

Measurement of the Λ_b^0 lifetime in pp collisions at $\sqrt{s} = 7$ TeV



The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: A measurement of the Λ_b^0 lifetime using the decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$ in proton-proton collisions at $\sqrt{s} = 7$ TeV is presented. The data set, corresponding to an integrated luminosity of about 5 fb^{-1} , was recorded with the CMS experiment at the Large Hadron Collider using triggers that selected dimuon events in the J/ψ mass region. The Λ_b^0 lifetime is measured to be 1.503 ± 0.052 (stat.) ± 0.031 (syst.) ps.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

The study of b baryons is a necessary ingredient to understand b-hadron phenomenology. The heavy-quark expansion model of nonperturbative quantum chromodynamics provides a framework for predicting properties of heavy-flavour hadrons, including their lifetimes. Here, a simple description is used where the heavy b quark is surrounded by a light quark or diquark system. Estimates can be made of the lifetime and of the ratio of lifetimes between particles sharing the same heavy-quark flavour [1–8]. The early calculation predicted a spread of the lifetimes of order 5% among all b hadrons [1] and the ratio of the Λ_b^0 and B^0 lifetimes, $\tau_{\Lambda_b^0}/\tau_{B^0}$, to be greater than 0.90 [9] (see also table 12 in the autumn 2012 on-line update at <http://www.slac.stanford.edu/xorg/hfag/>). The initial measurements of the b-baryon lifetime were generally lower than predicted [9], which motivated more refined calculations. This resulted in predictions as low as $\tau_{\Lambda_b^0}/\tau_{B^0} = 0.86 \pm 0.05$ [10]. An overview of the current state of the predictions and measurements can be found in ref. [9]. Measurements of the Λ_b^0 lifetime prior to 2011 can be found in refs. [11–27]. More recent measurements of the Λ_b^0 lifetime include: $1.537 \pm 0.045 \pm 0.014$ ps from CDF [28], $1.303 \pm 0.075 \pm 0.035$ ps from D0 [29], and $1.449 \pm 0.036 \pm 0.017$ ps from ATLAS [30], where the first uncertainties are statistical and the second are systematic.

In this paper, a measurement of $\tau_{\Lambda_b^0}$ is presented, using the decay $\Lambda_b^0 \rightarrow J/\psi\Lambda$, with $\Lambda \rightarrow p\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$. The kinematically analogous channel $B^0 \rightarrow J/\psi K_S^0$, with $K_S^0 \rightarrow \pi^+\pi^-$, is used as a cross-check, with selection criteria similar to those for the Λ_b^0 analysis. Charge-conjugate states are assumed throughout this paper. The measurement is made using proton-proton collision data at $\sqrt{s} = 7$ TeV recorded by the Compact Muon Solenoid (CMS) experiment operating at the Large Hadron Collider (LHC). The data set for this measurement was collected in 2011 using J/ψ -enriched dimuon triggers, and corresponds to an integrated luminosity of about 5 fb^{-1} [31].

2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. The main subdetectors used for the analysis are the silicon tracker, consisting of silicon pixel and silicon strip layers, and the muon system. The tracker is immersed in a 3.8 T axial magnetic field of the superconducting solenoid. The pixel tracker consists of three barrel layers and two endcap disks at each barrel end. The strip tracker has 10 barrel layers and 12 endcap disks at each barrel end. The tracker provides an impact parameter resolution of $\sim 15 \mu\text{m}$ and a transverse momentum (p_T) resolution of about 1.5% for 100 GeV particles. Charged hadrons, including pions and protons, are not explicitly identified by their type. Muons are measured in gas-ionisation detectors that are embedded in the steel return yoke outside the solenoid. In the barrel, there is a drift tube system interspersed with resistive plate chambers, and in the endcaps there is a cathode strip chamber system, also interspersed with resistive plate chambers. The first-level trigger used in this analysis is based on the muon system alone, while the high-level trigger uses additional information from the tracker. A detailed description of the CMS detector can be found in ref. [32].

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing towards the centre of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the pseudorapidity is defined by $\eta = -\ln[\tan(\theta/2)]$. The azimuthal angle is measured from the positive x axis in the plane perpendicular to the beam.

3 Event selection and efficiency modelling

Dimuon triggers optimised for selecting events with J/ψ candidates are used. The trigger requires two oppositely charged muons with an invariant mass compatible with the J/ψ -meson mass. The dimuon candidate must also be found in the central region (dimuon rapidity $|y_{\mu^+\mu^-}| < 1.25$), which is the region with the best impact parameter and dimuon invariant-mass resolution. With increasing instantaneous luminosity, the trigger requirements were adjusted several times during the data-taking period. In the course of data taking, the dimuon mass window was changed from 2.5-4.0 GeV to 2.30-3.35 GeV, while the minimum transverse momentum of the dimuon candidate was increased from 6.5 GeV to 13 GeV. Additional requirements were also added during this period: the distance of closest approach between the two muons was required to be less than 0.5 cm, the vertex-fit χ^2 probability of the two muons was required to be greater than 0.5%, and the two muons were required to bend away from each other in the tracker.

The four charged particles ($\mu^+\mu^-\text{p}\pi^-$) in the decay channel $\Lambda_b^0 \rightarrow J/\psi\Lambda$ allow for a full reconstruction of the Λ_b^0 baryon. The selection requirements are chosen to maximise the ratio of signal yield to the square root of the signal-plus-background yield. Events with two oppositely charged muons are selected. The muons are reconstructed using information from the tracker and the muon system. The muon candidates must be within the kinematic acceptance of the detector by demanding the muon transverse momentum p_T^μ satisfies $p_T^\mu >$

3.5 GeV for muon pseudorapidity $|\eta^\mu| < 1.2$, and $p_T^\mu > 3.0$ -3.5 GeV for $1.2 < |\eta^\mu| < 1.6$, where the p_T^μ threshold decreases linearly as a function of $|\eta^\mu|$. The muon candidates are also required to have a track χ^2 per degree of freedom less than 1.8, at least 11 tracker hits, at least two hits in the pixel system, a match to at least one track segment in the muon system, and a transverse (longitudinal) impact parameter less than 3 cm (30 cm) with respect to the primary event vertex. The preliminary choice for the primary vertex is the one with the highest sum of the squares of p_T of the tracks associated with it. The two muons are then used to form a J/ψ candidate.

A Λ candidate is formed using oppositely charged tracks with the proton candidate required to have $p_T > 1.8$ GeV and the pion candidate $p_T > 0.46$ GeV. The higher-momentum track is taken as the proton.

Kinematic vertex fits are used to identify the Λ_b^0 candidates [33]. An initial unconstrained fit is used to measure three selection parameters. First, the proton-pion invariant mass ($m_{p\pi^-}$) is found from the Λ candidate tracks and is required to be within 6 MeV of the world-average Λ mass [34]. The Λ candidates are rejected if the dipion invariant mass $m_{\pi^+\pi^-}$ is within 10 MeV of the K_S^0 mass [34], when the proton candidate is assigned a pion mass. Then, the dimuon invariant mass ($m_{\mu^+\mu^-}$) is determined from an unconstrained fit to the J/ψ candidate tracks and is required to be within 300 MeV of its world-average value [34]. Finally, a pointing angle is measured for the Λ candidate, which is defined as the angle between the momentum of the reconstructed Λ particle and the vector between its production and decay vertices. The pointing angle is required to be less than 0.015 rad.

To determine the proper decay time t of a Λ_b^0 candidate, another kinematic vertex fit is performed where the two muon tracks and the Λ candidate are constrained to come from a common vertex, with the Λ and J/ψ candidate masses constrained to their respective nominal values [34]. The Λ vertex-fit χ^2 probability must be greater than 10%. The separation between the Λ vertex and the eventual primary vertex (as defined below) must be larger than 10σ , where σ is the calculated uncertainty in the relative position. In addition, the Λ vertex must be at least 3 cm away from the mean pp collision position in the transverse plane.

Multiple pp interactions per bunch crossing are present in the data. The reconstructed event vertex with the smallest impact parameter in the z direction to the Λ_b^0 candidate trajectory is selected as the primary production vertex. The position of the primary vertex is recalculated excluding the tracks from the Λ_b^0 decay if they were used for the initial primary-vertex reconstruction. The proper decay time t is found for each Λ_b^0 candidate by calculating the ratio of the decay length and the momentum of the Λ_b^0 , divided by the world-average Λ_b^0 mass [34].

As a cross-check, the B^0 lifetime, τ_{B^0} , is determined using the $B^0 \rightarrow J/\psi K_S^0$ channel. A completely analogous procedure is followed to find the B^0 candidates, replacing the proton-track hypothesis with a pion-track hypothesis and fitting for a K_S^0 candidate instead of a Λ candidate. The K_S^0 candidates are formed assuming both tracks are pions (the higher-momentum one is required to have $p_T > 1.8$ GeV, the lower-momentum one to have $p_T > 0.5$ GeV), with $m_{\pi^+\pi^-}$ within 12 MeV of the world-average value [34]. A candidate is vetoed if replacing the pion-mass hypothesis by the proton mass yields an invariant

mass $m_{p\pi^-}$ within 10 MeV of the Λ mass [34]. The pointing angle and other kinematic requirements are the same as those for the Λ_b^0 selection.

Simulated event samples are used to model the signal and background distributions. The PYTHIA 6.422 [35] event generator is used, with the Λ_b^0 lifetime fixed to 1.425 ps [34] and the b-hadron decays described by the EVTGEN 9.1 simulation package [36]. The particle propagation and detector simulation is performed using GEANT4 9.4 [37], and the events are fully reconstructed with the same software as the data. The differences between the reconstructed and generated values for the proper decay time, the flight length, and the candidate Λ_b^0 momentum are found to be compatible with zero in the simulated sample. The sideband-subtracted data distributions in each of the selection variables are compared to those in simulated data and found to be consistent within their uncertainties. The overall reconstruction and selection efficiency as a function of the proper decay time t is determined from the simulated signal samples by calculating the ratio of the numbers of reconstructed and generated Λ_b^0 (B^0) candidates in bins of proper decay time. Figure 1 displays the ratio of the reconstruction and selection efficiencies measured from simulation to the overall average efficiency, as a function of the proper decay time for the B^0 (top) and Λ_b^0 (bottom). The efficiencies are consistent with being independent of the proper decay time, as shown by the solid horizontal line in each plot. The Λ_b^0 efficiency depends on various kinematic variables such as the Λ_b^0 transverse momentum. Therefore, a comprehensive comparison of the distributions of these variables between the data and the Monte Carlo simulation was performed, and in all cases the distributions were found to be consistent.

4 Proper decay time fit

Unbinned extended maximum-likelihood fits are performed to determine the Λ_b^0 and B^0 lifetimes. The input variables are the invariant mass m , proper decay time t , and its uncertainty σ_t , calculated per candidate from the kinematic vertex fit using full error propagation. The likelihood fit is implemented using the ROOFIT 3.53 package [38]. The likelihood function (ignoring the normalisation terms for simplicity) is

$$\begin{aligned} \mathcal{L} = \prod_i & \left[N_{\text{sig}} \cdot G2(m_i; m_{\text{sig}}, \sigma_{m_1}, \sigma_{m_2}, f) \cdot e^{-t/\tau_{\text{sig}}} \otimes G(t_i; \mu, S \cdot \sigma_{t,i}) \right. \\ & + N_{\text{prompt}} \cdot P(m_i; a) \cdot G(t_i; \mu, S \cdot \sigma_{t,i}) \\ & \left. + N_{\text{nonprompt}} \cdot P(m_i; a) \cdot e^{-t/\tau_{\text{nonprompt}}} \otimes G(t_i; \mu, S \cdot \sigma_{t,i}) \right], \end{aligned} \tag{4.1}$$

where the index i goes over the events, N_{sig} is the number of signal events, N_{prompt} is the number of prompt background events not coming from b-hadron decays, and $N_{\text{nonprompt}}$ is the corresponding number of nonprompt background events coming from b-hadron decays. The prompt background is dominated by J/ψ mesons directly produced in the pp collision, while the nonprompt background is dominated by J/ψ mesons from decays of b hadrons. In both cases, the J/ψ mesons are combined with real or misidentified Λ candidates from the event. The parameters τ_{sig} and $\tau_{\text{nonprompt}}$ denote the lifetime of the signal and of nonprompt background, respectively. In eq. (4.1), the $G2$ function is the sum of two Gaussians with

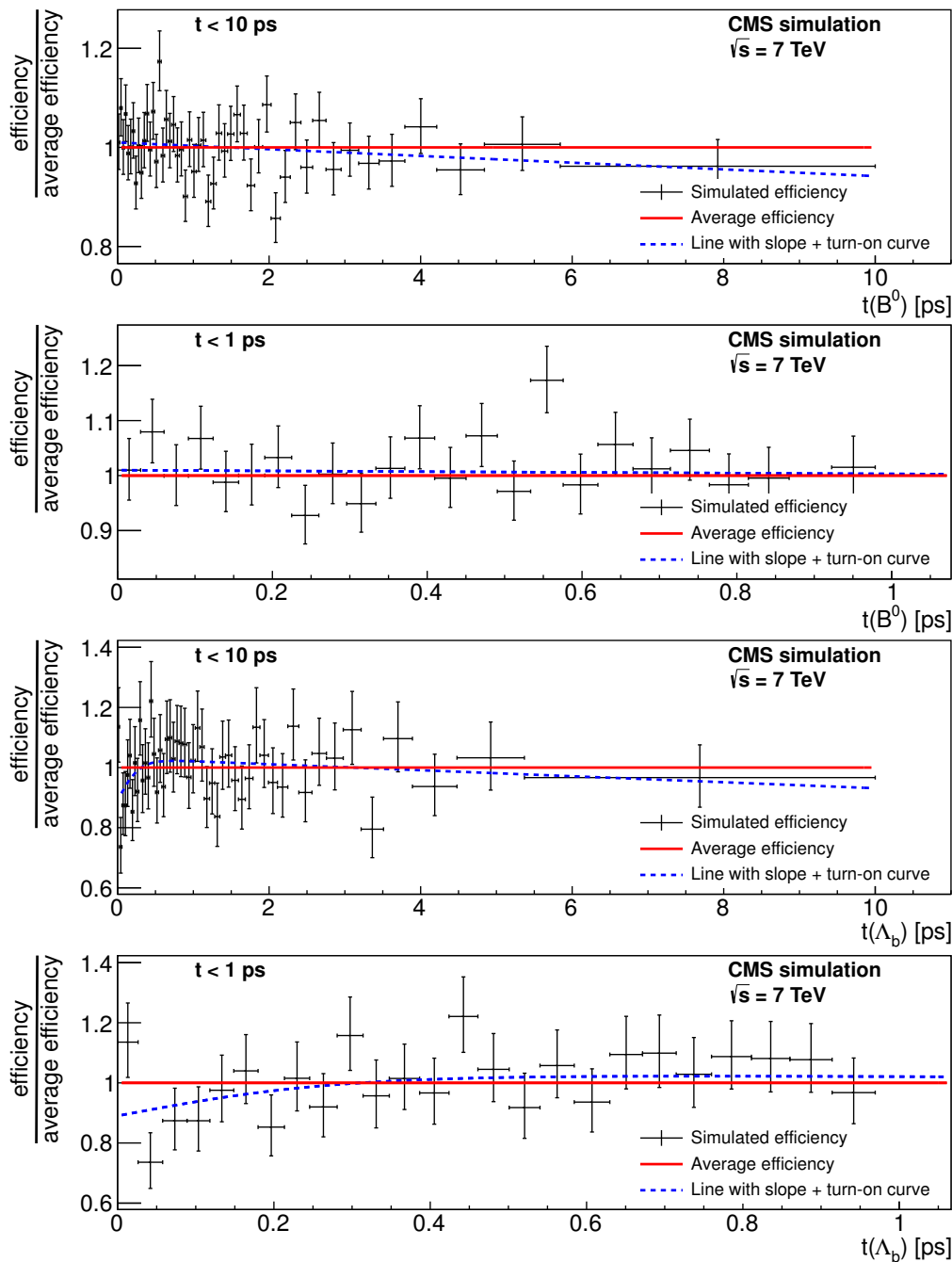


Figure 1. The ratio of the reconstruction and selection efficiencies to the overall average efficiency as a function of proper decay time for B^0 (upper two plots) and Λ_b^0 (lower two plots). The second and fourth plots show the B^0 and Λ_b^0 efficiency ratios, respectively, for smaller proper decay times $t < 1$ ps. The horizontal solid lines show a ratio of 1, while the dashed lines display the results from fitting the efficiencies to the function given by eq. (5.1).

a common mean m_{sig} and widths σ_{m_1} and σ_{m_2} , and the parameter f denotes the relative fraction of the area of the two Gaussians. The function G refers to a single Gaussian

Hadron	N_{sig}	m (MeV)	τ (ps)
Λ_b^0	1013 ± 40	5619.7 ± 0.5	1.503 ± 0.052
B^0	6772 ± 87	5278.9 ± 0.2	1.526 ± 0.019

Table 1. Summary of the fit results for Λ_b^0 and B^0 with their statistical uncertainties.

describing the detector lifetime resolution, with a mean μ and a width $S \cdot \sigma_{t,i}$, where S is a scale factor determined from the fit. This resolution function is common to all three likelihood components since the σ_t distributions do not differ significantly. The effect of using this simplifying assumption on σ_t is evaluated as a systematic uncertainty and found to be negligible. For the background components, the invariant-mass m distribution is parameterised by a normalised first-degree polynomial of slope a , $P(m; a)$. The prompt and nonprompt backgrounds share the same slope. The maximum-likelihood fit to the data is performed allowing all parameters to vary.

5 Results

Projections of the invariant-mass and proper decay time distributions and the results of the fits for the B^0 and Λ_b^0 are shown in the upper panels of figures 2 and 3, respectively. The lower panels in each figure give the proper decay time projections and fit results for low-mass sideband (left), signal (center), and high-mass sideband (right) regions of the invariant-mass distribution. The signal region is defined to be within 2σ of the mass peak, where σ is the mass resolution obtained by integrating the double-Gaussian signal function with its parameter values determined from the fit. The low-mass sideband region goes from 5.15 (5.4) GeV to within 3σ below the peak, and the high-mass sideband region runs from 3σ above the peak to 5.75 (6.0) GeV for the B^0 (Λ_b^0). The lower plot in each panel of figures 2 and 3 displays the pull distribution for the corresponding data and fit results shown in the upper plot.

The results from the fits are summarised in table 1, where the uncertainties are statistical only. The measured B^0 lifetime shown in the table is consistent with the world-average value of 1.519 ± 0.007 ps [34]. The mass values for both Λ_b^0 and B^0 given in the table compare well with the world-average values [34].

The fitting procedure is validated by studying simulated pseudo-experiments in which the proper decay time distributions are generated using different lifetime values. The resulting lifetime measurements found from the fit are compatible with being unbiased, and the width of the pull distribution, (measured value – input value)/uncertainty, is consistent with 1.0.

Sources of systematic uncertainty are detector alignment, efficiency as a function of proper decay time, event selection, and fit model. To estimate possible effects due to uncertainties in the alignment, nine different simulated samples with distorted geometries are produced and analysed [39]. The lifetime difference between the nominal result and the sample that produces the largest deviation (scaled to the estimated residual misalignment present in the detector) is taken as the systematic uncertainty from this source.

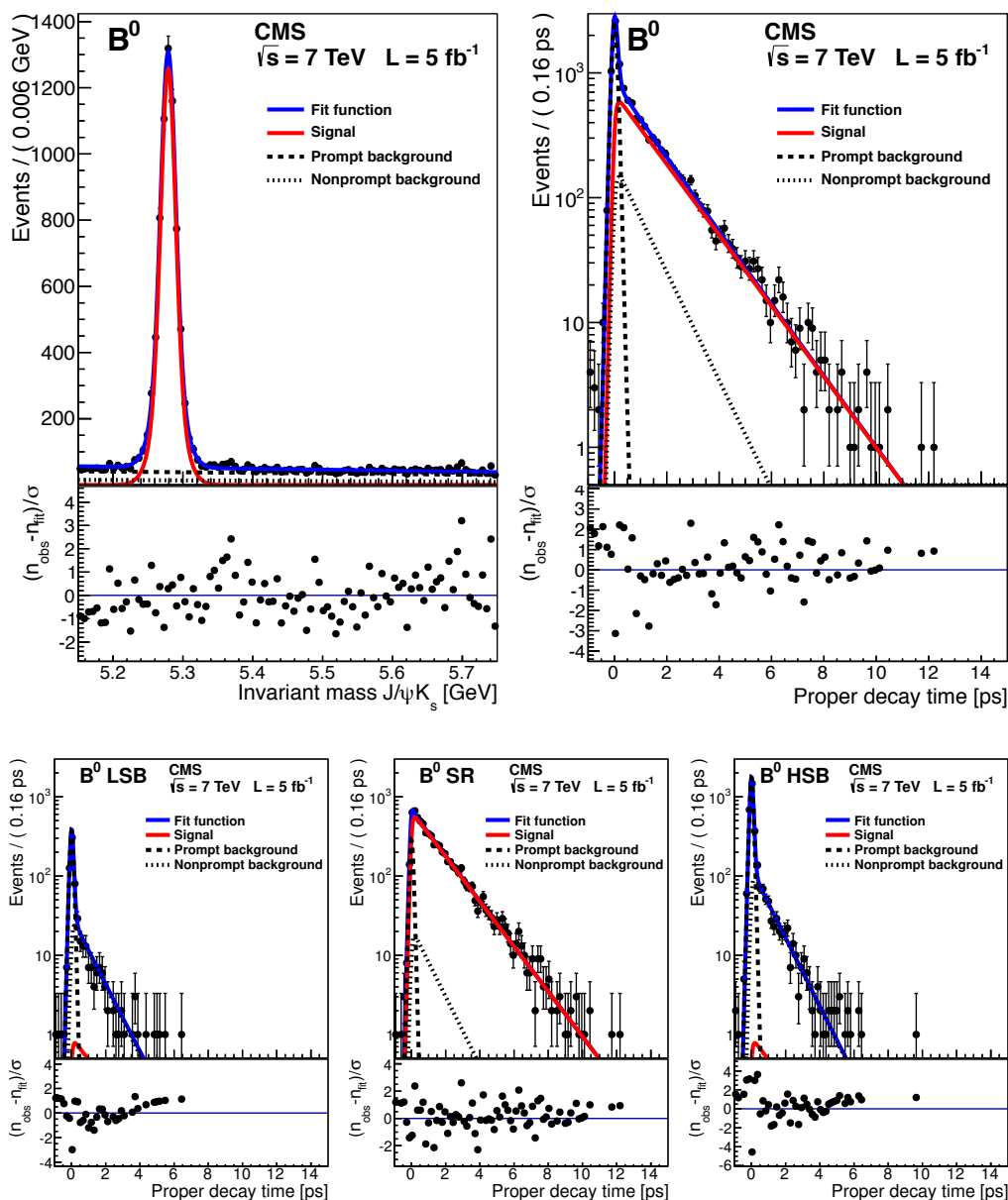


Figure 2. Projections of the invariant-mass and proper decay time distributions and the results of the fit are shown for the B^0 decay in the upper panels. The dark solid lines give the results of the overall fit to the data. The lighter solid lines are the signal contributions, and the dashed and dotted lines show the prompt and nonprompt background contributions, respectively. The lower panels display the proper decay time projections for the low-mass sideband (LSB, left), the signal (SR), and the high-mass sideband (HSB, right) regions defined in the text. The lower plots in each panel give the corresponding pull distributions for the data and fit results shown. All plots are from the same fit.

Since the overall efficiency, determined through simulation, is consistent with being independent of the proper decay time, as shown in figure 1, no efficiency correction is used

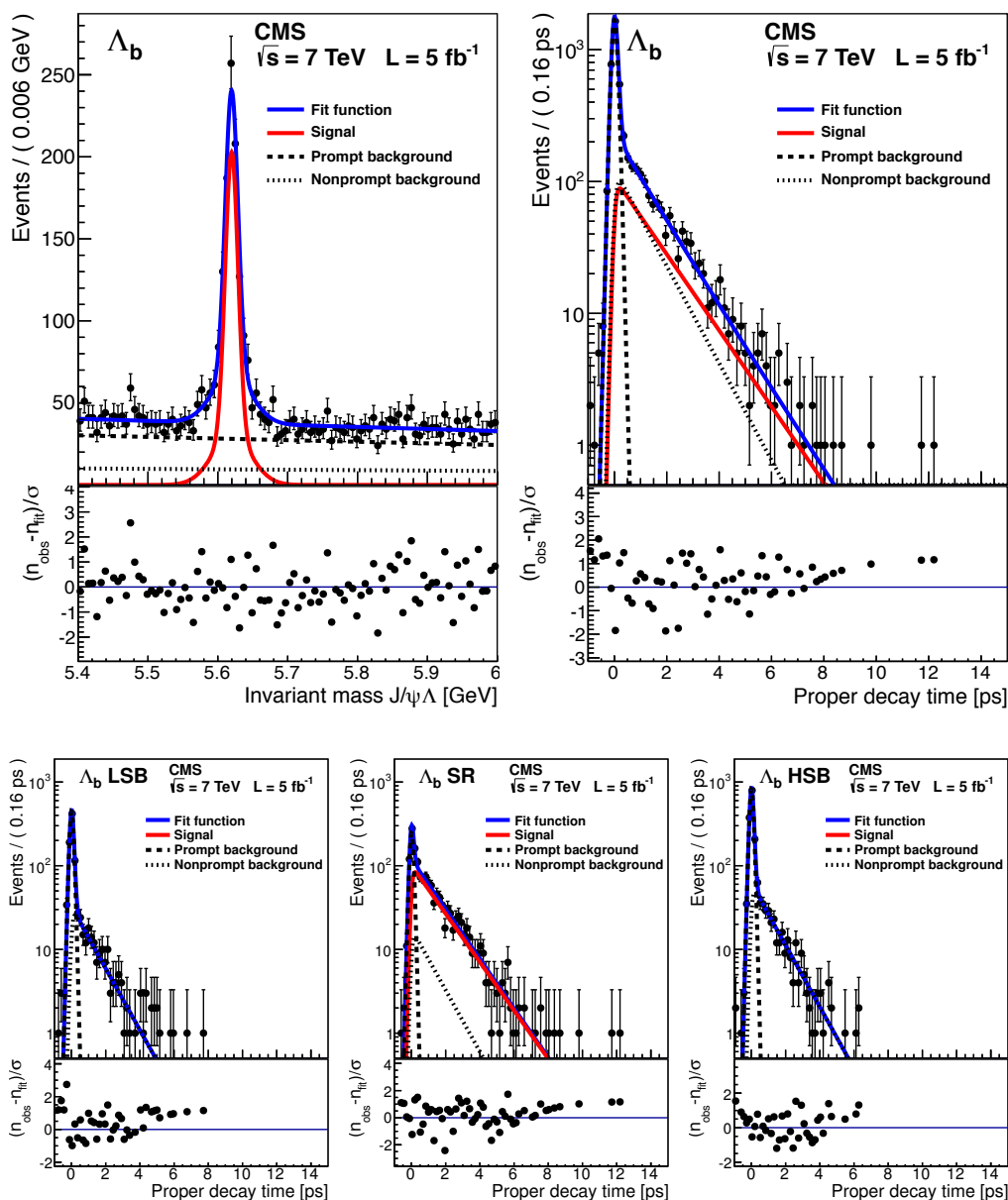


Figure 3. Projections of the invariant-mass and proper decay time distributions and the results of the fit are shown for the Λ_b^0 decay in the upper panels. The dark solid lines give the results of the overall fit to the data. The lighter solid lines are the signal contributions, and the dashed and dotted lines show the prompt and nonprompt background contributions, respectively. The lower panels display the proper decay time projections for the low-mass sideband (LSB, left), the signal (SR), and the high-mass sideband (HSB, right) regions defined in the text. The lower plots in each panel give the corresponding pull distributions for the data and fit results shown. All plots are from the same fit.

in the lifetime result. Nevertheless, the effect of a possible proper-decay-time-dependent efficiency is included as a systematic uncertainty. To this end, the efficiency is included

Source	Systematic uncertainty (ps)
Alignment	0.005
Efficiency	0.030
Event selection	0.005
Fit model	0.004
Total	0.031

Table 2. Summary of the systematic uncertainties in the Λ_b^0 lifetime measurement.

in the likelihood function in eq. (4.1) as a function of the measured proper decay time. The difference between the lifetime found using a constant efficiency (i.e. no efficiency in the likelihood) and that found using the fitted efficiency function is taken as a systematic uncertainty. The efficiency is fit to the function

$$\varepsilon(t) = p_0 \cdot \left(1 + p_1 t + \frac{p_2}{1 + e^{-t/p_3}} \right), \tag{5.1}$$

where the free parameters p_i are determined from the fit. This parameterisation has the useful feature that as the parameter p_2 goes to 0, the function becomes a straight line, which is consistent with the behaviour of the B^0 efficiencies shown in figure 1. The results of fitting this function to the B^0 and Λ_b^0 efficiencies are shown by the dashed lines in figure 1.

To account for possible biases from the event selection criteria, a systematic uncertainty is calculated from the difference between the observed and expected values in simulated events using the full analysis chain.

Simulated pseudo-experiments produced with different input parameter values and different modelling of the fit functions are used to estimate the corresponding systematic uncertainties on the lifetime measurement. Variations include: using two different lifetimes to describe the nonprompt background to control the possible presence of a second nonprompt background component, varying the prompt and nonprompt background, varying the lifetime of the nonprompt background to control possible correlation to the lifetime of the background, and using larger per-event uncertainties for the background components to control a possible mismodelling of the resolution. Extending the likelihood function in eq. (4.1) from a single detector lifetime resolution σ_t for all three components to individual resolutions per component showed a negligible effect. Table 2 gives the systematic uncertainties from the four sources and their sum in quadrature, which is taken as the overall systematic uncertainty on the Λ_b^0 lifetime measurement.

Checks are also performed to see if any detector effect leads to a systematic deviation not covered by the ones previously discussed. This is done by dividing the data sample into parts, where each of the partitions is expected to give the same results. The checks are performed with azimuthal angle, pseudorapidity, transverse momentum, run era, muons bending away or towards each other, and number of primary interaction vertices. No statistically significant effects are seen. For the Λ_b^0 channel, we also remove the K_S^0 -mass-veto requirement on the Λ candidate and find a negligible effect on the lifetime result.

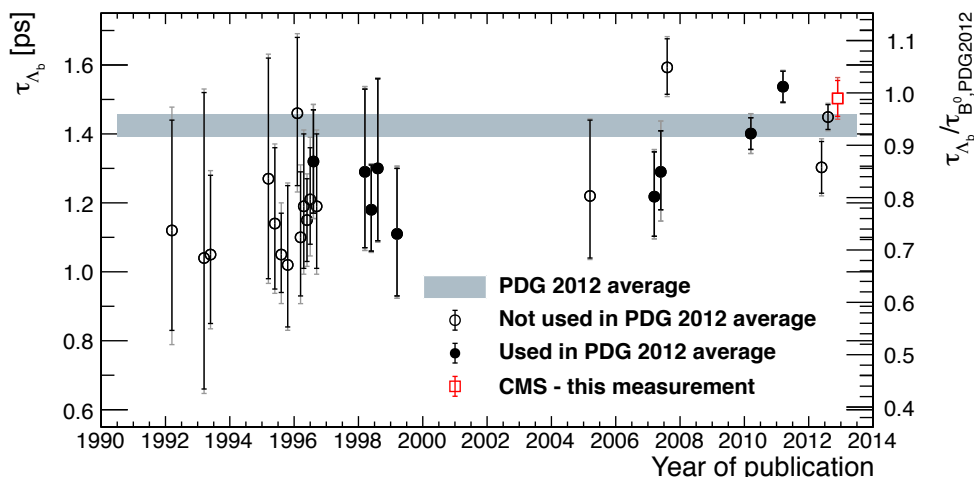


Figure 4. Evolution over time of the Λ_b^0 lifetime measurements (left scale) [11–30] and the ratio of the measurements to the 2012 world-average B^0 lifetime τ_{B^0} [34] (right scale). The values shown as open circles were not included in the Particle Data Group (PDG) 2012 average [34], displayed as the band, while those shown as filled circles were included. The result of this analysis is shown by the open square. The inner error bars represent the statistical uncertainties, and the outer error bars show the combined statistical and systematic uncertainties added in quadrature. Where needed, points have been shifted slightly along the time axis to enhance clarity.

6 Summary

A measurement of the Λ_b^0 lifetime has been presented using the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda$ in pp collisions at $\sqrt{s} = 7$ TeV with the CMS detector. From a data set corresponding to an integrated luminosity of about 5 fb^{-1} , the Λ_b^0 lifetime is found to be $\tau_{\Lambda_b^0} = 1.503 \pm 0.052$ (stat.) ± 0.031 (syst.) ps. The kinematically similar decay $B^0 \rightarrow J/\psi K_S^0$ was used as a cross-check, confirming that no efficiency correction was needed. The Λ_b^0 lifetime result is in agreement with the world-average value of 1.425 ± 0.032 ps [34] and has a precision comparable to that of other recent measurements [28–30]. As illustrated in figure 4, this new result confirms the tendency of the more recent measurements that give larger lifetimes, in better agreement with the early theoretical predictions [1, 9].

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spillbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, A. Kalogeropoulos, J. Keaveney, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, A. Popov⁵, M. Selvaggi, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

N. Belyi, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson,

M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

T.S. Anjos^b, C.A. Bernardes^b, F.A. Dias^{a,7}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, C. Lagana^a, F. Marinho^a, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev², P. Iaydjiev², S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Asawatrangkuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, C.A. Carrillo Montoya, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁸, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁹, A. Ellithi Kamel¹⁰, M.A. Mahmoud¹¹, A. Mahrous¹², A. Radi^{13,14}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹⁵, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁶, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁶, F. Drouhin¹⁶, J.-C. Fontaine¹⁶, D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, M. Vander Donckt, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁷

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, S. Beranek, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov⁵

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann², A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁸, A. Bethani, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, F. Costanza, C. Diez Pardos, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann¹⁸, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, J. Salfeld-Nebgen, R. Schmidt¹⁸, T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille¹⁹, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, D. Troendle, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff², C. Hackstein, F. Hartmann², T. Hauth², M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov⁵, J.R. Komaragiri, A. Kornmayer², P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos,
I. Papadopoulos, E. Paradas

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, B. Radics, F. Sikler, V. Veszpremi,
G. Vesztergombi²¹, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu,
L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra,
M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain,
R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla,
A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait²², A. Gurtu²³, G. Kole,
S. Kumar, M. Maity²⁴, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida,
K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei²⁵, H. Bakhshiansohi, S.M. Etesami²⁶, A. Fahim²⁵, H. Hesari, A. Jafari,
M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁷,
M. Zeinali

University College Dublin, Dublin, Ireland

M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c},
N. De Filippis^{a,c,2}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a,

B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, P. Verwilligen^a, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^{a,2}, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

P. Fabbriatore^a, R. Musenich^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, F. De Guio^{a,b}, L. Di Matteo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni, M.T. Lucchini², S. Malvezzi^a, R.A. Manzoni^{a,b,2}, A. Martelli^{a,b,2}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Università della Basilicata (Potenza) ^c, Università G. Marconi (Roma) ^d, Napoli, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Cosa^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, M. Biasotto^{a,28}, D. Bisello^{a,b}, A. Branca^{a,b}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, M. Galanti^{a,b,2}, F. Gasparini^{a,b}, U. Gasparini^{a,b}, P. Giubilato^{a,b}, A. Gozzelino^a, M. Gulmini^{a,28}, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^{a,29}, P. Azzurri^a, G. Bagliesi^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c,2}, R. Dell'Orso^a, F. Fiori^{a,c}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,29}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a, C. Vernieri^{a,c}

INFN Sezione di Roma ^a, Università di Roma ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli^{a,b}, M. Grassi^{a,b,2}, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, L. Soffi^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b}, M. Costa^{a,b}, D. Dattola^a, N. Demaria^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,2}, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^{a,2}, G. Della Ricca^{a,b}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, D. Montanino^{a,b}, A. Penzo^a, A. Schizzi^{a,b}, A. Zanetti^a

Kangwon National University, Chunchon, Korea

T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, Y.D. Oh, H. Park, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, S.K. Park, Y. Roh

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

I. Grigelionis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, MexicoH. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³⁰, R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, PortugalN. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Rodrigues Antunes, J. Seixas², J. Varela, P. Vischia**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁷, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³¹, M. Ekmedzic, D. Krpic³¹, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas², N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto,

J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, J.F. Benitez, C. Bernet⁸, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi³², D. d’Enterria, A. Dabrowski, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, B. Hegner, A. Hinzmam, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, G. Rolandi³³, C. Rovelli³⁴, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, M. Stoye, A. Tsirou, G.I. Veres²¹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁶, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁷, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁸, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

C. Amsler³⁹, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴⁰, S. Cerci⁴¹, C. Dozen, I. Dumanoglu, E. Eskut,
S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut,
K. Ozdemir, S. Ozturk⁴², A. Polatoz, K. Sogut⁴³, D. Sunar Cerci⁴¹, B. Tali⁴¹, H. Topakli⁴⁰,
M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler,
G. Karapinar⁴⁴, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac,
M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁶, S. Ozkorucuklu⁴⁷, N. Sonmez⁴⁸

Istanbul Technical University, Istanbul, Turkey

H. Bahtiyar⁴⁹, E. Barlas, K. Cankocak, Y.O. Günaydin⁵⁰, F.I. Vardarli, M. Yücel

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes,
G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁶, K. Nirunpong, A. Poll,
S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁵¹, K.W. Bell, A. Belyaev⁵¹, C. Brew, R.M. Brown, D.J.A. Cockerill,
J.A. Coughlan, K. Harder, S. Harper, J. Jackson, E. Olaiya, D. Petyt, B.C. Radburn-Smith,
C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey,
G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne
Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie,
R. Lane, R. Lucas³⁶, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi,
J. Nash, A. Nikitenko³⁸, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁵², D.M. Raymond,
S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta,
T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie,
W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, U.S.A.

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, U.S.A.

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, U.S.A.

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, U.S.A.

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

University of California, Davis, Davis, U.S.A.

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, U.S.A.

V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein[†], E. Takasugi, P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, U.S.A.

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano², G. Hanson, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, U.S.A.

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵³, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, U.S.A.

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutelyov, S. Lowette, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, U.S.A.

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, U.S.A.

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, U.S.A.

D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵⁴, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁵, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, U.S.A.

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D.H. Moon, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, U.S.A.

U. Akgun, E.A. Albayrak, B. Bilki⁵⁶, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel, F. Ozok⁴⁹, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁵⁸, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurciu, A.V. Gritsan, G. Hu, P. Maksimovic, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, U.S.A.

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, J.S. Wood

Kansas State University, Manhattan, U.S.A.

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, U.S.A.

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, U.S.A.

A. Apyan, G. Bauer, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, Y. Kim, M. Klute, Y.S. Lai, A. Levin, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, U.S.A.

B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, U.S.A.

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, R. Gonzalez Suarez, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.

J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, U.S.A.

A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.

D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, U.S.A.

L. Antonelli, B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, G. Williams, B.L. Winer, H. Wolfe

Princeton University, Princeton, U.S.A.

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, U.S.A.

E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, F. Wang, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, U.S.A.

S. Guragain, N. Parashar

Rice University, Houston, U.S.A.

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, U.S.A.

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, U.S.A.

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath,

S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

University of Tennessee, Knoxville, U.S.A.

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, U.S.A.

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁹, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Duderø, C. Jeong, K. Kovitangoon, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, U.S.A.

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, U.S.A.

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, U.S.A.

M. Anderson, D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, K. Kaadze, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, R. Loveless, A. Mohapatra, M.U. Mozer, I. Ojalvo, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

⋮

†: Deceased

1 : Also at Vienna University of Technology, Vienna, Austria

2 : Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

3 : Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

4 : Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

5 : Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

6 : Also at Universidade Estadual de Campinas, Campinas, Brazil

7 : Also at California Institute of Technology, Pasadena, U.S.A.

8 : Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

- 9 : Also at Suez Canal University, Suez, Egypt
- 10 : Also at Cairo University, Cairo, Egypt
- 11 : Also at Fayoum University, El-Fayoum, Egypt
- 12 : Also at Helwan University, Cairo, Egypt
- 13 : Also at British University in Egypt, Cairo, Egypt
- 14 : Now at Ain Shams University, Cairo, Egypt
- 15 : Also at National Centre for Nuclear Research, Swierk, Poland
- 16 : Also at Université de Haute Alsace, Mulhouse, France
- 17 : Also at Joint Institute for Nuclear Research, Dubna, Russia
- 18 : Also at Brandenburg University of Technology, Cottbus, Germany
- 19 : Also at The University of Kansas, Lawrence, U.S.A.
- 20 : Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21 : Also at Eötvös Loránd University, Budapest, Hungary
- 22 : Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 23 : Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 24 : Also at University of Visva-Bharati, Santiniketan, India
- 25 : Also at Sharif University of Technology, Tehran, Iran
- 26 : Also at Isfahan University of Technology, Isfahan, Iran
- 27 : Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28 : Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 29 : Also at Università degli Studi di Siena, Siena, Italy
- 30 : Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
- 31 : Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 32 : Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 33 : Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 34 : Also at INFN Sezione di Roma, Roma, Italy
- 35 : Also at University of Athens, Athens, Greece
- 36 : Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 37 : Also at Paul Scherrer Institut, Villigen, Switzerland
- 38 : Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 39 : Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 40 : Also at Gaziosmanpasa University, Tokat, Turkey
- 41 : Also at Adiyaman University, Adiyaman, Turkey
- 42 : Also at The University of Iowa, Iowa City, U.S.A.
- 43 : Also at Mersin University, Mersin, Turkey
- 44 : Also at Izmir Institute of Technology, Izmir, Turkey
- 45 : Also at Ozyegin University, Istanbul, Turkey
- 46 : Also at Kafkas University, Kars, Turkey
- 47 : Also at Suleyman Demirel University, Isparta, Turkey
- 48 : Also at Ege University, Izmir, Turkey
- 49 : Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 50 : Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
- 51 : Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 52 : Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 53 : Also at Utah Valley University, Orem, U.S.A.
- 54 : Also at Institute for Nuclear Research, Moscow, Russia

- 55 : Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 56 : Also at Argonne National Laboratory, Argonne, U.S.A.
- 57 : Also at Erzincan University, Erzincan, Turkey
- 58 : Also at Yildiz Technical University, Istanbul, Turkey
- 59 : Also at Kyungpook National University, Daegu, Korea