\mp \tau^\pm$  MC events to study the detector response and to calculate signal reconstruction efficiencies. To estimate backgrounds, we use MC samples of  $B_s^{(*)} \bar{B}_s^{(*)}$  and  $B_{u,d}^{(*)} \bar{B}_{u,d}^{(*)} X$  events, with  $B_s \leftrightarrow \bar{B}_s$ ,  $B_d \leftrightarrow \bar{B}_d$  mixing [15], and  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events. These samples, referred to as generic MC, are equivalent to six times the data luminosity. The Belle data are converted into the Belle II format [16], and the particle and event reconstruction are performed within the basf2 framework [17, 18] of the Belle II experiment.

The  $B_s^0$  and  $\bar{B}_s^0$  mesons are produced in the process  $e^+e^- \rightarrow \Upsilon(5S) \rightarrow B_s^{(*)0} \bar{B}_s^{(*)0}$ , with  $B_s^{*0} \rightarrow B_s^0 \gamma$ ,  $\bar{B}_s^{*0} \rightarrow \bar{B}_s^0 \gamma$  and with fast  $B_s^0 \leftrightarrow \bar{B}_s^0$  mixing, such that half of the events contain same flavor  $B_s$  pairs. The  $\Upsilon(5S)$  resonance production cross section is  $340 \pm 16$  pb [19], and  $f_s$ , its total branching fraction for decays to  $B_s^{(*)0} \bar{B}_s^{(*)0}$ , is  $0.201 \pm 0.031$  [15]. Therefore, the Belle data sample is estimated to contain  $(16.6 \pm 2.7) \times 10^6 B_s$  mesons.

### 3 Event selection and analysis overview

Hereafter,  $B_s$  refers to either  $B_s^0$  or  $\bar{B}_s^0$ , and the inclusion of charge-conjugated modes is implied. In this analysis, one  $B_s$  is reconstructed in a semileptonic decay mode  $\bar{B}_s^0 \rightarrow D_s^+ \ell^- (X) \bar{\nu}_\ell$  and used as a tag, where  $X$  stands for any particles such as  $\pi$  or a combination of pions, and the signal  $B_s \rightarrow \ell^- \tau^+$  is searched for in the mode  $\tau^+ \rightarrow \ell^+ \bar{\nu}_\tau \nu_\ell$ . We label the primary and secondary leptons from the  $\tau$  decay on the signal side  $B_s$  as  $\ell_1$  and  $\ell_2$ , and the lepton on the tag side as  $\ell_3$ . In short, we search for  $B_s \rightarrow \ell_1^- \tau^+ (\rightarrow \ell_2^+ \bar{\nu}_\tau \nu_\ell)$  with  $\bar{B}_s^0$  tagged by the decay  $\bar{B}_s^0 \rightarrow D_s^+ \ell_3^- (X) \bar{\nu}_{\ell_3}$ . Figure 1 shows a schematic diagram of the process, separated into signal and tag sides. To avoid biasing the results, all selection criteria are determined in a “blind” manner, i.e., they are optimized using MC samples only, before the experimental data in the signal region are revealed.

For charged particles, aside for pions from  $K_S^0$ , the distance of nearest approach of the track perpendicular to and along the beam direction, with respect to the nominal interaction point, are required to be less than 0.5 cm and 2.0 cm, respectively. The  $K_S^0$  candidates are reconstructed by combining two oppositely charged particles (assumed to be pions) with an invariant mass between 487 and 508 MeV/ $c^2$ ; this range corresponds to approximately three standard deviations ( $\pm 3\sigma$ ) in the invariant mass resolution around the nominal  $K_S^0$  mass [15]. Such candidates are further subjected to a neural network-based identification [20]. The  $\pi^0$  candidates are reconstructed from pairs of photons detected as ECL clusters without any associated charged tracks in the CDC. The energy of each



**Figure 1.** A schematic diagram of the process under study, separated into signal and tag sides.

photon is required to be greater than 50 MeV if the photon is detected in the barrel region ( $32.2^\circ < \theta < 128.7^\circ$ , where  $\theta$  is its polar angle), greater than 100 MeV if the photon is in the forward endcap region ( $12.4^\circ < \theta < 31.4^\circ$ ), and greater than 150 MeV if the photon is in the backward endcap region ( $130.7^\circ < \theta < 155.1^\circ$ ) [11, 12]. The invariant mass of each photon pair is required to be between 120 and 150 MeV/ $c^2$ ; this range corresponds to a window of approximately  $\pm 3\sigma$  in the invariant mass resolution around the nominal  $\pi^0$  mass, and the reconstructed  $\pi^0$  momentum in the c.m. frame ( $p_{\pi^0}^*$ ) must be greater than 0.2 GeV/ $c$ . A mass constrained fit to the nominal  $\pi^0$  mass is performed to improve momentum resolution.

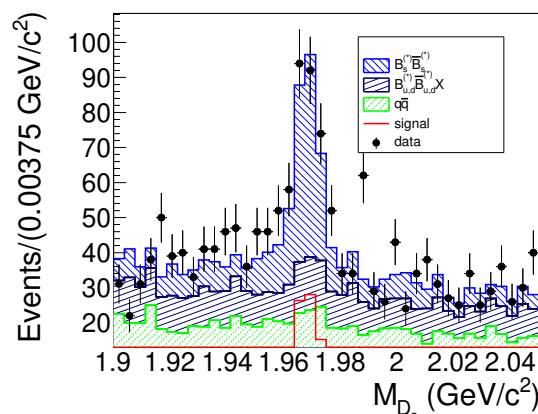
To identify charged hadrons, we use information on the light yield from the ACC, crossing time from the TOF, and specific ionization from the CDC. This information is combined into likelihoods  $\mathcal{L}_K$  and  $\mathcal{L}_\pi$  for a given track to be a  $K^+$  or  $\pi^+$ , respectively. To identify  $K^+$  or  $\pi^+$  tracks, we require  $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$  or  $\mathcal{L}_\pi/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$ . This requirement is more than 93% efficient in identifying pions, with a  $K^+$  mis-identification rate below 5%. Muon candidates are selected based on information from the KLM [21]. We calculate a normalized muon likelihood ratio  $\mathcal{R}_\mu = \mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K)$ , where  $\mathcal{L}_\mu$  is the likelihood for muons, and require  $\mathcal{R}_\mu > 0.9$ . This requirement has an efficiency of 85–92% and a probability of misidentifying a hadron as a muon below 7%. Electron candidates are

identified using the ratio of calorimetric cluster energy to particle momentum, the shower shape in the ECL, the matching of the track with the ECL cluster, the specific ionization in the CDC, and the number of photoelectrons in the ACC [22]. This information is used to calculate a normalized electron likelihood ratio  $\mathcal{R}_e = \mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_{\text{had}})$ , where  $\mathcal{L}_e$  is the likelihood for electrons and  $\mathcal{L}_{\text{had}}$  is a product of hadron likelihoods. We require  $\mathcal{R}_e > 0.9$ . This requirement has an efficiency of 84–92% and a probability of misidentifying a hadron as an electron below 1%.

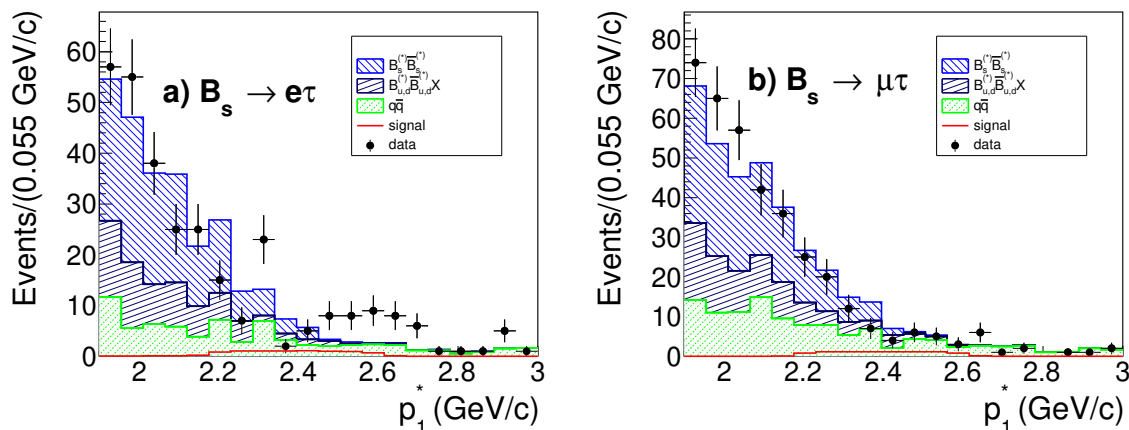
For the signal side  $B_s \rightarrow \ell_1^- \tau^+ (\rightarrow \ell_2^+ \bar{\nu}_\tau \nu_{\ell_2})$ , we require that the two leptons  $\ell_1$  and  $\ell_2$  have opposite charges and that  $p_1^* > p_2^*$ ,  $p_1^* > p_3^*$ , and  $p_1^* > 1.9 \text{ GeV}/c$ , where  $p_1^*$ ,  $p_2^*$  and  $p_3^*$  are the momenta of  $\ell_1$ ,  $\ell_2$  and  $\ell_3$  in the c.m. frame. To suppress background coming from  $J/\psi \rightarrow \ell^+ \ell^-$ , the candidate is rejected if the invariant mass of the two leptons  $M_{\ell_1 \ell_2}$  satisfies  $M_{\ell_1 \ell_2} \in [3.01, 3.12] \text{ GeV}/c^2$  for the  $B_s \rightarrow e^- \tau^+ (\rightarrow e^+ \bar{\nu}_\tau \nu_e)$  mode, and  $M_{\ell_1 \ell_2} \in [3.05, 3.12] \text{ GeV}/c^2$  for the  $B_s \rightarrow \mu^- \tau^+ (\rightarrow \mu^+ \bar{\nu}_\tau \nu_\mu)$  mode. The wider asymmetric veto interval for the electron mode is due to bremsstrahlung energy loss.

For the tag side  $\bar{B}_s^0 \rightarrow D_s^+ \ell_3^- (X) \bar{\nu}_{\ell_3}$ , the charge of  $\ell_3$  can be opposite to or the same as  $\ell_1$ , as  $B_s$  mixing produces equal numbers of opposite and same charge combinations. However, we accept only combinations where the charges of  $\ell_1$  and  $\ell_3$  are the same; this significantly reduces combinatorial background. We reconstruct  $D_s$  meson candidates with opposite charge to  $\ell_3$  from the following five decay modes:  $D_s^+ \rightarrow \phi \pi^+$ ,  $\bar{K}^{*0} K^+$ ,  $\phi \rho^0 \pi^+$ ,  $K_S^0 K^+$  and  $\phi \rho^+$ . Here,  $\rho^0$ ,  $\rho^+$ ,  $\bar{K}^{*0}$  and  $\phi$  are reconstructed through  $\rho^0 \rightarrow \pi^+ \pi^-$ ,  $\rho^+ \rightarrow \pi^+ \pi^0$ ,  $\bar{K}^{*0} \rightarrow K^- \pi^+$  and  $\phi \rightarrow K^+ K^-$ , and candidates are required to have a reconstructed invariant mass  $625 \text{ MeV}/c^2 < M_{\pi^+ \pi^- (\pi^+ \pi^0)} < 925 \text{ MeV}/c^2$  for  $\rho^0 (\rho^+)$ ,  $845 \text{ MeV}/c^2 < M_{K^+ \pi^-} < 945 \text{ MeV}/c^2$  for  $\bar{K}^{*0}$ , and  $1.01 \text{ GeV}/c^2 < M_{K^+ K^-} < 1.03 \text{ GeV}/c^2$  for  $\phi$ . The  $D_s$  candidate is then combined with an  $e$  or  $\mu$  to form a  $B_s$  meson candidate. Figure 2 shows the mass distribution of  $D_s^+$  meson candidates. The mass of the  $D_s^+$  candidate is required to be between 1.96 and 1.98  $\text{ GeV}/c^2$ . These mass windows correspond to  $\pm 3\sigma$  in the invariant mass resolution around the nominal masses [15]. Figure 3 shows the  $p_1^*$  distribution for  $B_s \rightarrow e^- \tau^+$  and  $B_s \rightarrow \mu^- \tau^+$  after initial selections.

The background comes from the continuum  $e^+ e^- \rightarrow q \bar{q}$  process and  $e^+ e^- \rightarrow B_s^{(*)0} \bar{B}_s^{(*)0}$ ,  $B^{(*)} \bar{B}^{(*)} X$ . The continuum events have final-state particles momenta spatially correlated in two directions forming jet-like structures, while particles from  $B_s^{(*)0} \bar{B}_s^{(*)0}$  events are distributed almost uniformly over the full solid angle in the c.m. frame. We use this difference in the topology to suppress the continuum background. The background from  $B_s^{(*)0} \bar{B}_s^{(*)0}$  or  $B^{(*)} \bar{B}^{(*)} X$  are suppressed using other variables characterizing the signal decay chains. We form a single FastBDT [23] classifier trained using simulated samples with the following discriminating variables as input:  $p_2^*$ ;  $p_3^*$ ; the extra energy from the tracks and clusters not used for signal and tag reconstruction in the calorimeter; the sum of the energy of the clusters and charged tracks in the c.m. frame; the missing energy which is the absolute value of the sum of the four-momenta of all charged candidates; the invariant mass squared of the sum of the four-momenta of all charged candidates;  $(2E_{\text{beam}}^* E_{D_s \ell_3}^* - m_{B_s}^2 c^4 - M_{D_s \ell_3}^2 c^4)/(2|\vec{p}_{B_s}^*||\vec{p}_{D_s \ell_3}^*|c^2)$ ; the cosine of the angle between  $p_1^*$  and  $p_2^*$ ; the mass of the  $D_s^+$  candidate; and 16 modified Fox-Wolfram moments [24, 25] calculated from the signal  $B_s$  daughters and the particles from the rest of the event. Here,  $E_{\text{beam}}^*$  is the



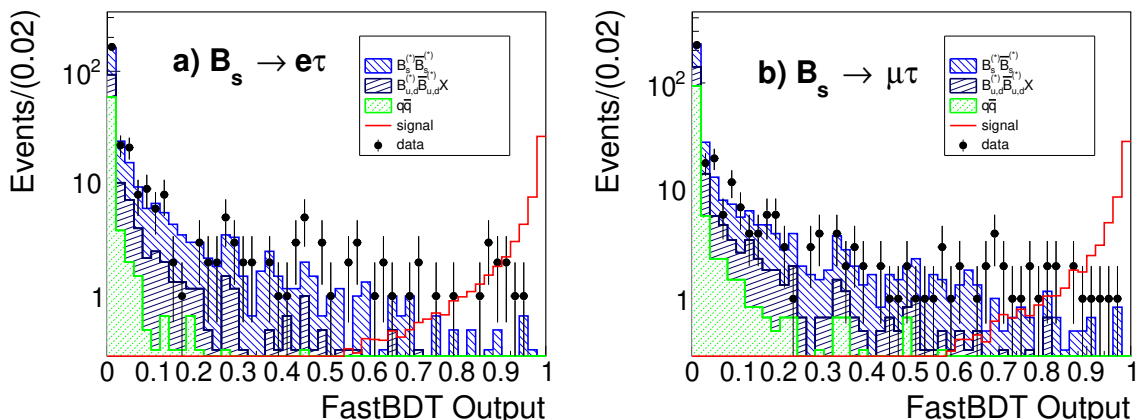
**Figure 2.** The  $M_{D_s}$  distribution of signal MC, generic MC and data. The different background component in generic MC are indicated by different colours as shown in the legend. The MC samples are normalized with respect to the data luminosity. The signal component corresponds to  $\mathcal{B} = 1 \times 10^{-2}$ .



**Figure 3.** The  $p_1^*$  distribution of signal MC, generic MC and data in  $B_s \rightarrow e^- \tau^+$  (a) and  $B_s \rightarrow \mu^- \tau^+$  (b) modes. The different background components in generic MC are indicated by different colours as shown in the legend. The MC samples are normalized with respect to the data luminosity. The signal components correspond to  $\mathcal{B} = 1 \times 10^{-3}$ .

beam energy in the c.m. frame,  $m_{B_s}$  is the nominal  $B_s$  mass,  $|\vec{p}_{B_s}^*| = \left(\sqrt{E_{\text{beam}}^{*2} - m_{B_s}^2 c^2}\right)/c$ , and  $E_{D_s \ell_3}^*$ ,  $\vec{p}_{D_s \ell_3}^*$  and  $M_{D_s \ell_3}$  are calculated from the reconstructed  $D_s \ell_3$  system.

These variables do not have a significant correlation with the signal extraction variable  $p_1^*$ . The FastBDT classifier output  $\mathcal{O}_{\text{FastBDT}}$  ranges from zero, where background events peak, to one, where signal events peak. For each signal mode, we choose selection criteria on  $\mathcal{O}_{\text{FastBDT}}$  that optimize a figure-of-merit (FOM) [26]. The FOM is defined as  $\epsilon_{\text{sig}}/[(a/2) + \sqrt{N_B}]$ , where  $a = 3$ ,  $\epsilon_{\text{sig}}$  is the reconstruction efficiency of signal events as determined from MC simulation, and  $N_B$  is the number of background events expected within the signal region of  $p_1^* \in [2.1, 2.7]$  GeV/c. Figure 4 shows the FastBDT output distributions. Based



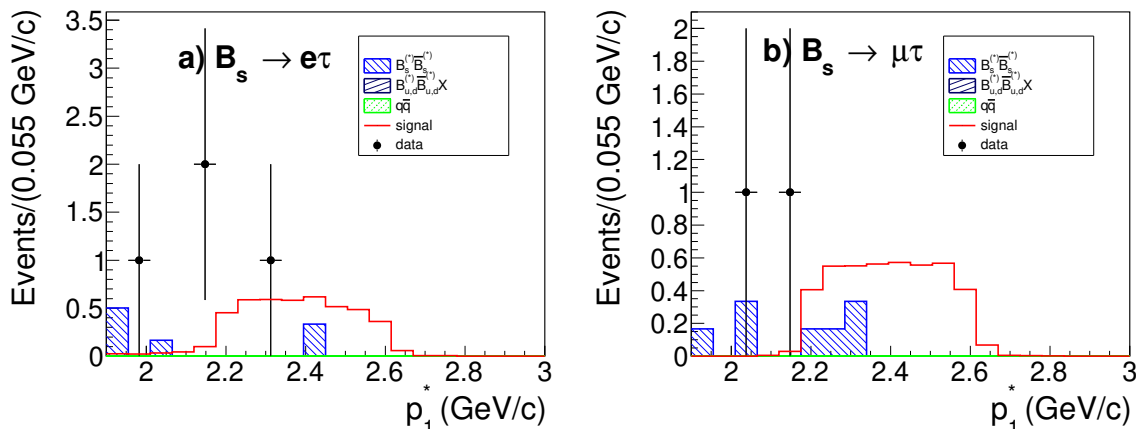
**Figure 4.** The  $\mathcal{O}_{\text{FastBDT}}$  distribution of signal MC, generic MC and data in  $B_s \rightarrow e^- \tau^+$  (a) and  $B_s \rightarrow \mu^- \tau^+$  (b) modes. The different background components in generic MC are indicated by different colours as shown in the legend. The MC samples are normalized with respect to the data luminosity. The signal components correspond to  $\mathcal{B} = 1 \times 10^{-2}$ . The distributions are shown on a logarithmic scale.

on FOM studies, we require  $\mathcal{O}_{\text{FastBDT}} > 0.90$  for  $B_s \rightarrow e^- \tau^+$  and  $\mathcal{O}_{\text{FastBDT}} > 0.94$  for  $B_s \rightarrow \mu^- \tau^+$  modes. These criteria reject 98% of the background events with 40% signal loss. After applying all selection criteria, 8–9% of events have multiple signal candidates. For these events, the candidate with the highest FastBDT output is retained. This criterion is found to select the correct signal candidate 91% of the time for both decay modes. The reconstruction efficiencies from the signal simulations are 0.032% and 0.031% for  $B_s \rightarrow e^- \tau^+$  and  $B_s \rightarrow \mu^- \tau^+$ , respectively. Figure 5 shows the  $p_1^*$  distribution after applying the selection on  $\mathcal{O}_{\text{FastBDT}}$ . We observe three events for  $B_s \rightarrow e^- \tau^+$  and one event for  $B_s \rightarrow \mu^- \tau^+$  in the signal region.

#### 4 Systematic uncertainties

A summary of systematic uncertainties is shown in table 1. In order to estimate the systematic uncertainty of the  $\mathcal{O}_{\text{FastBDT}}$  selection, we use 711  $\text{fb}^{-1}$  data sample taken at the  $\Upsilon(4S)$  and reconstruct  $B^- \rightarrow D^0 \pi^-$  decays, tagging the other side  $B^+$  by  $B^+ \rightarrow \bar{D}^0 \ell^+ \nu$ . Here, the signal side  $D^0$  is reconstructed in the mode  $K^- \pi^+$ , while the tag side  $\bar{D}^0$  is reconstructed in the three decay modes  $\bar{D}^0 \rightarrow K^+ \pi^-$ ,  $K_S^0 \pi^+ \pi^-$ , and  $K^+ \pi^- \pi^+ \pi^-$ . In this study,  $\pi^-$  from  $B^-$  is treated as  $\ell_1$  in the signal mode,  $K^-$  from  $D^0$  as  $\ell_2$ , and  $\pi^+$  from  $D^0$  is neglected. With these changes, the topology of these events becomes similar to our signal mode, and we use the same MVA as for the signal without retraining. For this control sample study, we apply  $M_{D^0} \in [1.85, 1.88] \text{ GeV}/c^2$  for both the  $D^0$  in the signal side and  $\bar{D}^0$  in the tag side,  $|\Delta E| < 0.05 \text{ GeV}$  and  $M_{bc} > 5.2 \text{ GeV}/c^2$ . Here,  $M_{bc}$  and  $\Delta E$  are defined by  $M_{bc} = \left( \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^*|^2 c^2} \right) / c^2$  and  $\Delta E = E_B^* - E_{\text{beam}}^*$ , where  $E_B^*$  and  $\vec{p}_B^*$  are the energy and momentum of the reconstructed  $B$  meson in the c.m. frame.





**Figure 5.** The  $p_1^*$  distribution of signal MC, generic MC and data in (a)  $B_s \rightarrow e^- \tau^+$  and (b)  $B_s \rightarrow \mu^- \tau^+$  modes. The different background components in generic MC are indicated by different colours as shown in the legend. The MC samples are normalized with respect to the data luminosity. The signal component correspond to  $\mathcal{B} = 1 \times 10^{-3}$ .

Source	$B_s \rightarrow e^- \tau^+$	$B_s \rightarrow \mu^- \tau^+$
$\bar{B}_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell$ tag	15.0	15.0
FastBDT selection	3.3	3.7
Lepton ID	4.3	3.5
Tracking	0.7	0.7
$\tau \rightarrow \ell \nu_\tau \bar{\nu}_\ell$ branching fraction	0.2	0.2
Number of $B_s$	16.1	16.1
Total	22.7	22.6

**Table 1.** Estimated fractional systematic errors (%).

We extract the signals from a fit to  $M_{bc}$  with and without the  $\mathcal{O}_{\text{FastBDT}}$  selection. The efficiencies for  $\mathcal{O}_{\text{FastBDT}} > 0.90$  [0.94] that are used in  $B_s \rightarrow e^- \tau^+$  [ $B_s \rightarrow \mu^- \tau^+$ ] are calculated to be  $(69.3 \pm 1.7)\%$  [ $(64.7 \pm 1.7)\%$ ] for MC and  $(69.9 \pm 1.6)\%$  [ $(65.6 \pm 1.7)\%$ ] for data. The uncertainty in the ratio of the data and MC efficiencies is assigned as the systematic uncertainty; these values are 3.3% for  $B_s \rightarrow e^- \tau^+$  and 3.7% for  $B_s \rightarrow \mu^- \tau^+$ .

The semileptonic branching fraction of  $B_s$  is poorly known, so we estimate the systematic uncertainty of tagging from the data, using a control sample of  $\bar{B}_s^0 \rightarrow D_s^+(X) \ell^- \bar{\nu}_\ell$ , i.e. the  $B_s \rightarrow \ell^- \tau^+$  mode is replaced by  $B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell$ . In this control sample study, the signal side  $B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell$  is reconstructed using three  $D_s$  decay modes  $D_s^- \rightarrow \phi(\rightarrow K^+ K^-) \pi^-$ ,  $K_S^0 K^-$ , and  $K^{*0}(\rightarrow K^+ \pi^-) K^-$ . The tag-side  $\bar{B}_s^0 \rightarrow D_s^+(X) \ell^- \bar{\nu}_\ell$  is reconstructed in the same way as for the  $B_s \rightarrow \ell^- \tau^+$  analysis. We require the mass of the tag-side  $D_s$  meson candidate to be  $1.96 < M_{D_s} < 1.98 \text{ GeV}/c^2$ . We also require the momentum of the tag-side lepton to be greater than  $1.0 \text{ GeV}/c$  and  $\mathcal{O}_{\text{FastBDT}}$  to be greater than 0.2. If there are multiple combinations in one event, the one with the highest FastBDT output is retained. We

extract the signal by performing a one-dimensional unbinned fit to  $M_{D_s}$  on the signal side. We find the signal yields  $34.3 \pm 6.7$  and  $37.0 \pm 6.8$  for MC and data events, respectively, which are consistent within the uncertainty. These yields are approximately proportional to the square of the tagging efficiency including the branching fraction of semi-leptonic  $B_s$  decay to  $D_s$ , so we take half the uncertainty on the yields to be the systematic uncertainty from the tag side reconstruction. Taking into account additional contributions due to different  $D_s$  reconstruction and FastBDT selection in this control sample study, we assign 15.0% as the systematic uncertainty from the tag side reconstruction. This uncertainty includes the contribution of the uncertainty on the branching fraction of the semi-leptonic  $B_s$  decay to  $D_s$  as well as the effect of the reconstruction and selection on  $D_s$  and  $\ell$ .

Other systematic uncertainties arise from the signal-side leptons  $\ell_1$  and  $\ell_2$ . The systematic uncertainty due to charged track reconstruction is estimated to be 0.35% per track by using the partially reconstructed  $D^{*-} \rightarrow \bar{D}^0\pi^-$ ,  $\bar{D}^0 \rightarrow \pi^-\pi^+K_S^0$  and  $K_S^0 \rightarrow \pi^+\pi^-$  events [27]. The systematic uncertainties due to lepton identification are 4.3% and 3.5% for  $B_s \rightarrow e^-\tau^+$  and  $B_s \rightarrow \mu^-\tau^+$  decay modes, respectively. The systematic uncertainties due to the  $\tau$  decay branching fractions are 0.2% [15]. In addition, the systematic uncertainty due to  $B_s$  meson counting is estimated as 16.1%. The total systematic uncertainty is taken as the sum in quadrature of all individual contributions.

## 5 Results and summary

In the signal region, we find three events for  $B_s \rightarrow e^-\tau^+$  and one event for  $B_s \rightarrow \mu^-\tau^+$ , as shown in figure 5. The expected number of background events in the signal region,  $N_{\text{bkg}}^{\text{exp}}$ , is estimated from the number of events in the sideband, scaled by the ratio of events in the signal region and sideband without the  $\mathcal{O}_{\text{FastBDT}}$  selection as determined from MC simulation. Here, the sidebands are defined as  $p_1^* \in [1.9, 2.1]$  GeV/ $c$  and  $p_1^* \in [2.7, 3.0]$  GeV/ $c$ . We find  $N_{\text{bkg}}^{\text{exp}} = 0.68 \pm 0.69$  for  $B_s \rightarrow e^-\tau^+$  and  $N_{\text{bkg}}^{\text{exp}} = 0.77 \pm 0.78$  for  $B_s \rightarrow \mu^-\tau^+$ . The number of observed events in the electron mode is larger but not inconsistent with the expected number, and the probability of obtaining three or more events with  $N_{\text{bkg}}^{\text{exp}} = 0.68 \pm 0.69$  is 7.3%. The  $p_1^*$  distribution of the three events in the electron mode is different from the expectation for the signal. Thus we calculate upper limits on the branching fractions.

To calculate this limit, we use the POLE program [28, 29] with the relation  $\mathcal{B} = (N_{\text{obs}} - N_{\text{bkg}}^{\text{exp}})/(N_{B_s} \times \epsilon_{\text{sig}})$ , where  $N_{\text{obs}}$  is the number of the observed events,  $N_{B_s}$  is the number of  $B_s$  mesons in the data  $(16.6 \pm 2.7) \times 10^6$ , and  $\epsilon_{\text{sig}}$  is the signal efficiency including the branching fraction of  $\tau$ . The uncertainties on  $\epsilon_{\text{sig}}$  and  $N_{B_s}$  listed in section 4, together with the uncertainty of  $N_{\text{bkg}}^{\text{exp}}$ , are taken into account in the upper limit estimation [28]. Since the uncertainty in  $f_s$  is significant, we report the upper limit not only on the branching fraction but also on  $f_s \times \mathcal{B}(B_s \rightarrow \ell^-\tau^+)$ . Table 2 summarizes the results, including the upper limit.

To summarize, we have searched for the decays  $B_s^0 \rightarrow \ell^\mp\tau^\pm$  using the Belle data sample of  $121 \text{ fb}^{-1}$  collected at the  $\Upsilon(5S)$  resonance. From the observed signal yields, we

	$\epsilon$ (%)	$N_{\text{bkg}}^{\text{exp}}$	$N_{\text{obs}}$	$\mathcal{B}$ ( $\times 10^{-4}$ )	$f_s \times \mathcal{B}$ ( $\times 10^{-4}$ )
$B_s \rightarrow e^- \tau^+$	$0.031 \pm 0.007$	$0.68 \pm 0.69$	3	$< 14$	$< 5.5$
$B_s \rightarrow \mu^- \tau^+$	$0.030 \pm 0.007$	$0.77 \pm 0.78$	1	$< 7.3$	$< 2.9$

**Table 2.** Efficiency ( $\epsilon$ ), expected background events ( $N_{\text{bkg}}^{\text{exp}}$ ), observed events ( $N_{\text{obs}}$ ) and the 90% C.L. upper limits on  $\mathcal{B}$  and  $f_s \times \mathcal{B}$ .

set upper limits

$$\mathcal{B}(B_s^0 \rightarrow e^\mp \tau^\pm) < 14 \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^\mp \tau^\pm) < 7.3 \times 10^{-4}$$

at 90% confidence level. Our limit on the  $B_s^0 \rightarrow e^\mp \tau^\pm$  decay rate is the first such limit reported. The sensitivity to these modes can be improved in the future with the Belle II experiment, which could collect a much larger data sample at the  $\Upsilon(5S)$  resonance, and apply enhanced analysis techniques such as full reconstruction of the tag  $\bar{B}_s^0$  [30].

## Acknowledgments

This work, based on data collected using the Belle detector, which was operated until June 2010, was supported by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council including grants DP180102629, DP170102389, DP170102204, DE220100462, DP150103061, FT130100303; Austrian Federal Ministry of Education, Science and Research (FWF) and FWF Austrian Science Fund No. P 31361-N36; the National Natural Science Foundation of China under Contracts No. 11675166, No. 11705209; No. 11975076; No. 12135005; No. 12175041; No. 12161141008; Key Research Program of Frontier Sciences, Chinese Academy of Sciences (CAS), Grant No. QYZDJ-SSW-SLH011; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. LTT17020; the Czech Science Foundation Grant No. 22-18469S; Horizon 2020 ERC Advanced Grant No. 884719 and ERC Starting Grant No. 947006 “InterLeptons” (European Union); the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft, the Excellence Cluster Universe, and the VolkswagenStiftung; the Department of Atomic Energy (Project Identification No. RTI 4002) and the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; National Research Foundation (NRF) of Korea Grant Nos. 2016R1D1A1B02012900, 2018R1A2B3003643, 2018R1A6A1A06024970, RS202200197659, 2019R1I1A3A01058933, 2021R1A6A1A03043957, 2021R1F1A1060423, 2021R1F1A1064008, 2022R1A2C1003993; Radiation Science Research Institute, Foreign Large-size Research Facility Application Supporting project, the Global Science Experimental Data Hub Center of the Korea Institute of Science and Technology Information and KREONET/GLORIAD; the Polish Ministry of Science and Higher Education and the

National Science Center; the Ministry of Science and Higher Education of the Russian Federation, Agreement 14.W03.31.0026, and the HSE University Basic Research Program, Moscow; University of Tabuk research grants S-1440-0321, S-0256-1438, and S-0280-1439 (Saudi Arabia); the Slovenian Research Agency Grant Nos. J1-9124 and P1-0135; Ikerbasque, Basque Foundation for Science, Spain; the Swiss National Science Foundation; the Ministry of Education and the Ministry of Science and Technology of Taiwan; and the United States Department of Energy and the National Science Foundation. These acknowledgements are not to be interpreted as an endorsement of any statement made by any of our institutes, funding agencies, governments, or their representatives. We thank the KEKB group for the excellent operation of the accelerator; the KEK cryogenics group for the efficient operation of the solenoid; and the KEK computer group and the Pacific Northwest National Laboratory (PNNL) Environmental Molecular Sciences Laboratory (EMSL) computing group for strong computing support; and the National Institute of Informatics, and Science Information NETwork 6 (SINET6) for valuable network support. S.N. is supported by JSPS KAKENHI grant JP17K05474.

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] SUPER-KAMIOKANDE collaboration, *Tau neutrinos favored over sterile neutrinos in atmospheric muon-neutrino oscillations*, *Phys. Rev. Lett.* **85** (2000) 3999 [[hep-ex/0009001](#)] [[INSPIRE](#)].
- [2] D. London and J. Matias, *B Flavour Anomalies: 2021 Theoretical Status Report*, *Ann. Rev. Nucl. Part. Sci.* **72** (2022) 37 [[arXiv:2110.13270](#)] [[INSPIRE](#)].
- [3] U. Egede, S. Nishida, M. Patel and M.-H. Schune, *Electroweak Penguin Decays of b-Flavored Hadrons*, *Ann. Rev. Nucl. Part. Sci.* **72** (2022) 283 [[arXiv:2205.05222](#)] [[INSPIRE](#)].
- [4] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski and J. Rosiek, *Lepton-flavour violating B decays in generic Z' models*, *Phys. Rev. D* **92** (2015) 054013 [[arXiv:1504.07928](#)] [[INSPIRE](#)].
- [5] A.D. Smirnov, *Vector leptoquark mass limits and branching ratios of  $K_L^0, B^0, B_s \rightarrow l_i^+ l_j^-$  decays with account of fermion mixing in leptoquark currents*, *Mod. Phys. Lett. A* **33** (2018) 1850019 [[arXiv:1801.02895](#)] [[INSPIRE](#)].
- [6] I. de Medeiros Varzielas and G. Hiller, *Clues for flavor from rare lepton and quark decays*, *JHEP* **06** (2015) 072 [[arXiv:1503.01084](#)] [[INSPIRE](#)].
- [7] D. Bečirević, N. Košnik, O. Sumensari and R. Zukanovich Funchal, *Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive  $b \rightarrow s l_1 l_2$  modes*, *JHEP* **11** (2016) 035 [[arXiv:1608.07583](#)] [[INSPIRE](#)].
- [8] LHCb collaboration, *Search for the lepton-flavour-violating decays  $B_s^0 \rightarrow \tau^\pm \mu^\mp$  and  $B^0 \rightarrow \tau^\pm \mu^\mp$* , *Phys. Rev. Lett.* **123** (2019) 211801 [[arXiv:1905.06614](#)] [[INSPIRE](#)].
- [9] S. Kurokawa and E. Kikutani, *Overview of the KEKB accelerators*, *Nucl. Instrum. Meth. A* **499** (2003) 1 [[INSPIRE](#)].

- [10] T. Abe et al., *Achievements of KEKB*, *Prog. Theor. Exp. Phys.* **2013** (2013) 03A001 [INSPIRE].
- [11] A. Abashian et al., *The Belle Detector*, *Nucl. Instrum. Meth. A* **479** (2002) 117 [INSPIRE].
- [12] BELLE collaboration, *Physics Achievements from the Belle Experiment*, *Prog. Theor. Exp. Phys.* **2012** (2012) 04D001 [arXiv:1212.5342] [INSPIRE].
- [13] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [INSPIRE].
- [14] R. Brun, F. Bruyant, M. Maire, A.C. McPherson and P. Zancarini, *GEANT 3: user's guide Geant 3.10, Geant 3.11*, rev. version edition, CERN, Geneva (1987) [CERN-DD-EE-84-01].
- [15] PARTICLE DATA collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2022** (2022) 083C01 [INSPIRE].
- [16] M. Gelb et al., *B2BII: Data Conversion from Belle to Belle II*, *Comput. Softw. Big Sci.* **2** (2018) 9 [arXiv:1810.00019] [INSPIRE].
- [17] BELLE-II FRAMEWORK SOFTWARE Group, *The Belle II Core Software*, *Comput. Softw. Big Sci.* **3** (2019) 1 [arXiv:1809.04299] [INSPIRE].
- [18] BELLE II collaboration, *Belle II Analysis Software Framework (basf2): release-06-00-00*, Zenodo (2011) [DOI:10.5281/ZENODO.5574116].
- [19] BELLE collaboration, *Precise measurement of the branching fractions for  $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$  and first measurement of the  $D_s^{*+} D_s^{*-}$  polarization using  $e^+e^-$  collisions*, *Phys. Rev. D* **87** (2013) 031101 [arXiv:1208.0323] [INSPIRE].
- [20] BELLE collaboration, *Measurement of time-dependent CP asymmetries in  $B^0 \rightarrow K_S^0 \eta \eta$  decays*, *Phys. Rev. D* **97** (2018) 092003 [arXiv:1803.07774] [INSPIRE].
- [21] A. Abashian et al., *Muon identification in the Belle experiment at KEKB*, *Nucl. Instrum. Meth. A* **491** (2002) 69 [INSPIRE].
- [22] K. Hanagaki, H. Kakuno, H. Ikeda, T. Iijima and T. Tsukamoto, *Electron identification in Belle*, *Nucl. Instrum. Meth. A* **485** (2002) 490 [hep-ex/0108044] [INSPIRE].
- [23] T. Keck, *FastBDT: A Speed-Optimized Multivariate Classification Algorithm for the Belle II Experiment*, *Comput. Softw. Big Sci.* **1** (2017) 2 [INSPIRE].
- [24] G.C. Fox and S. Wolfram, *Observables for the Analysis of Event Shapes in  $e^+e^-$  Annihilation and Other Processes*, *Phys. Rev. Lett.* **41** (1978) 1581 [INSPIRE].
- [25] BELLE collaboration, *Evidence for  $B^0 \rightarrow \pi^0 \pi^0$* , *Phys. Rev. Lett.* **91** (2003) 261801 [hep-ex/0308040] [INSPIRE].
- [26] G. Punzi, *Sensitivity of searches for new signals and its optimization*, *eConf C030908* (2003) MODT002 [physics/0308063] [INSPIRE].
- [27] BELLE collaboration, *Measurements of Branching Fractions of  $\tau$  Lepton Decays with one or more  $K_S^0$* , *Phys. Rev. D* **89** (2014) 072009 [arXiv:1402.5213] [INSPIRE].
- [28] J. Conrad, O. Botner, A. Hallgren and C. Pérez de los Heros, *Including systematic uncertainties in confidence interval construction for Poisson statistics*, *Phys. Rev. D* **67** (2003) 012002 [hep-ex/0202013] [INSPIRE].
- [29] F. Tegenfeldt, *ftegenfe/polepp*, <https://github.com/ftegenfe/polepp>.
- [30] T. Keck et al., *The Full Event Interpretation: An Exclusive Tagging Algorithm for the Belle II Experiment*, *Comput. Softw. Big Sci.* **3** (2019) 6 [arXiv:1807.08680] [INSPIRE].