Evidence for modification of $b$ quark hadronization in high-multiplicity $pp$ collisions at $\sqrt{s} = 13$ TeV

LHCb collaboration†

Abstract

The production rate of $B^0_s$ mesons relative to $B^0$ mesons is measured by the LHCb experiment in $pp$ collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV over the forward rapidity interval $2 < y < 4.5$ as a function of the charged particle multiplicity measured in the event. Evidence at the 3.4σ level is found for an increase of the ratio of $B^0_s$ to $B^0$ cross-sections with multiplicity at transverse momenta below 6 GeV/$c$, with no significant multiplicity dependence at higher transverse momentum. Comparison with data from $e^+e^-$ collisions implies that the density of the hadronic medium may affect the production rates of $B$ mesons. This is qualitatively consistent with the emergence of quark coalescence as an additional hadronization mechanism in high-multiplicity collisions.

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†Authors are listed at the end of this Letter.
Measurements of $B$ mesons at colliders offer unique probes of the hadronization process by which single quarks evolve into color-neutral hadrons. In contrast to light quarks, the large mass of $b$ quarks suppresses their production via non-perturbative processes. In addition there is no $b$ content in the valence quark distribution of the incoming beam particles \[1\]. Therefore, production of $b\bar{b}$ pairs at hadron colliders is dominated by hard parton-parton interactions in the initial stages of the collisions, and is well described by perturbative QCD calculations \[2,4\].

The fraction of $b$ quarks that pair with an $s$ quark to form $B^0_s$ mesons, $f_s$, and the fraction that pair with a light $d$ quark to form $B^0$ mesons, $f_d$, are determined through the hadronization process. One mechanism for hadronization is fragmentation, where showers of partons produced by outgoing quarks form into hadrons \[5,6\]. Measurements of $B$ hadron production in $e^+e^-$ collisions at the $\Upsilon(5S)$ \[7,9\] and $Z^0$ \[10,13\] resonances give consistent values for the ratio $f_s/f_d$, which is often interpreted as evidence for the universality of $b$ quark fragmentation assumed by QCD factorization theorems \[14\]. However, measurements at hadron colliders have shown that the ratio $f_s/f_d$ has a dependence on the collision center-of-mass energy and the $B$ meson transverse momentum $p_T$ \[15-19\]. The fraction of $b$ quarks which hadronize into baryons also varies with $p_T$ \[20,21\]. Additionally, recent measurements have shown that charm quark hadronization differs between $e^+e^-$ and $pp$ collisions \[22\]. The reason for these variations is not immediately clear, and may be explained by hadronization mechanisms other than fragmentation \[23\].

An alternative hadronization process, quark coalescence, can occur when a quark produced in the collision combines with another quark to form a color singlet hadron. Models incorporating coalescence are successful at reproducing a range of measurements from fixed-target experiments and colliders \[24-28\]. Coalescence calculations generally require multiple quark wavefunctions to overlap in position and velocity, so the fraction of hadrons produced by this mechanism is expected to increase with the number of quarks produced in the collision. The effect is expected to be most prominent at relatively low $p_T$, which is the range where the bulk of the particles created in the collision are found. Coalescence can also lead to enhanced production of baryons at low $p_T$, and is especially important in high-energy heavy ion collisions where a large volume of deconfined quark-gluon plasma (QGP) is formed \[29-31\]. Data from the CMS collaboration has shown that $B^0$ production may be enhanced relative to $B^+$ production in PbPb collisions when compared to $pp$ collisions \[32,33\]. However, significant uncertainties and the relatively high $p_T$ range covered by that data preclude drawing firm conclusions on the influence of coalescence on $B$ hadronization.

Recent measurements in $pp$ collisions have shown some behaviors similar to those associated with the formation of QGP in collisions of heavy nuclei \[34,36\]. Among these effects is an enhanced yield of light-quark baryons and mesons with strangeness in collisions where a relatively large number of charged particles are produced \[37\], which was originally proposed as a QGP signature \[38\]. If hadronization via coalescence emerges as a mechanism for forming final state $B$ hadrons, then the production rates of $B^0_s$ hadrons could increase relative to the production of $B^0$ hadrons as particle multiplicity increases.

This Letter describes LHCb measurements of the ratio of $B^0_s$ to $B^0$ cross sections, $\sigma_{B^0_s}/\sigma_{B^0}$, as a function of charged particle multiplicity and $p_T$. Both the $B^0_s$ and $B^0$ candidates are reconstructed through their decays to the $J/\psi\pi^+\pi^-$ final state, where the $J/\psi$ decays into a $\mu^+\mu^-$ pair. This decay mode provides similar yields for both $B^0_s$ and $B^0$ mesons. Here multiplicity is represented by the number of charged tracks.
reconstructed in a silicon strip detector that surrounds the $pp$ interaction region, the LHCb VELO detector [39,40]. These measurements use a sample of $pp$ collisions collected at a center-of-mass energy $\sqrt{s} = 13\text{ TeV}$, corresponding to an integrated luminosity of $5.4\text{ fb}^{-1}$.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [41,42]. Events considered in this analysis are required to satisfy a series of triggers designed to select the decay $J/\psi \rightarrow \mu^+\mu^-$ and have one reconstructed $pp$ interaction point (primary vertex). Each muon candidate is required to penetrate the hadron absorber layers in the LHCb muon system and have $p_T > 500\text{ MeV}/c$. Candidate $J/\psi$ mesons are formed from pairs of oppositely charged muon candidates that have an invariant mass near the known $J/\psi$ mass and originate from a vertex that is displaced from the primary vertex. Charged pion candidates are identified by the response of the LHCb ring-imaging Cherenkov detectors, and are required to have total momentum $p > 3\text{ GeV}/c$ and transverse momentum $p_T > 750\text{ MeV}/c$. Candidate $\mu^+\mu^-\pi^+\pi^-$ combinations that form a good quality common vertex are retained, and the tracks are refit with kinematic constraints that fix the $\mu^+\mu^-$ invariant mass to the known $J/\psi$ mass, and require all four tracks to have the same origin point [43].

Simulation is required to model the effects of the detector acceptance and the selection requirements. In the simulation, $pp$ collisions are generated using PYTHIA [44] with a specific LHCb configuration [45]. Decays of unstable particles are described by EVTGEN [46]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [47] as described in Ref. [48]. The $p_T$ distributions of the simulated $B^0$ and $B^0_s$ mesons, the invariant mass distributions of $\pi^+\pi^-$ pairs from their decays, and simulated event multiplicity distributions are weighted to match background-subtracted distributions that are extracted from the data using the sPlot method [49].

The multiplicity metrics used in this analysis are the total number of charged tracks reconstructed in the VELO detector, $N_{\text{VELO\,tracks}}$, and the subset of VELO tracks that point in the backward direction, away from the LHCb spectrometer, $N_{\text{back\,tracks}}$. The backward tracks cover a pseudorapidity interval of approximately $-3.5 < \eta < -1.5$, providing a multiplicity estimate that is measured in a different region than the signal. The VELO detector and its performance are described in detail in Refs. [39,40]. Figure 1 shows the distributions of $N_{\text{VELO\,tracks}}$ and $N_{\text{back\,tracks}}$ for both NoBias events and $B^0$ signal events with one reconstructed primary vertex, which requires at least five reconstructed tracks. NoBias events are selected based on the Large Hadron Collider beam clock, which indicates that a bunch crossing has occurred, without any other trigger requirements. The distributions for $B^0$ signal events are extracted from the data, and background is removed using the sPlot method [49]. The results are quoted in terms of normalized multiplicity, defined as the number of tracks at the center of a given multiplicity interval divided by the mean number of tracks in NoBias events, which are $\langle N_{\text{VELO\,tracks}} \rangle_{\text{NoBias}} = 37.7$ and $\langle N_{\text{back\,tracks}} \rangle_{\text{NoBias}} = 11.1$, with negligibly small uncertainties. For comparison, the mean number of $N_{\text{VELO\,tracks}}$ and $N_{\text{back\,tracks}}$ are $71.1 \pm 0.1$ and $17.4 \pm 0.3$ for $B^0$ signal events, respectively, where the uncertainty is due to the statistical uncertainty on the track distributions. In some respects, the low- and high-multiplicity data samples approach the hadronic environments achieved in $e^+e^-$ collisions and heavy-ion collisions, respectively.

The sample containing signal events is divided into intervals of multiplicity, and in each interval a likelihood fit is performed on the $J/\psi\pi^+\pi^-$ invariant mass spectrum to
Figure 1: Distribution of the number of VELO tracks and backward tracks for NoBias events (red) and $B^0$ signal events (blue), each with only one primary vertex. The vertical scale is arbitrary.

determine the ratio of $B^0_s$ to $B^0$ yields. Examples of the $J/\psi \pi^+ \pi^-$ mass distribution in low- and high-multiplicity intervals are shown in Fig. 2. An increase of the $B^0_s$ yield relative to the $B^0$ yield in the high-multiplicity interval is apparent. The $B^0_s$ and $B^0$ peaks are each represented in the fit by a sum of two Crystal Ball functions, which have tail parameters constrained to values determined by simulation. The background contribution is represented by an exponential function, which is found to provide a good description of the purely combinatorial $J/\psi \pi^+ \pi^-$ mass spectrum with like-sign dipions. All multiplicity intervals are fit simultaneously, where the signal shapes are constrained to be the same in each interval, but their normalization and the background parameters are allowed to vary. The $B^0_s$ and $B^0$ line shapes are nearly identical, and variations of the fit functions have a negligible effect on the extracted ratio of $B^0_s$ to $B^0$ yields.

Figure 2: Measured $J/\psi \pi^+ \pi^-$ invariant mass distributions and fit projections in the multiplicity ranges a) $30 < N_{\text{VELO tracks}}^\text{VELO} \leq 40$ and b) $100 < N_{\text{VELO tracks}}^\text{VELO} \leq 125$. 


The ratio of cross-sections $\frac{\sigma_{B^0}}{\sigma_{B^0}}$ is found by calculating

$$\frac{\sigma_{B^0}}{\sigma_{B^0}} = \frac{N_{B^0}}{N_{B^0}} \times \frac{B_{B^0}}{B_{B^0}} \times \frac{\varepsilon_{\text{acc}}^{B^0}}{\varepsilon_{\text{acc}}^{B^0}} \times \frac{\varepsilon_{\text{trig}}^{B^0}}{\varepsilon_{\text{trig}}^{B^0}} \times \frac{\varepsilon_{\text{PID}}^{B^0}}{\varepsilon_{\text{PID}}^{B^0}} \times \frac{\varepsilon_{\text{reco}}^{B^0}}{\varepsilon_{\text{reco}}^{B^0}}$$

(1)

where $N_{B^0}/N_{B^0}$ is the ratio of $B^0$ to $B^0$ signal yields returned by the fit, $B_{B^0}/B_{B^0}$ is the ratio of $B^0$ to $B^0$ branching fractions to $J/\psi\pi^+\pi^-$ [19,50], and $\varepsilon_{\text{acc}}^{B^0}/\varepsilon_{\text{acc}}^{B^0}$, $\varepsilon_{\text{trig}}^{B^0}/\varepsilon_{\text{trig}}^{B^0}$, $\varepsilon_{\text{PID}}^{B^0}/\varepsilon_{\text{PID}}^{B^0}$, and $\varepsilon_{\text{reco}}^{B^0}/\varepsilon_{\text{reco}}^{B^0}$ are ratios of the LHCb acceptance and the trigger, particle identification, and reconstruction efficiencies for $B^0$ to $B^0$ mesons, respectively. Due to the similarities of the $B^0_s$ and $B^0$ decays, many systematic uncertainties partially cancel in this ratio of cross sections. The ratio of the LHCb acceptance for the decays $\varepsilon_{\text{acc}}^{B^0}/\varepsilon_{\text{acc}}^{B^0}$ is found, using simulation, to be consistent with unity, with an uncertainty of $\sim 1\%$ due to the uncertainty on the weights applied to the simulation in order to match the data. The ratio of trigger efficiencies $\varepsilon_{\text{trig}}^{B^0}/\varepsilon_{\text{trig}}^{B^0}$ is determined from data to be consistent with unity, with an uncertainty of $\sim 1\%$, using techniques described in Ref. [51], where the uncertainty comes from statistical uncertainties on the data sample. The ratio of particle identification efficiencies $\varepsilon_{\text{PID}}^{B^0}/\varepsilon_{\text{PID}}^{B^0}$ is found using calibrated samples of identified muons and pions obtained from the data, and is consistent with unity with an uncertainty of $\sim 1\%$ due to the finite size of the calibration sample. The only term with a significant difference from unity is the ratio of reconstruction efficiencies, which is found to be $\varepsilon_{\text{reco}}^{B^0}/\varepsilon_{\text{reco}}^{B^0} = 0.86 \pm 0.04$ for the $p_T$-integrated sample. This is due to the difference in the dipion mass distributions produced in the $B^0_s$ and $B^0$ decays: the $B^0_s$ decay is dominated by contributions from intermediate $f_0(980)$ and $f_0(1500)$ states [52], which are reconstructed with higher efficiency than the lower-mass $p^0(770)$ intermediate state that is significant in $B^0$ decays [53]. The uncertainty on this correction is due to the statistical uncertainty on the weights extracted from the data that are applied to the simulation in order to match the measured $B$ meson $p_T$ and dipion mass distributions.

The ratio of cross-sections for the multiplicity-integrated samples is found to be $\sigma_{B^0}/\sigma_{B^0} = 0.30 \pm 0.01 \pm 0.03$, where the first uncertainty is statistical and the second is systematic. This measurement agrees with previous LHCb measurements of $f_s/f_d$ using different decay channels [19] within 1.5 standard deviations.

The multiplicity dependence of $\sigma_{B^0}/\sigma_{B^0}$ is shown in Fig. 3 for two different multiplicity metrics. The vertical error bars (boxes) represent point-to-point uncorrelated (fully correlated) uncertainties, while the horizontal error bars represent the bin width. Numerical values are given in the supplemental material [54]. In the left panel, the ratio shows an increasing trend with the total VELO multiplicity, where multiplicity is normalized to the mean value found in NoBias collisions. Also shown are the $\sigma_{B^0}/\sigma_{B^0}$ values measured in $e^+e^-$ collisions at the $Y(5S)$ and $Z^0$ resonances [55], which are in good agreement with the data at low multiplicity. The right panel shows the same ratio versus the normalized $N_{\text{tracks}}$. No significant dependence is observed on the multiplicity measured in the backward region. The dependence on total multiplicity, compared to the lack of dependence on multiplicity measured at backward rapidity, could indicate that the mechanism responsible for the increase in the $\sigma_{B^0}/\sigma_{B^0}$ ratio is related to the local particle density in a similar rapidity interval as the $B$ mesons themselves.

The multiplicity dependence of $\sigma_{B^0}/\sigma_{B^0}$ is shown in three different intervals of $B$ meson $p_T$ in Fig. 4. Numerical values are given in the supplemental material [54]. The lowest $p_T$ interval, $0 < p_T < 6$ GeV/$c$, encompasses $B$ mesons with $p_T$ approximately...
equal to or less than their mass. In this $p_T$ interval, at low multiplicity the $\sigma_{B^0}/\sigma_{B^0}$ ratio is consistent with values measured in $e^+e^-$ collisions, and increases with multiplicity. A line fit to these data returns a slope of $0.075 \pm 0.022 \left(N_{\text{tracks}}^{\text{VELO}} / N_{\text{tracks}}^{\text{NoBias}}\right)^{-1}$, which differs from zero by 3.4 standard deviations and thereby provides evidence for an increase of the the $\sigma_{B^0}/\sigma_{B^0}$ ratio. This fit considers only the point-to-point uncorrelated uncertainties; since all data points must move simultaneously within the correlated uncertainties, they have no effect on the extracted slope.

For comparison, the ratio of cross sections calculated by the PYTHIA event generator is also shown. Events are generated with and without color reconnection (CR), a process which allows partons produced by from different interactions in the collision to be connected by color lines \[\text{[56, 57]}\]. Color reconnection was introduced to model charged particle production in hadron collisions, and is thought to be especially important in high-multiplicity collisions where multiple-parton interactions are significant. Both sets of PYTHIA calculations show a rise with multiplicity, which is more pronounced when CR is included. The PYTHIA models agree with the data at relatively low multiplicity, but both scenarios give values that are lower than the central values of the data at high multiplicity.

The measurements in higher $p_T$ intervals, $6 < p_T < 12$ GeV/$c$ and $12 < p_T < 20$ GeV/$c$, display no significant dependence on multiplicity and are consistent with data from $e^+e^-$ collisions. This behavior is expected in a scenario where low-$p_T$ $b$ quarks with relatively low velocity recombine with $s$ quarks produced in high-multiplicity collisions, while the wavefunctions of higher $p_T$ $b$ quarks have less overlap with the low-$p_T$ bulk of the quarks produced in the collision. These high-$p_T$ $b$ quarks would thereby dominantly hadronize via fragmentation in vacuum, as in $e^+e^-$ collisions, rather than via coalescence. Again, both sets of PYTHIA calculations show a rising trend, which is more pronounced when color reconnection is included. However, here the uncertainties on the data prevent

![Figure 3: Ratio of cross sections $\sigma_{B^0}/\sigma_{B^0}$ versus the normalized multiplicity of a) all VELO tracks, and b) backward VELO tracks. The vertical error bars (boxes) represent point-to-point uncorrelated (fully correlated) uncertainties. The horizontal bands show the values measured in $e^+e^-$ collisions.](#)
discrimination between the two scenarios. Lines fit to the $6 < p_T < 12$ GeV/$c$ and $12 < p_T < 20$ GeV/$c$ data have slopes that are consistent with zero within 0.2 and 1.3 standard deviations, respectively.

In summary, LHCb measurements in $pp$ collisions at $\sqrt{s} = 13$ TeV show evidence that the production of $B^0$ mesons is enhanced relative to $B^0$ mesons in collisions with high charged-particle multiplicity, indicating that strangeness enhancement is present in $B$ hadron production. In collisions with relatively low charged-particle multiplicity, and for $B$ mesons with $p_T > 6$ GeV/$c$, the rate of $B^0$ production relative to $B^0$ production is consistent with what is measured in $e^+e^-$ collisions. These measurements are qualitatively consistent with expectations based on the emergence of quark coalescence as an additional hadronization mechanism, rather than fragmentation alone. These results could indicate that interactions of the $b$ quarks with the local hadronic environment influence the hadronization process, thereby breaking factorization of $b$ quark hadronization between $e^+e^-$ and hadron collisions.

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LHCb collaboration

R. Aaij 34, A.S.W. Abdelmotteleb 56, C. Abellan Beteta 44, F. Abudinén 65, T. Ackermans 54, B. Adeva 40, M. Adinolfi 48, H. Afsharnia 9, C. Agapopoulou 15, C.A. Aidala 76, S. Aiola 25, Z. Ajaltouni 9, S. Akar 59, K. Akiba 34, J. Albrecht 12, F. Alessio 42, M. Alexander 34, A. Alfonso Albero 36, Z. Aliouche 13, P. Alvarez Cartelle 49, S. Amato 14, J.L. Amey 48, Y. Ambis 11, 41, 42, L. An 42, L. Anderlini 22, M. Andersson 44, A. Andreianov 38, M. Andreotti 14, D. Andreou 62, D. Ao 6, F. Archilli 17, A. Artamonov 38, M. Artuso 62, E. Aslanides 16, M. Atzeni 44, B. Audurier 12, S. Bachmann 17, M. Bachmayer 44, J.J. Back 56, A. Bailly-reyre 13, P. Baladron Rodriguez 46, V. Balagura 12, W. Baldini 31, J. Baptista de Souza Leite 4, M. Barbetti 22, R.J. Barlow 56, 74, S. Barsuk 34, W. Barter 59, M. Bartolini 24, F. Baryshnikov 38, J.M. Basels 14, G. Bassi 29, B. Batsukh 16, A. Battig 15, A. Bay 47, A. Beck 34, M. Becker 13, F. Bedeschi 8, I.B. Bediaga 14, A. Beiter 62, V. Belavin 58, S. Belin 40, V. Bello 44, K. Belous 38, I. Belov 38, I. Belyaev 38, G. Bencivenni 23, E. Ben-Haim 13, A. Berezhnoy 38, R. Bernet 44, D. Berninghoff 17, H.C. Bernstein 62, C. Bertella 50, A. Bertolin 26, C. Betancourt 14, F. Betti 55, Ia. Bezshykio 6, S. Bhasin 14, J. Bhom 14, L. Bian 67, M.S. Bieker 15, N.V. Biesuz 21, S. Bifani 47, P. Billoir 13, A. Biolkhim 32, M. Birch 53, F.C.R. Bishop 41, A. Bitadze 49, A. Bizzeti 57, M.P. Blago 59, S. Blake 59, F. Blanc 59, S. Blusk 62, D. Bobulka 52, J.A. Boelhaue 15, O. Boente Garcia 60, T. Boettcher 59, A. Boldyrev 38, N. Bondar 38, 42, S. Borghi 56, M. Borsato 17, J.T. Borisuk 22, S.A. Bouchiba 44, T.J.V. Bowcock 55, 42, A. Boyer 42, C. Bozzi 21, M.J. Bradley 55, S. Braun 66, A. Brea Rodriguez 46, J. Brodzicka 97, A. Brossa Gonzano 94, D. Brundu 27, A. Buonaura 44, L. Buonincontri 29, A.T. Burke 56, C. Burr 42, A. Bursche 46, A. Butkevich 98, J.S. Butler 32, J. Buytaert 42, W. Byczynski 42, S. Cadeddu 27, H. Cai 67, R. Calabrese 21, L. Calefico 15, 13, E. Cali 24, R. Calladine 47, M. Calvi 26, M. Calvo Gomez 74, P. Camargo Magalhaes 55, P. Campana 44, D.H. Campora Perez 73, A.F. Campoverde Quezada 9, S. Capelli 26, L. Capriotti 20, A. Carbone 20, G. Carboni 24, R. Cardinale 24, A. Cardini 27, I. Carli 4, P. Carniti 26, L. Carus 14, A. Casais Vidal 40, R. Caspary 17, G. Casse 54, M. Cattaneo 42, G. Cavallero 42, V. Cavallini 21, S. Celani 43, J. Cerasoli 16, D. Cervenkov 15, A.J. Chadwick 15, M.G. Chapman 15, M. Charles 15, Ph. Charpentier 42, C.A. Chavez Barajas 5, M. Chefdeville 8, C. Chen 15, S. Chen 4, A. Chernov 35, S. Chernyshenko 46, V. Chobanova 49, S. Cholak 43, M. Chrzaszcz 35, A. Chubynkin 6, V. Chulikov 38, P. Ciambrone 23, M.F. Cicala 50, X. Cid Vidal 40, G. Ciezarek 42, G. Ciuillo 21, P.E.L. Clarke 52, M. Clemenec 42, H.V. Clifft 45, J. Cloosier 42, J.L. Clobbedick 60, V. Coco 42, J.A.B. Coelho 14, J. Cogner 10, E. Cogneras 6, L. Cojocaru 39, P. Collins 42, T. Colombo 42, L. Congedo 18, A. Contu 27, N. Cooke 47, G. Coombs 53, I. Corredoira 40, G. Corti 42, B. Couturier 44, D.C. Craik 58, J. Crkovska 61, M. Cruz Torres 14, R. Currie 52, C.L. Da Silva 61, S. Dadabaev 39, L. Dai 60, E. Dall’Occo 15, J. Dalseno 40, C. D’Ambrosio 12, A. Danilina 38, P. d’Argent 17, J.E. Davies 56, A. Davis 56, O. De Aguiar Francisco 34, J. de Boer 44, K. De Bruyn 74, S. De Capua 56, M. De Cian 34, U. De Freitas Carneiro Da Graca 15, E. De Lucia 25, J.M. De Miranda 15, L. De Paula 49, M. De Serio 10, D. De Simone 44, P. De Simone 24, F. De Vellis 13, J.A. de Vries 38, C.T. Dean 61, F. Debernardis 19, D. Decamp 31, V. Dediu 10, L. Del Buono 14, B. Delaney 62, H.-P. Dembinski 15, V. Denysenko 4, O. Deschamps 4, F. Dettori 27, B. Dey 71, A. Di Ciccio 54, P. Di Nezza 21, S. Didenko 38, L. Dieste Maronas 40, S. Ding 62, V. Dobishuk 46, A. Dolmatov 38, C. Dong
V. Zhukov, Q. Zou, S. Zucchelli, D. Zuliani, G. Zunica.

1 Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2 Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3 Center for High Energy Physics, Tsinghua University, Beijing, China
4 Institute Of High Energy Physics (IHEP), Beijing, China
5 School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
6 University of Chinese Academy of Sciences, Beijing, China
7 Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China
8 Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France
9 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
10 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
11 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
12 Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
13 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
14 I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
15 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
16 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
17 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
18 School of Physics, University College Dublin, Dublin, Ireland
19 INFN Sezione di Bari, Bari, Italy
20 INFN Sezione di Bologna, Bologna, Italy
21 INFN Sezione di Ferrara, Ferrara, Italy
22 INFN Sezione di Firenze, Firenze, Italy
23 INFN Laboratori Nazionali di Frascati, Frascati, Italy
24 INFN Sezione di Genova, Genova, Italy
25 INFN Sezione di Milano, Milano, Italy
26 INFN Sezione di Milano-Bicocca, Milano, Italy
27 INFN Sezione di Cagliari, Monserrato, Italy
28 Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy
29 INFN Sezione di Pisa, Pisa, Italy
30 INFN Sezione di Roma La Sapienza, Roma, Italy
31 INFN Sezione di Roma Tor Vergata, Roma, Italy
32 Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
33 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
34 AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
35 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
36 National Center for Nuclear Research (NCBJ), Warsaw, Poland
37 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
38 Affiliated with an institute covered by a cooperation agreement with CERN
39 ICCUB, Universitat de Barcelona, Barcelona, Spain
40 Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
41 Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
42 European Organization for Nuclear Research (CERN), Geneva, Switzerland
43 Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
44 Physik-Institut, Universität Zürich, Zürich, Switzerland
45 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
46 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
47 University of Birmingham, Birmingham, United Kingdom
48 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
49 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
50 Department of Physics, University of Warwick, Coventry, United Kingdom
School of Physics and Technology, Wuhan University, Wuhan, China, associated to 3
Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, associated to 13
Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to 17
Eotvos Loránd University, Budapest, Hungary, associated to 42
INFN Sezione di Perugia, Perugia, Italy, associated to 21
Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to 32
Universiteit Maastricht, Maastricht, Netherlands, associated to 32
DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to 39
Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to 53
University of Michigan, Ann Arbor, MI, United States, associated to 62

Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
Central South U., Changsha, China
Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
Excellence Cluster ORIGINS, Munich, Germany
Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Firenze, Firenze, Italy
Università di Genova, Genova, Italy
Università degli Studi di Milano, Milano, Italy
Università di Milano Bicocca, Milano, Italy
Università di Padova, Padova, Italy
Università di Perugia, Perugia, Italy
Scuola Normale Superiore, Pisa, Italy
Università di Pisa, Pisa, Italy
Università della Basilicata, Potenza, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Siena, Siena, Italy
Università di Urbino, Urbino, Italy
† Deceased

STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Maryland, College Park, MD, United States
Los Alamos National Laboratory (LANL), Los Alamos, NM, United States
Syracuse University, Syracuse, NY, United States
School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to 50
Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to 2
Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to 7
Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to 3

Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
Central South U., Changsha, China
Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
Excellence Cluster ORIGINS, Munich, Germany
Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Firenze, Firenze, Italy
Università di Genova, Genova, Italy
Università degli Studi di Milano, Milano, Italy
Università di Milano Bicocca, Milano, Italy
Università di Padova, Padova, Italy
Università di Perugia, Perugia, Italy
Scuola Normale Superiore, Pisa, Italy
Università di Pisa, Pisa, Italy
Università della Basilicata, Potenza, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Siena, Siena, Italy
Università di Urbino, Urbino, Italy
† Deceased