Measurement of angular parameters from the decay $B^0 \rightarrow K^{*0}\mu^{+}\mu^{-}$ in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

Abstract

Angular distributions of the decay $B^0 \rightarrow K^{*0}\mu^{+}\mu^{-}$ are studied using a sample of proton-proton collisions at $\sqrt{s} = 8$ TeV collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 20.5 fb$^{-1}$. An angular analysis is performed to determine the $P_1$ and $P'_5$ parameters, where the $P'_5$ parameter is of particular interest because of recent measurements that indicate a potential discrepancy with the standard model predictions. Based on a sample of 1397 signal events, the $P_1$ and $P'_5$ parameters are determined as a function of the dimuon invariant mass squared. The measurements are in agreement with predictions based on the standard model.

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1 Introduction

Phenomena beyond the standard model (SM) of particle physics can become manifest directly, via the production of new particles, or indirectly, by modifying the production and decay properties of SM particles. Analyses of flavor-changing neutral current decays are particularly sensitive to the effects of new physics because these decays are highly suppressed in the SM. An example is the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, where $K^{*0}$ indicates the $K^{*0}(892)$ meson, with the charge conjugate reaction implied here and elsewhere in this Letter unless otherwise stated. An angular analysis of this decay as a function of the dimuon invariant mass squared ($q^2$) allows its properties to be thoroughly investigated.

The differential decay rate for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ can be written in terms of $q^2$ and three angular variables as a combination of spherical harmonics, weighted by $q^2$-dependent angular parameters. These angular parameters in turn depend upon complex decay amplitudes, which are described by Wilson coefficients in the relevant effective Hamiltonian \[1\]. There can be different formulations of the angular parameters, in this Letter we present measurements of the so-called $P_1$ and $P'_5$ \[2, 3\].

New physics can modify the values of these angular parameters \[1, 2, 4-18\] relative to the SM \[1, 19-25\]. While previous measurements of some of these parameters by the BaBar, Belle, CDF, CMS, and LHCb experiments were found to be consistent with the SM predictions \[26-31\], the LHCb Collaboration recently reported a discrepancy larger than 3 standard deviations with respect to the SM predictions for the $P'_5$ parameter \[32, 33\], and the Belle Collaboration reported a discrepancy almost as large \[34\].

The new measurements presented in this Letter of the $P_1$ and $P'_5$ angular parameters in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays are performed using a sample of events collected in proton–proton (pp) collisions at a center-of-mass energy of 8 TeV with the CMS detector at the CERN LHC. The data correspond to an integrated luminosity of $20.5 \pm 0.5 \text{ fb}^{-1}$ \[35\]. The $K^{*0}$ meson is reconstructed through its decay to $K^+ \pi^-$, and the $B^0$ meson by fitting to a common vertex the tracks from two oppositely charged muon candidates and the tracks from the $K^{*0}$ decay. The values of $P_1$ and $P'_5$ are measured by fitting the distributions of events as a function of three angular variables: the angle between the $\mu^+$ and the $B^0$ in the dimuon rest frame, the angle between the $K^+$ and the $B^0$ in the $K^{*0}$ rest frame, and the angle between the dimuon and the $K\pi$ decay planes in the $B^0$ rest frame. The measurements are performed in the $q^2$ range from 1 to 19 GeV$^2$. Data in the ranges $8.68 < q^2 < 10.09 \text{ GeV}^2$ and $12.90 < q^2 < 14.18 \text{ GeV}^2$ correspond to $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow \psi' K^{*0}$ decays, respectively, and are used as control samples, since they have the same final state as the nonresonant decays of interest. Here, $\psi'$ denotes the $\psi(2S)$ meson.

CMS previously exploited the same data set used in this analysis to measure two other angular parameters in the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay as function of $q^2$: the forward-backward asymmetry of the muons, $A_{FB}$, and the $K^{*0}$ longitudinal polarization fraction, $F_L$, as well as the differential branching fraction \[31\]. After a simplification of the theoretical decay rate expression, this previous measurement was performed using two out of the three angular variables. The analysis presented in this Letter shares with the previous analysis, together with the data set, the criteria used for selecting signal events, which are reported in Section 3 for completeness.

2 The CMS detector

A detailed description of the CMS detector, together with the coordinate system and the standard kinematic variables, can be found in Ref. \[36\]. The main detector components used in this
analysis are the silicon tracker and the muon detection systems. The silicon tracker, positioned within a superconducting solenoid that provides an axial magnetic field of 3.8 T, consists of three pixel layers and ten strip layers (four of which have a stereo view) in the barrel region, accompanied by similar pixel and strip detectors in each endcap region, for a total pseudo-rapidity coverage of $|\eta| < 2.5$. For tracks with transverse momenta $1 < p_T < 10 \text{ GeV}$ and $|\eta| < 1.4$, the resolutions are typically 1.5% in $p_T$ and 25–90 (45–150) $\mu\text{m}$ in the transverse (longitudinal) impact parameter \[37\]. Muons are measured in the range $|\eta| < 2.4$ with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The probability for a pion, kaon, or proton to be misidentified as a muon is less than $2.5 \times 10^{-3}$, $0.5 \times 10^{-3}$, and $0.6 \times 10^{-3}$, respectively, for $p_T > 4 \text{ GeV}$ and $|\eta| < 2.4$. The muon identification efficiency is greater than 0.80 (0.98) for $p_T > 3.5 \text{ GeV}$ and $|\eta| < 1.2$ (1.2 < $|\eta| < 2.4$) \[38\]. In addition to the tracker and muon detectors, CMS is equipped with electromagnetic and hadronic calorimeters.

Events are selected using a two-level trigger system \[39\]. The first level consists of specialized hardware processors that use information from the calorimeters and muon systems to select events of interest at a rate of around 90 kHz. A high-level trigger processor farm further decreases the event rate to less than 1 kHz before data storage.

3 Reconstruction, event selection, and efficiency

The criteria used to select the candidate events during data taking (trigger) and after full event reconstruction (offline) make use of the relatively long lifetime of $B^0$ mesons, which leads them to decay an average of about 1 mm from their production point. The trigger uses only muon information to select events, while the offline selection includes the full reconstruction of all decay products.

All events used in this analysis were recorded with the same trigger, requiring two identified muons of opposite charge to form a vertex that is displaced from the pp collision region (beamspot). Multiple pp collisions in the same or nearby beam crossings (pileup) cause multiple vertices in the same event. The beamspot position (most-probable collision point) and size (the extent of the luminous region covering 68% of the collisions in each dimension) were continuously measured through Gaussian fits to reconstructed pileup vertices as part of the online data quality monitoring. The trigger required each muon to have $p_T > 3.5 \text{ GeV}$, $|\eta| < 2.2$, and to pass within 2 cm of the beam axis. The dimuon system was required to have $p_T > 6.9 \text{ GeV}$, a vertex fit $\chi^2$ probability larger than 10%, and a separation of the vertex relative to the beamspot in the transverse plane of at least $3\sigma$, where $\sigma$ includes the calculated uncertainty in the vertex position and the measured size of the beamspot. In addition, the cosine of the angle in the transverse plane between the dimuon momentum vector and the vector from the beamspot to the dimuon vertex was required to be greater than 0.9.

The offline reconstruction requires at least two oppositely charged muons and at least two oppositely charged hadrons. The muons are required to match those that triggered the event. The matching is performed by requiring an offline muon to match a trigger-level muon within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.1$, where $\Delta \eta$ and $\Delta \phi$ are the pseudorapidity and azimuthal angle differences, respectively, between the directions of the trigger-level and offline muons. Offline muons must, in addition, satisfy general muon identification requirements. For example, the muon track candidate from the silicon tracker must match a track segment from the muon detector, the $\chi^2$ per degree of freedom in a global fit to the silicon tracker and muon detector hits must be less than 1.9, there must be at least six silicon tracker hits, including at least two
from the pixel detector, and the transverse (longitudinal) impact parameter with respect to the beamspot must be less than 3 (30) cm. The dimuon system at the offline level is required to satisfy the same requirements as specified above for the trigger level.

The charged hadron candidates are required to fail the muon identification criteria, have $p_T > 0.8$ GeV, and an extrapolated distance $d$ of closest approach to the beamspot in the transverse plane greater than twice the sum in quadrature of the uncertainty in $d$ and the beamspot transverse size. For at least one of the two possible identity assignments—that the positively charged hadron is a kaon and the negatively charged hadron a pion, or vice versa—the invariant mass of the hadron pair must lie within 90 MeV of the nominal $K^0$ mass \[40\]. To remove contamination from $\phi(1020) \rightarrow K^+K^-$ decays, we temporarily assign the kaon mass to both charged hadrons, and then eliminate the candidate if the resulting invariant mass of the hadron pair is less than 1.035 GeV. The $B^0$ candidates are obtained by fitting the four charged tracks to a common vertex, and applying a vertex constraint to improve the resolution of the track parameters. The $B^0$ candidates must have $p_T > 8$ GeV, $|\eta| < 2.2$, vertex fit $\chi^2$ probability larger than 10%, vertex transverse separation $L$ from the beamspot greater than 12 times the sum in quadrature of the uncertainty in $L$ and the beamspot transverse size, and $\cos\alpha_{xy} > 0.9994$, where $\alpha_{xy}$ is the angle in the transverse plane between the $B^0$ momentum vector and the line-of-flight between the beamspot and the $B^0$ vertex. The invariant mass $m$ of the $B^0$ candidate must lie within 280 MeV of the nominal $B^0$ mass ($m_{B^0}$) \[40\] for either the $K^-\pi^+\mu^+\mu^-$ or $K^+\pi^-\mu^+\mu^-$ possibility. The selection criteria are optimized using signal event samples from simulation and background event samples from sideband data in $m$. The sideband includes both a low- and a high-mass region and is defined by $3\sigma_m < |m - m_{B^0}| < 280$ MeV, where $\sigma_m$ is the average mass resolution ($\approx 45$ MeV) obtained from fitting a sum of two Gaussian functions with a common mean to simulated signal events. After applying the selection criteria, about 5% of the events have more than one candidate. A single candidate is chosen based on the best $B^0$ vertex $\chi^2$ probability.

For each of the selected events, the dimuon invariant mass $q$ and its uncertainty $\sigma_q$ are calculated. We define $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow \psi' K^{*0}$ control samples through the requirements $|q - m_{J/\psi}| < 3\sigma_q$ and $|q - m_{\psi'}| < 3\sigma_q$, respectively, where $m_{J/\psi}$ and $m_{\psi'}$ are the nominal masses \[40\] of the indicated meson. The average value of $\sigma_q$ is about 26 MeV.

The remaining event sample still contains contributions from $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow \psi' K^{*0}$ decays, mainly because of unreconstructed soft photons in the charmonium decay, i.e., $J/\psi$ or $\psi' \rightarrow \mu^+\mu^-\gamma$. These events have a low value of $q$ and fall outside the control sample selection described above. They also have a low value of $m$ and can be selectively removed using a combined requirement on $q$ and $m$. For $q < m_{J/\psi}$ ($q > m_{J/\psi}$), we require $|(m - m_{B^0}) - (q - m_{J/\psi})| > 160$ (60) MeV. For $q < m_{\psi'}$ ($q > m_{\psi'}$), we require $|(m - m_{B^0}) - (q - m_{\psi'})| > 60$ (30) MeV. Using Monte Carlo (MC) simulation, these requirements were set so that less than 10% of the background events originate from the control channels.

The selection criteria are such that they do not depend upon the choice of the primary vertex, and their optimization procedure makes use of both MC simulated signal events generated with the same pileup distribution as in data, and sideband data. After applying these requirements, 3191 events remain.

The selected four-track vertex is identified as a $B^0$ or $\bar{B}^0$ candidate depending on whether the $K^+\pi^-$ or $K^-\pi^+$ invariant mass is closest to the nominal $K^{*0}$ mass. The fraction of candidates assigned to the incorrect state is estimated from simulation to be 12–14%, depending on $q^2$.

The global efficiency, $\epsilon$, is the product of the acceptance and the combined trigger, reconstruction, and selection efficiencies, all of which are obtained from MC simulated event samples.
The pp collisions are simulated using the PYTHIA \textsuperscript{41} event generator, version 6.424, with particle decays described by the \textsc{evtgen} \textsuperscript{42} generator, version 9.1, in which final-state radiation is generated using \textsc{photos} \textsuperscript{43}. The default matrix element in PYTHIA is used to describe the events. The simulated particles are propagated through a detailed model of the detector based on \textsc{geant4} \textsuperscript{44}. The reconstruction and selection of the generated events proceed as for the data. Separate samples of events are generated for $B^0 \rightarrow K^0 \mu^+ \nu \rightarrow K^+ \pi^- \mu^+ \mu^-$, $J/ \psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$, and $\psi' K^{*0} \rightarrow \mu^+ \mu^+ K^+ \pi^-$. The distribution of pp collision vertices in each sample is adjusted to match the observed distribution.

The acceptance is obtained from generator-level events, i.e., before the particle propagation with \textsc{geant4}, and is defined as the fraction of events with $p_T(B^0) > 8$ GeV and $|\eta(B^0)| < 2.2$ that satisfy the single-muon requirements $p_T(\mu) > 3.3$ GeV and $|\eta(\mu)| < 2.3$. These criteria are less restrictive than the final selection criteria in order to account for finite detector resolution, since they are applied to generator-level quantities. Only events satisfying the acceptance criteria are processed through the \textsc{geant4} simulation, the trigger simulation, and the reconstruction software.

The combined trigger, reconstruction, and selection efficiency is given by the ratio of the number of events that satisfy the trigger and selection requirements and have a reconstructed $B^0$ candidate compatible with a generated $B^0$ meson, relative to the number of events that satisfy the acceptance criteria. The generated and reconstructed $B^0$ are considered to be compatible if the reconstructed $K^+$ candidate appears within a distance $\Delta R$ of the generated $K^+$ meson, and analogously for the $\pi^-$, $\mu^+$, and $\mu^-$, where $\Delta R = 0.3$ for the hadrons and $\Delta R = 0.004$ for the muons. Requiring all four particles in the $B^0$ decay to be matched results in an efficiency of 99.6% (0.4% of the events have a correctly reconstructed $B^0$ candidate that is not matched to a generated $B^0$ meson) and a purity of 99.5% (0.5% of the matched candidates do not correspond to a correctly reconstructed $B^0$ candidate). Efficiencies are determined for both correctly tagged (the K and $\pi$ have the correct charge) and mistagged (the K and $\pi$ charges are reversed) candidates.

Using simulation, we search for possible backgrounds that might peak in the $B^0$ mass region. The event selection is applied to inclusive MC samples of $B^0_\mu B^{0+}$, and $\Lambda_b$ decays to $J/ \psi X$ and $\psi' X$, where X denotes all possible SM particles required to complete the known exclusive decay channels, and with the $J/ \psi$ and $\psi'$ decaying to $\mu^+ \mu^-$. No evidence for a peaking structure near the $B^0$ mass is found. The distributions of the few events that satisfy the selection criteria are similar to the shape of the combinatorial background. As an additional check, we generate events with $B_s^0 \rightarrow K^{*0}(K^+ \pi^-)\mu^+ \mu^-$ decays, using the same branching fraction as for $B^0 \rightarrow K^{*0}(K^+ \pi^-)\mu^+ \mu^-$. About 70 such events, integrated over $q^2$, are found to cluster near the $B_s$ mass. This background is considered negligible since it should be rescaled by the ratio of branching fractions $B(B_s^0 \rightarrow J/ \psi K^{*0})/B(B^0 \rightarrow J/ \psi K^{*0}) \approx 10^{-2}$ \textsuperscript{40}. Possible backgrounds from events with hadrons misidentified as muons or with muons misidentified as hadrons, e.g., from random D mesons associated with random stable charged hadrons or from $B^0 \rightarrow DX$ or $B^0 \rightarrow J/ \psi K^+$ decays, are considered negligible because of the good muon identification capabilities of the CMS detector \textsuperscript{38}. We also investigated possible background from events in which a $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay is combined with a random pion, and from events with a $\Lambda_b \rightarrow p K \mu^+ \mu^-$ decay in which the proton is assigned the pion mass. Both these potential sources of background are found to be negligible. The low-mass sideband might be affected by background events that have a different origin with respect to the combinatorial background that characterizes the signal region, e.g., partially reconstructed multibody B decays. We address this possible background contamination in Section \ref{sec:background}.
4 Analysis method

This analysis measures the $P_1$ and $P'_S$ values in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays as a function of $q^2$. Figure 4 illustrates the angular variables needed to describe the decay: $\theta_\ell$ is the angle between the positive (negative) muon momentum and the direction opposite to the $B^0$ ($\bar{B}^0$) momentum in the dimuon rest frame, $\theta_K$ is the angle between the kaon momentum and the direction opposite to the $B^0$ ($\bar{B}^0$) momentum in the $K^{*0}$ ($\bar{K}^{*0}$) rest frame, and $\varphi$ is the angle between the plane containing the two muons and the plane containing the kaon and the pion in the $B^0$ rest frame. Although the $K^+ \pi^-$ invariant mass is required to be consistent with that of a $K^{*0}$ meson, there can be a contribution from spinless (S-wave) $K^+ \pi^-$ combinations [25,[5,47]. This is parametrized with three terms: $F_S$, which is related to the S-wave fraction, and $A_S$ and $A_S'$, which are the interference amplitudes between the S- and P-wave decays. Including these components, the angular distribution of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays can be written as [25]:

$$
\frac{1}{\Delta q^2} \frac{d^4 \Gamma}{d \theta_\ell \ d \cos \theta_K \ d \cos \varphi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left( F_S + A_S \cos \theta_K \right) \left( 1 - \cos^2 \theta_\ell \right) \right.
$$

$$
+ A_S^2 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell \cos \varphi} \left[ \frac{1}{2} \frac{1}{2} \left( 1 - F_L \right) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_\ell \right) \right.
$$

$$
+ \frac{1}{2} \left( 1 - F_L \right) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_\ell \right) \left[ \frac{1}{2} \left( 1 - F_L \right) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_\ell \right) \right.
$$

$$
+ \frac{1}{2} P_1 \left( 1 - F_L \right) \left( 1 - \cos^2 \theta_K \right) \left( 1 - \cos^2 \theta_\ell \right) \cos 2\varphi
$$

$$
+ \frac{1}{2} P'_S \cos \theta_K \sqrt{F_L \left( 1 - F_L \right)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell \cos \varphi} \right\},
$$

(1)

where $F_L$ denotes the longitudinal polarization fraction of the $K^{*0}$. This expression is an exact simplification of the full angular distribution, obtained by folding the $\varphi$ and $\theta_\ell$ angles about zero and $\pi/2$, respectively. Specifically, if $\varphi < 0$, then $\varphi \rightarrow -\varphi$, and the new $\varphi$ domain is $[0, \pi]$. If $\theta_\ell > \pi/2$, then $\theta_\ell \rightarrow \pi - \theta_\ell$, and the new $\theta_\ell$ domain is $[0, \pi/2]$. We use this simplified version of the expression because of difficulties in the fit convergence with the full angular distribution due to the limited size of the data sample. This simplification exploits the odd symmetry of the angular variables with respect to $\varphi = 0$ and $\theta_\ell = \pi/2$ in such a manner that the cancellation around these angular values is exact. This cancellation remains approximately valid even after accounting for the experimental acceptance because the efficiency is symmetric with respect to the folding angles.

For each $q^2$ bin, the observables of interest are extracted from an unbinned extended maximum-likelihood fit to four variables: the $K^+ \pi^- \mu^+ \mu^-$ invariant mass $m$ and the three angular variables $\theta_\ell$, $\theta_K$, and $\varphi$. The unnormalized probability density function (pdf) in each $q^2$ bin has the following form:

$$
pdf(m, \theta_K, \theta_\ell, \varphi) = Y_S^C \left[ S^C(m) \ S^C(\theta_K, \theta_\ell, \varphi) \ e^C(\theta_K, \theta_\ell, \varphi) \right]
$$

$$
+ \frac{f_M}{1 - f_M} \left[ S^M(m) \ S^M(-\theta_K, -\theta_\ell, \varphi) \ e^M(\theta_K, \theta_\ell, \varphi) \right]
$$

$$
+ Y_B \ B^M(m) \ B^K(\theta_K) \ B^{\theta}(\theta_\ell) \ B^{\psi}(\varphi),
$$

(2)
where the three terms on the righthand side correspond to correctly tagged signal events, mistagged signal events, and background events. The parameters $Y_S$ and $Y_B$ are the yields of correctly tagged signal events and background events, respectively, and are determined in the fit. The parameter $f^M$ is the fraction of signal events that are mistagged and is determined from simulation. Its value ranges from 0.124 to 0.137 depending on the $q^2$ bin.

The signal mass probability functions $S^C(m)$ and $S^M(m)$ are each the sum of two Gaussian functions, with a common mean for all four Gaussian functions, and describe the mass distribution for correctly tagged and mistagged signal events, respectively. In the fit, the mean, the four Gaussian function’s width parameters, and the two fractions specifying the relative contributions, with a common mean for all four Gaussian functions, and describe the mass distribution for correctly tagged signal events and background events, respectively, and are determined in the fit. The parameter $f^M$ is the fraction of signal events that are mistagged and is determined from simulation. Its value ranges from 0.124 to 0.137 depending on the $q^2$ bin.

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The efficiency for mistagged events has a monotonic decrease for increasing $\cos \theta_K$, while it is maximal near $\cos \theta_K = -1$. The efficiency for mistagged events becomes relatively flat in $\cos \theta_{\ell}$ for larger values of $q^2$. The efficiency for correctly tagged events has a minimum at $\cos \theta_{\ell} \approx 0$ for $q^2 < 10 \text{GeV}^2$, while it is maximal near $\cos \theta_K = 0$ for $q^2 < 10 \text{GeV}^2$.

The above equations describe the signal and background contributions to the decay $B^0 \to K^{*0}(K^+ \pi^-)\mu^+\mu^-$. The efficiency for mistagged events has a monotonic decrease for increasing $\cos \theta_K$, while it is maximal near $\cos \theta_K = -1$. The efficiency for mistagged events becomes relatively flat in $\cos \theta_{\ell}$ for larger values of $q^2$. The efficiency for correctly tagged events has a minimum at $\cos \theta_{\ell} \approx 0$ for $q^2 < 10 \text{GeV}^2$, while it is maximal near $\cos \theta_K = 0$ for $q^2 < 10 \text{GeV}^2$.
For large values of \( q^2 \) a mild maximum also appears near \( \cos \theta_K = 1 \).

The fit is performed in two steps. The initial fit does not include a signal component and uses the sideband data in \( m \) to obtain the \( B^m(m) \), \( B^{0\pi}(\theta_K) \), \( B^{0\ell}(\theta) \), and \( B^{0\ell}(\varphi) \) distributions. The distributions obtained in this step are then fixed for the second step, which is a fit to the data over the full mass range. The fitted parameters in the second step are the angular parameters \( P_1 \), \( P'_5 \), and \( A_S^5 \), and the yields \( Y_S^C \) and \( Y_S \). To avoid difficulties in the convergence of the fit related to the limited number of events, the angular parameters \( F_L, F_S, \) and \( A_S \) are fixed to previous measurements [31].

The expression describing the angular distribution of \( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) decays, Eq. (1), and also its more general form in Ref. [25], can become negative for certain values of the angular parameters. In particular, the pdf in Eq. (2) is only guaranteed to be positive for a particular subset of the \( P_1, P'_5, \) and \( A_S^5 \) parameter space. The presence of such a boundary greatly complicates the numerical maximization process of the likelihood by MINUIT [50] and especially the error determination by MINOS [50], in particular near the boundary between physical and unphysical regions. Therefore, the second fit step is performed by discretizing the \( P_1, P'_5 \) two-dimensional space and by maximizing the likelihood as a function of the nuisance parameters \( Y_S^C, Y_B, \) and \( A_S^5 \) at fixed values of \( P_1 \) and \( P'_5 \). Finally, the distribution of the likelihood values is fit with a bivariate Gaussian distribution. The position of the maximum of this distribution inside the physical region provides the measurements of \( P_1 \) and \( P'_5 \).

The interference terms \( A_S \) and \( A_S^5 \) must vanish if either of the two interfering components vanish. These constraints are implemented by requiring \( |A_S| < \sqrt{12F_S(1-F_S)}F_L f \) and \( |A_S^5| < \sqrt{3F_S(1-F_S)(1-F_L)(1+P_1)} f \), where \( f \) is a ratio related to the S- and P-wave line shapes, calculated to be 0.89 near the \( K^{*0} \) meson mass [25]. The constraint on \( A_S \) is naturally satisfied since \( F_S, F_L, \) and \( A_S \) are taken from previous measurements [31].

To ensure correct coverage for the uncertainties, the Feldman–Cousins method [51] is used with nuisance parameters. Two main sets of pseudo-experimental samples are generated. The first (second) set, used to compute the coverage for \( P_1 \) (\( P'_5 \)), is generated by assigning values to the other parameters as obtained by profiling the bivariate Gaussian distribution description of the likelihood determined from data at fixed \( P_1 \) (\( P'_5 \)) values. When fitting the pseudo-experimental samples, the same fit procedure as applied to the data is used.

The fit formalism and results are validated through fits to pseudo-experimental samples, MC simulation samples, and control channels. Additional details, including the size of the systematic uncertainties assigned on the basis of these fits, are described in Section 5.

5 Systematic uncertainties

The systematic uncertainty studies are described below and summarized in Table 1 in the same order.

The adequacy of the fit function and the procedure to determine the parameters of interest are validated in three ways. First, a large, statistically precise MC signal sample with approximately 400 times the number of events as the data is used to verify that the fitting procedure produces results consistent with the input values to the simulation. The difference between the input and output values in this check is assigned as a simulation mismodeling systematic uncertainty. It is also verified that fitting a sample with only either correctly tagged or mistagged events yields the correct results. Second, 200 subsamples are extracted randomly from the large MC signal sample and combined with background events obtained from the pdf in Eq. (2) to
mimic independent data sets of similar size to the data. These are used to estimate a fit bias by comparing the average values of the results obtained by fitting the 200 samples to the results obtained using the full MC signal sample. Much of the observed bias is a consequence of the fitted parameters lying close to the boundaries of the physical region. Third, 200 pseudo-experiments, each with the same number of events as the data sample, are generated in each \( q^2 \) bin using the pdf in Eq. (2), with parameters obtained from the fit to the data. Fits to these 200 samples do not reveal any additional systematic uncertainty.

Table 1: Systematic uncertainties in \( P_1 \) and \( P'_5 \). For each source, the range indicates the variation over the bins in \( q^2 \).

| Source                                | \( P_1 \times 10^{-3} \) | \( P'_5 \times 10^{-3} \) |
|---------------------------------------|--------------------------|---------------------------|
| Simulation mismodeling                | 1–33                     | 10–23                     |
| Fit bias                              | 5–78                     | 10–120                    |
| Finite size of simulated samples      | 29–73                    | 31–110                    |
| Efficiency                            | 17–100                   | 5–65                      |
| K\(\pi\) mistagging                   | 8–110                    | 6–66                      |
| Background distribution               | 12–70                    | 10–51                     |
| Mass distribution                     | 12                       | 19                        |
| Feed-through background               | 4–12                     | 3–24                      |
| \( F_L, F_S, A_S \) uncertainty propagation | 0–210               | 0–210                     |
| Angular resolution                    | 2–68                     | 0.1–12                    |
| Total                                 | 100–230                  | 70–250                    |

Because the efficiency functions are estimated from a finite number of simulated events, there is a corresponding statistical uncertainty in the efficiency. Alternatives to the default efficiency function are obtained by generating 100 new distributions for the numerator and the denominator of the efficiency ratio based on the default kernel density estimators as pdfs, and rederiving new kernel density estimators for each trial. The effect of these different efficiency functions on the final result is used to estimate the systematic uncertainty.

The efficiency determination is checked by comparing efficiency-corrected results obtained from the control channels with the corresponding world average values. The \( B^0 \to J/\psi K^{*0} \) control sample contains 165 000 events, compared with 11 000 events for the \( B^0 \to \psi' K^{*0} \) sample. Because of its greater statistical precision, we rely on the \( B^0 \to J/\psi K^{*0} \) sample to perform the check of the efficiency determination for the angular variables. We do this by measuring the longitudinal polarization fraction \( F_L \) in the \( B^0 \to J/\psi K^{*0} \) decays. We find \( F_L = 0.537 \pm 0.002 \) (stat), compared with the world average value \( 0.571 \pm 0.007 \) (stat+syst) [40]. The difference of 0.034 is propagated to \( P_1 \) and \( P'_5 \) by taking the root-mean-square (RMS) of the respective distributions resulting from refitting the data 200 times, varying \( F_L \) within a Gaussian distribution with a standard deviation of 0.034. As a cross-check that the efficiency is not affected by a \( q^2 \)-dependent offset, we measure the ratio of branching fractions

\[
B(B^0 \to \psi'K^{*0})/B(B^0 \to J/\psi K^{*0}) = 0.480 \pm 0.008 \text{ (stat)} \pm 0.055 \text{ (R}_{\mu\mu}^{\text{eff}}),
\]

by means of efficiency-corrected yields including both correctly and wrongly tagged events (the same central value is obtained also separately for the two subsets of events), where \( R_{\mu\mu}^{R} \) refers to the ratio \( B(J/\psi \to \mu^+\mu^-)/B(\psi' \to \mu^+\mu^-) \) of branching fractions. This is compared to the world average value \( 0.484 \pm 0.018 \text{ (stat)} \pm 0.011 \text{ (syst)} \pm 0.012 \text{ (R}_{\mu\mu}^{\text{eff}}) \) [40], where \( R_{\mu\mu}^{R} \) refers to the corresponding ratio of branching fractions to \( e^+e^- \). The two results are seen to agree within the uncertainties.

To evaluate the uncertainty in the mistag fraction \( f_M \), we allow this fraction to vary in a fit to the events in the \( B^0 \to J/\psi K^{*0} \) control sample. We find \( f_M = (14.5 \pm 0.5)\% \), compared to
the result from simulation (13.7 ± 0.1)%. The difference of 0.8 is propagated to $P_1$ and $P'_5$ by
determining the RMS of the respective distributions obtained from refitting the data 10 times,
varying $f^M$ within a Gaussian distribution with a standard deviation of 0.8.

The systematic uncertainty associated with the functions used to model the angular distribu-
tion of the background is obtained from the statistical uncertainty in the background shape,
as these shapes are fixed in the final fit. This uncertainty is determined by fitting the data 200
times, varying the background parameters within their Gaussian uncertainties, and taking the
RMS of the angular parameter values as the systematic uncertainty.

The low-mass sideband might contain partially reconstructed multibody $B^0$ decays. We test
this possibility by refitting the data with a 180 MeV-wide low-mass sideband, i.e., starting at
$\approx 5.1$ GeV instead of $\approx 5.0$ GeV. No significant differences are seen in the measurement of $P_1$
and $P'_5$, and therefore no systematic uncertainty is assigned.

To evaluate the systematic uncertainty associated with the signal mass pdfs $S^C(m)$ and $S^M(m)$,
we fit the $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow \psi K^{*0}$ control samples allowing two of the width values
in the four Gaussian terms to vary at a time. The maximum change in $P_1$ and $P'_5$ for either of the
two control channels is taken as the systematic uncertainty for all $q^2$ bins.

The $q^2$ bin just below the $J/\psi (\psi')$ control region, and the $q^2$ bin just above, may be contaminated
with $B^0 \rightarrow J/\psi K^{*0}$ ($B^0 \rightarrow \psi' K^{*0}$) “feed-through” events that are not removed by the selection
procedure. A special fit in these two bins is performed, in which an additional background
term is added to the pdf. This background distribution is obtained from simulated $B^0 \rightarrow J/\psi K^{*0}$
($B^0 \rightarrow \psi' K^{*0}$) events, with the background yield as a fitted parameter. The resulting changes in $P_1$
and $P'_5$ are used as estimates of the systematic uncertainty associated with this contribution.

To determine the uncertainty associated with the values of $F_L$, $F_S$, and $A_S$, 10 pseudo-experiments
per $q^2$ bin are generated using the pdf parameters determined from the fit to data. The number of events in these pseudo-experiments is 100 times that of the data. The pseudo-experiments are then fit twice, once with the same procedure as for the data and once with $P_1$, $P'_5$, $A_S$, $F_L$, $F_S$, and $A_S$ allowed to vary. The average ratio $\rho$ of the statistical uncertainties in $P_1$ and $P'_5$ from
the first fit to that in the second fit is used to compute the systematic uncertainty, which is propor-
tional to the confidence interval determined from the Feldman–Cousins method through the
coefficient $\sqrt{\rho^2 - 1}$. The stability of $\rho$ as a function of the number of events of the pseudo-
experiments is also verified. As a cross-check of our procedure concerning the fixed value of
$F_L$, we fit the two control regions either fixing $F_L$ or allowing it to vary, and find that the values
of $P_1$ and $P'_5$ are essentially unaffected. Moreover, we obtain the same values of $F_L$ as in our
previous study [31].

The effects of angular resolution on the reconstructed values of $\theta_K$ and $\theta_\ell$ are estimated by per-
foming two fits on the same set of simulated events. One fit uses the true values of the angular
variables and the other fit their reconstructed values. The difference in the fitted parameters
between the two fits is taken as an estimate of the systematic uncertainty.

The systematic uncertainties are determined for each $q^2$ bin, with the total systematic uncer-
tainty obtained by adding the individual contributions in quadrature.

As a note for future possible global fits of our $P_1$ and $P'_5$ data, the systematic uncertainties
associated with the efficiency, $K\pi$ mistagging, $B^0$ mass distribution, and angular resolution can
be assumed to be fully correlated bin-by-bin, while the remaining uncertainties can be assumed
to be uncorrelated.
6 Results

The events are fit in seven $q^2$ bins from 1 to 19 GeV$^2$, yielding 1397 signal and 1794 background events in total. As an example, distributions for two of these bins, along with the fit projections, are shown in Fig. 2. The fitted values of the signal yields, $P_1$, and $P'_5$ are given in Table 2 for the seven $q^2$ bins. The results for $P_1$ and $P'_5$ are shown in Fig. 3 along with those from the LHCb [33] and Belle [34] experiments. The fitted values of $A_5^S$ vary from $-0.052$ to $+0.057$.

Table 2: The measured signal yields, which include both correctly tagged and mistagged events, the $P_1$ and $P'_5$ values, and the correlation coefficients, in bins of $q^2$, for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays. The first uncertainty is statistical and the second is systematic. The bin ranges are selected to allow comparison with previous measurements.

| $q^2$ (GeV$^2$) | Signal yield | $P_1$ | $P'_5$ | Correlations |
|-----------------|--------------|-------|-------|--------------|
| 1.00–2.00       | 80 ± 12      | +0.12 ±0.46 ±0.10 | +0.10 ±0.32 ±0.07 | -0.0526 |
| 2.00–4.30       | 145 ± 16     | -0.69 ±0.58 ±0.23 | -0.57 ±0.34 ±0.18 | -0.0452 |
| 4.30–6.00       | 119 ± 14     | +0.53 ±0.33 ±0.19 | -0.96 ±0.22 ±0.25 | +0.4715 |
| 6.00–8.68       | 247 ± 21     | -0.47 ±0.20 ±0.15 | -0.64 ±0.15 ±0.13 | +0.0761 |
| 10.09–12.86     | 354 ± 23     | -0.53 ±0.14 ±0.15 | -0.69 ±0.11 ±0.13 | +0.6077 |
| 14.18–16.00     | 213 ± 17     | -0.33 ±0.24 ±0.20 | -0.66 ±0.20 ±0.18 | +0.4188 |
| 16.00–19.00     | 239 ± 19     | -0.53 ±0.19 ±0.16 | -0.56 ±0.12 ±0.07 | +0.4621 |

Two SM predictions, denoted SM-DHMV and SM-HEPfit, are available for comparison with the measured angular parameters. The SM-DHMV result, derived from Refs. [18] [25], updates the calculations from Ref. [52] to account for the known correlation between the different form factors [53]. It also combines predictions from light-cone sum rules, which are valid in the low-$q^2$ region, with lattice predictions at high $q^2$ [54] to obtain more precise determinations of the form factors over the full $q^2$ range. The hadronic charm quark loop contribution is obtained from Ref. [55]. The SM-HEPfit result, derived from Ref. [56], uses full QCD form factors [53] and obtains the hadronic contribution from LHCb data [33]. Reliable theoretical predictions are not available near the $J/\psi$ and $\psi'$ resonances. The two SM predictions are shown in comparison to the data in Fig. 3. Both sets of predictions are seen to be in agreement with the CMS results, although the agreement with the SM-DHMV prediction is somewhat better. Thus, we do not obtain evidence for physics beyond the SM. Qualitatively, the CMS measurements are compatible with the LHCb results. The Belle measurements lie systematically above both the CMS and LHCb results and the SM predictions.

7 Summary

Using proton-proton collision data recorded at $\sqrt{s} = 8$ TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of 20.5 fb$^{-1}$, an angular analysis has been performed for the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$. The signal sample consists of 1397 selected events. For each of seven bins between 1 to 19 GeV$^2$ in the dimuon invariant mass squared $q^2$, unbinned maximum-likelihood fits are performed on the distributions of the $K^+ \pi^- \mu^+ \mu^-$ invariant mass and three angular variables to obtain values of the $P_1$ and $P'_5$ parameters. The results are among the most precise to date for these parameters and are consistent with predictions based on the standard model.
Figure 2: Invariant mass and angular distributions of $K^+\pi^-\mu^+\mu^-$ events for (upper two rows) $2 < q^2 < 4.3\text{GeV}^2$ and (lower two rows) $4.3 < q^2 < 6\text{GeV}^2$. The projection of the results from the total fit, as well as for correctly tagged signal events, mistagged signal events, and background events, are also shown. The vertical bars indicate the statistical uncertainties.
Figure 3: CMS measurements of the $P_1$ and $P'_5$ angular parameters versus $q^2$ for $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays, in comparison to results from the LHCb [33] and Belle [34] Collaborations. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the $J/\psi$ and $\psi'$ resonances. The hatched regions show the predictions from two SM calculations described in the text, averaged over each $q^2$ bin.

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References

[1] W. Altmannshofer et al., “Symmetries and asymmetries of $B \to K^* \mu^+ \mu^-$ decays in the Standard Model and beyond”, JHEP 01 (2009) 019, doi:10.1088/1126-6708/2009/01/019, arXiv:0811.1214

[2] J. Matias, F. Mescia, M. Ramon, and J. Virto, “Complete anatomy of $\bar{B}_d \to \bar{K}^0(\to K \pi)\ell^+\ell^-$ and its angular distribution”, JHEP 04 (2012) 104, doi:10.1007/JHEP04(2012)104, arXiv:1202.4266

[3] S. Descotes-Genon, J. Matias, and J. Virto, “Global analysis of $b \to s \ell \ell$ anomalies”, JHEP 06 (2016) 092, doi:10.1007/JHEP06(2016)092, arXiv:1510.04239

[4] D. Melikhov, N. Nikitin, and S. Simula, “Probing right-handed currents in $B \to K^* \ell^+\ell^-$ transitions”, Phys. Lett. B 442 (1998) 381, doi:10.1016/S0370-2693(98)01271-4, arXiv:hep-ph/9807464

[5] A. Ali, P. Ball, L. T. Handoko, and G. Hiller, “A comparative study of the decays $B \to (K, K^*)\ell^+\ell^-$ in the standard model and supersymmetric theories”, Phys. Rev. D 61 (2000) 074024, doi:10.1103/PhysRevD.61.074024, arXiv:hep-ph/9910221

[6] Q.-S. Yan, C.-S. Huang, W. Liao, and S.-H. Zhu, “Exclusive semileptonic rare decays $B \to (K, K^*)\ell^+\ell^-$ in supersymmetric theories”, Phys. Rev. D 62 (2000) 094023, doi:10.1103/PhysRevD.62.094023, arXiv:hep-ph/0004262

[7] G. Buchalla, G. Hiller, and G. Isidori, “Phenomenology of nonstandard $Z$ couplings in exclusive semileptonic $b \to s$ transitions”, Phys. Rev. D 63 (2000) 014015, doi:10.1103/PhysRevD.63.014015, arXiv:hep-ph/0006136

[8] T. Feldmann and J. Matias, “Forward-backward and isospin asymmetry for $B \to K^* \ell^+\ell^-$ decay in the standard model and in supersymmetry”, JHEP 01 (2003) 074, doi:10.1088/1126-6708/2003/01/074, arXiv:hep-ph/0212158

[9] G. Hiller and F. Krüger, “More model-independent analysis of $b \to s$ processes”, Phys. Rev. D 69 (2004) 074020, doi:10.1103/PhysRevD.69.074020, arXiv:hep-ph/0310219

[10] F. Krüger and J. Matias, “Probing new physics via the transverse amplitudes of $B^0 \to K^*_0(\to K^-\pi^+)\ell^+\ell^-$ at large recoil”, Phys. Rev. D 71 (2005) 094009, doi:10.1103/PhysRevD.71.094009, arXiv:hep-ph/0502060

[11] W.-S. Hou, A. Hovhannisyan, and N. Mahajan, “$B \to K^* \ell^+\ell^-$ forward-backward asymmetry and new physics”, Phys. Rev. D 77 (2008) 014016, doi:10.1103/PhysRevD.77.014016, arXiv:0807.2589

[12] U. Egede et al., “New observables in the decay mode $\bar{B}_d \to \bar{K}^0\ell^+\ell^-$”, JHEP 11 (2008) 032, doi:10.1088/1126-6708/2008/11/032, arXiv:0807.2589

[13] T. Hurth, G. Isidori, J. F. Kamenik, and F. Mescia, “Constraints on new physics in MFV models: A model-independent analysis of $\Delta F = 1$ processes”, Nucl. Phys. B 808 (2009) 326, doi:10.1016/j.nuclphysb.2008.09.040, arXiv:0807.5039

[14] A. K. Alok et al., “New-physics contributions to the forward-backward asymmetry in $B \to K^*\mu^+\mu^-$”, JHEP 02 (2010) 053, doi:10.1007/JHEP02(2010)053, arXiv:0912.1382
[15] A. K. Alok et al., “New physics in $b \to s \mu^+ \mu^-$: CP-conserving observables”, *JHEP* **11** (2011) 121, [doi:10.1007/JHEP11(2011)121][arXiv:1008.2367].

[16] Q. Chang, X.-Q. Li, and Y.-D. Yang, “$B \to K^* \ell^+ \ell^-$, $K \ell^+ \ell^-$ decays in a family non-universal $Z'$ model”, *JHEP* **04** (2010) 052, [doi:10.1007/JHEP04(2010)052][arXiv:1002.2758].

[17] S. Descotes-Genon, D. Ghosh, J. Matias, and M. Ramon, “Exploring new physics in the $C_7$-$C_{7'}$ plane”, *JHEP* **06** (2011) 099, [doi:10.1007/JHEP06(2011)099][arXiv:1104.3342].

[18] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, “Implications from clean observables for the binned analysis of $B \to K^* \mu^+ \mu^-$ at large recoil”, *JHEP* **01** (2013) 048, [doi:10.1007/JHEP01(2013)048][arXiv:1207.2753].

[19] C. Bobeth, G. Hiller, and D. van Dyk, “The benefits of $B \to K^* \ell^+ \ell^-$ decays at low recoil”, *JHEP* **07** (2010) 098, [doi:10.1007/JHEP07(2010)098][arXiv:1006.5013].

[20] C. Bobeth, G. Hiller, D. van Dyk, and C. Wacker, “The decay $B \to K \ell^+ \ell^-$ at low hadronic recoil and model-independent $\Delta B = 1$ constraints”, *JHEP* **01** (2012) 107, [doi:10.1007/JHEP01(2012)107][arXiv:1111.2558].

[21] C. Bobeth, G. Hiller, and D. van Dyk, “General analysis of $B \to K(\ast) \ell^+ \ell^-$ decays at low recoil”, *Phys. Rev. D* **87** (2012) 034016, [doi:10.1103/PhysRevD.87.034016][arXiv:1212.2321].

[22] A. Ali, G. Kramer, and G. Zhu, “$B \to K^* \ell^+ \ell^-$ decay in soft-collinear effective theory”, *Eur. Phys. J. C* **47** (2006) 625, [doi:10.1140/epjc/s2006-02596-4][arXiv:hep-ph/0601034].

[23] W. Altmannshofer, P. Paradisi, and D. M. Straub, “Model-independent constraints on new physics in $b \to s$ transitions”, *JHEP* **04** (2012) 008, [doi:10.1007/JHEP04(2012)008][arXiv:1111.1257].

[24] S. Jäger and J. Martin Camalich, “On $B \to V \ell \ell$ at small dilepton invariant mass, power corrections, and new physics”, *JHEP* **05** (2013) 043, [doi:10.1007/JHEP05(2013)043][arXiv:1212.2263].

[25] S. Descotes-Genon, T. Hurth, J. Matias, and J. Virto, “Optimizing the basis of $B \to K(\ast) \ell^+ \ell^-$ observables in the full kinematic range”, *JHEP* **05** (2013) 137, [doi:10.1007/JHEP05(2013)137][arXiv:1303.5794].

[26] BaBar Collaboration, “Angular distributions in the decay $B \to K^* \ell^+ \ell^-$”, *Phys. Rev. D* **79** (2009) 031102, [doi:10.1103/PhysRevD.79.031102][arXiv:0804.4412].

[27] Belle Collaboration, “Measurement of the differential branching fraction and forward-backward asymmetry for $B \to K^{(*)} \ell^+ \ell^-$”, *Phys. Rev. Lett.* **103** (2009) 171801, [doi:10.1103/PhysRevLett.103.171801][arXiv:0904.0770].

[28] CDF Collaboration, “Measurements of the angular distributions in the decays $B \to K^{(*)} \mu^+ \mu^-$ at CDF”, *Phys. Rev. Lett.* **108** (2012) 081807, [doi:10.1103/PhysRevLett.108.081807][arXiv:1108.0695].
[29] LHCb Collaboration, “Differential branching fraction and angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$”, JHEP 08 (2013) 131, doi:10.1007/JHEP08(2013)131, arXiv:1304.6325.

[30] CMS Collaboration, “Angular analysis and branching fraction measurement of the decay $B^0 \to K^{*0}\mu^+\mu^-$”, Phys. Lett. B 727 (2013) 77, doi:10.1016/j.physletb.2013.10.017, arXiv:1308.3409.

[31] CMS Collaboration, “Angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ from pp collisions at $\sqrt{s} = 8$ TeV”, Phys. Lett. B 753 (2016) 424, doi:10.1016/j.physletb.2015.12.020, arXiv:1507.08125.

[32] LHCb Collaboration, “Measurement of form-factor-independent observables in the decay $B^0 \to K^{*0}\mu^+\mu^-$”, Phys. Rev. Lett. 111 (2013) 191801, doi:10.1103/PhysRevLett.111.191801, arXiv:1308.1707.

[33] CMS Collaboration, “CMS luminosity based on pixel cluster counting — Summer 2013 update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.

[34] CMS Collaboration, “Large hadron collider experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[35] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 9 (2014) P10009, doi:10.1088/1748-0221/9/01/P01020, arXiv:1609.02366.

[36] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, JINST 7 (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[37] CMS Collaboration, “The CMS trigger system”, JINST 12 (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[38] Particle Data Group, C. Patrignani et al., “The Review of Particle Physics”, Chin. Phys. C 40 (2016) 100001, doi:10.1088/1674-1137/40/10/100001.

[39] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, JHEP 05 (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[40] D. J. Lange, “The EvtGen particle decay simulation package”, Nucl. Instrum. Meth. A 462 (2001) 152, doi:10.1016/S0168-9002(01)0089-4.

[41] E. Barberio, and Z. Was, “Photos—a universal Monte Carlo for QED radiative corrections in Z and W decays”, Eur. Phys. J. C 45 (2006) 97, doi:10.1140/epjc/s2005-02396-4, arXiv:hep-ph/0506026.
[44] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[45] D. Bečirević and A. Tayduganov, “Impact of $B \to K^+ \ell^+ \ell^-$ on the new physics search in $B \to K^\ast \ell^+ \ell^-$ decay”, *Nucl. Phys. B* 868 (2013) 368, doi:10.1016/j.nuclphysb.2012.11.016, arXiv:1207.4004.

[46] J. Matias, “On the S-wave pollution of $B \to K^\ast \ell^+ \ell^-$ observables”, *Phys. Rev. D* 86 (2012) 094024, doi:10.1103/PhysRevD.86.094024, arXiv:1209.1525.

[47] T. Blake, U. Egede, and A. Shires, “The effect of S-wave interference on the $B_0 \to K^\ast 0 \ell^+ \ell^-$ angular observables”, *JHEP* 03 (2013) 027, doi:10.1007/JHEP03(2013)027, arXiv:1210.5279.

[48] D. W. Scott, “Multivariate density estimation: theory, practice, and visualization”. Wiley series in probability and mathematical statistics: Applied probability and statistics section. Wiley-Interscience, New York, Chichester, Brisbane, 1992. ISBN 0-471-54770-0.

[49] K. S. Cranmer, “Kernel estimation in high-energy physics”, *Comput. Phys. Commun.* 136 (2001) 198, doi:10.1016/S0010-4655(00)00243-5, arXiv:hep-ex/0011057.

[50] F. James and M. Roos, “Minuit—a system for function minimization and analysis of the parameter errors and correlations”, *Comput. Phys. Commun.* 10 (1975) 343, doi:10.1016/0010-4655(75)90039-9.

[51] A. Bharucha, D. M. Straub, and R. Zwicky, “$b \to v \ell^+ \ell^-$ in the standard model from light-cone sum rules reexamined”, *Phys. Rev. D* 71 (2005) 014029, doi:10.1103/PhysRevD.71.014029, arXiv:hep-ph/0412079.

[52] J. Matias, “On the S-wave pollution of $B \to K^\ast \ell^+ \ell^-$ observables”, *Phys. Rev. D* 86 (2012) 094024, doi:10.1103/PhysRevD.86.094024, arXiv:1209.1525.

[53] A. Bharucha, D. M. Straub, and R. Zwicky, “$b \to v \ell^+ \ell^-$ in the standard model from light-cone sum rules reexamined”, *JHEP* 03 (2013) 027, doi:10.1007/JHEP03(2013)027, arXiv:1210.5279.

[54] D. W. Scott, “Multivariate density estimation: theory, practice, and visualization”. Wiley series in probability and mathematical statistics: Applied probability and statistics section. Wiley-Interscience, New York, Chichester, Brisbane, 1992. ISBN 0-471-54770-0.

[55] K. S. Cranmer, “Kernel estimation in high-energy physics”, *Comput. Phys. Commun.* 136 (2001) 198, doi:10.1016/S0010-4655(00)00243-5, arXiv:hep-ex/0011057.

[56] F. James and M. Roos, “Minuit—a system for function minimization and analysis of the parameter errors and correlations”, *Comput. Phys. Commun.* 10 (1975) 343, doi:10.1016/0010-4655(75)90039-9.

[57] A. Bharucha, D. M. Straub, and R. Zwicky, “$b \to v \ell^+ \ell^-$ in the standard model from light-cone sum rules reexamined”, *Phys. Rev. D* 71 (2005) 014029, doi:10.1103/PhysRevD.71.014029, arXiv:hep-ph/0412079.

[58] J. Matias, “On the S-wave pollution of $B \to K^\ast \ell^+ \ell^-$ observables”, *Phys. Rev. D* 86 (2012) 094024, doi:10.1103/PhysRevD.86.094024, arXiv:1209.1525.

[59] D. W. Scott, “Multivariate density estimation: theory, practice, and visualization”. Wiley series in probability and mathematical statistics: Applied probability and statistics section. Wiley-Interscience, New York, Chichester, Brisbane, 1992. ISBN 0-471-54770-0.

[60] K. S. Cranmer, “Kernel estimation in high-energy physics”, *Comput. Phys. Commun.* 136 (2001) 198, doi:10.1016/S0010-4655(00)00243-5, arXiv:hep-ex/0011057.

[61] F. James and M. Roos, “Minuit—a system for function minimization and analysis of the parameter errors and correlations”, *Comput. Phys. Commun.* 10 (1975) 343, doi:10.1016/0010-4655(75)90039-9.

[62] A. Bharucha, D. M. Straub, and R. Zwicky, “$b \to v \ell^+ \ell^-$ in the standard model from light-cone sum rules reexamined”, *Phys. Rev. D* 71 (2005) 014029, doi:10.1103/PhysRevD.71.014029, arXiv:hep-ph/0412079.

[63] J. Matias, “On the S-wave pollution of $B \to K^\ast \ell^+ \ell^-$ observables”, *Phys. Rev. D* 86 (2012) 094024, doi:10.1103/PhysRevD.86.094024, arXiv:1209.1525.
A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut f"ur Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Er"o, M. Flechl, M. Friedl, R. Fruhwirth1, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler1, A. K"onig, N. Krammer, I. Kr"atschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck1, V. Sch"ofbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz1, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossovov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Lueti, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang

Ghent University, Ghent, Belgium
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov3, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Université de Mons, Mons, Belgium
N. Beliy

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Alda Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato4, E. Coelho, E.M. Da Costa, G.G. Da Silveira3, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote4, F. Torres Da Silva De Araujo, A. Vilela Pereira
Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
S. Ahuja, C.A. Bernardes, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante,
S.F. Novaes, Sandra S. Padula, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao,
Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang,
S. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, Q. Li, L. Linwei, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez,
M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval
Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis,
H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian
Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgammal, A. Mahrous

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkinä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besançon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.O. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram12, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte12, X. Coubez, J.-C. Fontaine12, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, 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, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov13, V. Sordini, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili14

Tbilisi State University, Tbilisi, Georgia
D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, V. Zhukov13

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teysier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl15
Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras\textsuperscript{16}, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo\textsuperscript{17}, J. Garay García, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel\textsuperscript{18}, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann\textsuperscript{18}, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klinger, R. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo\textsuperscript{15}, T. Peiffer, A. Perieanu, C. Scharf, P. Schlepper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann\textsuperscript{15}, S.M. Heindl, U. Husemann, F. Kassel, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

National Technical University of Athens, Athens, Greece
K. Kousouris

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, G. Pasztor, O. Sürányi, G.I. Veres\textsuperscript{19}

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horváth\textsuperscript{20}, Á. Hunyadi, F. Sikler, V. Veszprémi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi\textsuperscript{21}, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
M. Bartók\textsuperscript{19}, P. Raics, Z.L. Trocsanyi, B. Ujvari
IFNE Sezione di Catania a, Università di Catania b, Catania, Italy
S. Albergo a, b, S. Costa a, b, A. Di Mattia a, F. Giordano a, b, R. Potenza a, b, A. Tricomi a, b, C. Tuve a, b

IFNE Sezione di Firenze a, Università di Firenze b, Firenze, Italy
G. Barbagli a, K. Chatterjee a, b, V. Ciulli a, b, C. Civinini a, R. D’Alessandro a, b, E. Focardi a, b, P. Lenzi a, b, M. Meschini a, S. Paoletti a, L. Russo a, 29, G. Sguazzoni a, D. Strom a, L. Villani a, b, 15

IFNE Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera 15

IFNE Sezione di Genova a, Università di Genova b, Genova, Italy
V. Calvelli a, b, F. Ferro a, E. Robutti a, T. Sosi a, b

IFNE Sezione di Milano-Bicocca a, Università di Milano-Bicocca b, Milano, Italy
S. Buontempo a, N. Cavallo a, c, S. Di Guida a, d, 15, F. Fabozzi a, c, F. Fienga a, b, A.O.M. Iorio a, b, W.A. Khan a, L. Lista a, S. Meola a, d, 15, P. Paolucci a, d, 15, C. Sciaccio a, b, F. Thyssen a

IFNE Sezione di Napoli a, Università di Napoli ‘Federico II’ b, Napoli, Italy, Università della Basilicata c, Potenza, Italy, Università G. Marconi d, Roma, Italy
A. Benaglia a, A. Beschi a, b, L. Bria 15, F. Brivio a, b, V. Ciriolo a, b, 15, M.E. Dinardo a, b, P. Dini a, S. Fiorendi a, b, S. Gennai a, A. Ghezzi b, b, P. Govoni a, b, M. Malberti a, b, S. Malvezzi a, R.A. Manzioni a, b, D. Menasce a, L. Moroni a, M. Paganoni a, b, K. Pauwels a, b, D. Pedrini a, S. Pigazzini a, b, 15, N. Redaelli a, T. Tabarelli a, de Fatis a, b

IFNE Sezione di Napoli 15, Università di Napoli ‘Federico II’ b, Napoli, Italy, Università della Basilicata c, Potenza, Italy, Università G. Marconi d, Roma, Italy
S. Buontempo a, N. Cavallo a, c, S. Di Guida a, d, 15, F. Fabozzi a, c, F. Fienga a, b, A.O.M. Iorio a, b, W.A. Khan a, L. Lista a, S. Meola a, d, 15, P. Paolucci a, d, 15, C. Sciaccio a, b, F. Thyssen a

IFNE Sezione di Padova a, Università di Padova b, Padova, Italy, Università di Trento c, Trento, Italy
P. Azzidi a, N. Bacchetta a, L. Benato a, b, A. Boletti a, b, R. Carlin a, b, A. Carvalho Antunes De Oliveira a, b, P. Checchia a, M. Dall’Osso a, b, P. De Castro Manzano a, T. Dorigo a, U. Gasparini a, b, A. Gozzelino a, S. Lacaprara a, P. Lujan, M. Margoni a, b, A.T. Meneguzzo a, b, F. Montecassiano a, M. Passaseo a, N. Pozzobon a, b, S. Pigazzini a, b, 15, N. Redaelli a, T. Tabarelli a, de Fatis a, b

IFNE Sezione di Pavia a, Università di Pavia b, Pavia, Italy
A. Braghieri a, A. Magnani a, P. Montagna a, b, S.P. Ratti a, b, V. Re a, M. Ressegotti a, b, C. Riccardi a, b, P. Salvini a, I. Vai a, b, P. Vitulo a, b

IFNE Sezione di Perugia a, Università di Perugia b, Perugia, Italy
L. Alunni Solestizzi a, b, M. Biasini a, b, G.M. Bilei a, C. Cecchi a, b, D. Ciangottini a, b, L. Fano a, b, P. Lariccia a, b, R. Leonardi a, b, E. Manoni a, G. Mantovani a, b, V. Mariani a, b, M. Menichelli a, A. Rossi a, b, A. Santocchia a, b, D. Spiga a

IFNE Sezione di Pisa a, Università di Pisa b, Scuola Normale Superiore di Pisa c, Pisa, Italy
K. Androsov a, P. Azzurri a, 15, G. Bagliesi a, T. Boccali a, L. Borrello, R. Castaldi a, M.A. Ciocci a, b, R. Dell’Orso a, G. Fedi a, L. Giannini a, c, A. Giassi a, M.T. Grippo a, 29, F. Ligabue a, c, T. Lomtadze a, E. Manca a, c, G. Mandorli a, c, L. Martin a, b, A. Messineo a, b, F. Palla a, A. Rizzi a, b, A. Savoy-Navarro a, 30, P. Spagnolo a, R. Tenchini a, G. Tonelli a, b, A. Venturi a, P.G. Verdini a

IFNE Sezione di Roma a, Sapienza Università di Roma b, Rome, Italy
L. Barone a, b, F. Cavallari a, M. Cipriani a, b, N. Daci a, D. Del Re a, b, 15, E. Di Marco a, b, M. Diemoz a, S. Gelli a, b, E. Longo a, b, F. Margaroli a, b, B. Marzocchi a, b, P. Meridiani a, G. Organtini a, b, R. Paramatti a, b, F. Preiato a, b, S. Rahatlou a, b, C. Rovelli a, F. Santanastasio a, b

IFNE Sezione di Torino a, Università di Torino b, Torino, Italy, Università del Piemonte Orientale c, Novara, Italy
N. Amapane a, b, R. Arcidiacono a, c, S. Argiro a, b, M. Arneodo a, c, N. Bartosik a, R. Bellan a, b,
C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, F. Cenna\textsuperscript{a,b}, M. Costa\textsuperscript{a,b}, R. Covarelli\textsuperscript{a,b}, A. Degano\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, B. Kiani\textsuperscript{a,b}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, E. Monteil\textsuperscript{a,b}, M. Monteno\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, F. Ravera\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, K. Shchelina\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, A. Staiano\textsuperscript{a}, P. Traczyk\textsuperscript{a,b}

INFN Sezione di Trieste \textsuperscript{a}, Università di Trieste \textsuperscript{b}, Trieste, Italy

S. Belforte\textsuperscript{a}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea

A. Lee

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

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali\textsuperscript{31}, F. Mohamad Idris\textsuperscript{32}, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz\textsuperscript{33}, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

A. Morelos Pineda
University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

Institute of Instrumentation and Experimental Physics, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiyev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vasiliev, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lyakhovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
R. Chistov, M. Danilov, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev
Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, Y. Skovpen, D. Shtol

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, T. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernandez Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Perez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Alvarez Fernandez

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. Gonzalez Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virtos, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guban, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. MeiJers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petruciani, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, T. Reis, G. Rolandi, M. Rovere, H. Sakulin, C. Schäfer, C. Schwik, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Spicinas, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns, M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, L. Caminada, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà,
C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Maronneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D.A. Sanz Becerra, M. Schönberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
M.N. Bakirci, A. Bat, F. Boran, S. Damarsekin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos, E.E. Kangal, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozmehr, S. Ozturk, B. Tali, U.G. Tok, H. Topakli, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, G. Karapinar, K. Ocalan, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya, O. Kaya, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria,
A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner, S. Zahid

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, D. Cutts, A. Garabedian, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J. Ellision, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzenski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorne, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu
Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O’Dell, K. Pedro, O. Prokofiev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilski, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrjula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogu, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi
Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. CocoRos, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Shkhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D’Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephens, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alversions, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard
The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA
R. Ciesielski, K. Goulianos, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali, A. Castaneda Hernandez, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia
Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herron, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Suez University, Suez, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Helwan University, Cairo, Egypt
12: Also at Université de Haute Alsace, Mulhouse, France
13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
14: Also at Tbilisi State University, Tbilisi, Georgia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Also at University of Ruhuna, Matara, Sri Lanka
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Yazd University, Yazd, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Purdue University, West Lafayette, USA
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Gaziosmanpasa University, Tokat, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Cag University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Adiyaman University, Adiyaman, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Necmettin Erbakan University, Konya, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Utah Valley University, Orem, USA
64: Also at Beykent University, Istanbul, Turkey
65: Also at Bingol University, Bingol, Turkey
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Sinop University, Sinop, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea