

CERN-EP-2017-240
2018/06/19

CMS-BPH-15-008

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.

Published in Physics Letters B as doi:10.1016/j.physletb.2018.04.030.

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 parameters [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 of the P_1 and P'_5 angular parameters in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays presented in this Letter 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 μ^+ 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, ψ' 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 a 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, $d\mathcal{B}/dq^2$ [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 was performed with a blinded procedure: the definition of fit strategy and its validation, as well as background distribution determination have been performed on simulated samples, control region and signal side bands. The final fit on data has been done at the end of validation. 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 pseudorapidity coverage of $|\eta| < 2.5$. For tracks with transverse momenta $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the resolutions are typically 1.5% in p_T and 25–90 (45–150) μm 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 2.5×10^{-3} , 0.5×10^{-3} , and 0.6×10^{-3} , respectively, for $p_T > 4$ GeV and $|\eta| < 2.4$. The muon identification efficiency is greater than 0.80 (0.98) for $p_T > 3.5$ 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 (the 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 $p_T > 3.5$ GeV, $|\eta| < 2.2$, and to pass within 2 cm of the beam axis. The dimuon system was required to have $p_T > 6.9$ GeV, a vertex fit χ^2 probability larger than 10%, and a separation of the vertex relative to the beamspot in the transverse plane of at least 3 standard deviations, where the calculation of the standard deviation 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 χ^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. These selection criteria are chosen to optimize the muon identification efficiency as measured using $J/\psi \rightarrow \mu^+\mu^-$ decays in data. 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 χ^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 α_{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 σ_m is the average mass resolution (≈ 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 χ^2 probability.

For each of the selected events, the dimuon invariant mass q and its uncertainty σ_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 σ_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/ψ 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.

To avoid bias, the optimization of the selection criteria, and the fit strategy described below in Section 4, are determined before data in the signal region are examined. The selection criteria do not depend on 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, ϵ , 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 [41] event generator, version 6.424, with particle decays described by the EVTGEN [42] generator, version 9.1, in which final-state radiation is generated using PHOTOS [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 GEANT4 [44]. The reconstruction and selection of the generated events proceed as for the data. Separate samples of events are generated for B^0 decays to $K^{*0}\mu^+\mu^-$, $J/\psi K^{*0}$, and $\psi' K^{*0}$, with $K^{*0} \rightarrow K^+\pi^-$ and both J/ψ and ψ' decaying to $\mu^+\mu^-$. 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 GEANT4, and is defined as the fraction of events with $p_T(B^0) > 8 \text{ GeV}$ and $|\eta(B^0)| < 2.2$ that satisfy the single-muon requirements $p_T(\mu) > 3.3 \text{ GeV}$ 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 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 ΔR of the generated K^+ meson, and analogously for the π^- , μ^+ , and μ^- , 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 π have the correct charge) and mistagged (the K and π charges are reversed) candidates.

3.1 Background studies

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 , B_s , B^+ , and Λ_b decays to $J/\psi X$ and $\psi' X$, where X denotes all of the exclusive decay channels found in the PDG [40], and with the J/ψ and ψ' 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 $B_s \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$ decays. Assuming that the ratio of branching fractions $\mathcal{B}(B_s \rightarrow J/\psi K^{*0})/\mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) \approx 10^{-2}$ [40], less than one event passes our selection criteria.

Possible backgrounds from events with two hadrons misidentified as muons, in particular from the hadronic fully reconstructable $B^0 \rightarrow DX$ decays, are suppressed by the misidentification probability ($10^{-3} \times 10^{-3}$), and are thus considered negligible. Also, events from

$B^0 \rightarrow J/\psi K^{*0}$ decays, where a muon and a hadron are swapped, are suppressed by the hadron-to-muon misidentification probability (10^{-3}) and by the muon-to-hadron identification inefficiency (10^{-1}). In fact, given the amount of reconstructed $B^0 \rightarrow J/\psi K^{*0}$ events (165 k), we expect ≈ 16 events distributed in the two adjacent q^2 bins close to the J/ψ control region.

Backgrounds from semileptonic decays such as $B^0 \rightarrow D^- \pi^+$, $B^0 \rightarrow D^- K^+$, and $B^0 \rightarrow D^- \mu^+ \nu_\mu$, where D^- decays to $K^{*0} \mu^- \bar{\nu}_\mu$ and K^{*0} to $K^+ \pi^-$, are also studied using simulation. We estimate in data less than one event for each of the three decays populating the low-mass sideband. All these potential sources of background are evaluated in the whole q^2 range, excluding the J/ψ and ψ' control regions, and are found to be negligible.

The impact of other partially reconstructed multibody B decays that might affect the low-mass sideband is addressed in Section 5.

Backgrounds from events in which a $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay is combined with a random pion, and from events with a $\Lambda_b \rightarrow \Lambda^0 \mu^+ \mu^-$ decay, where Λ^0 decays to p K, in which the proton is assigned the pion mass, are found to be negligible. In fact, both processes are flavor-changing neutral-current decays, therefore they have a comparable branching fraction to our signal process. The former decay has a theoretical lower bound on the invariant mass that lies at ≈ 5.41 GeV. We search in data for an invariant mass peak around the B^+ world-average mass after computing the invariant mass for both $K^+ \mu^+ \mu^-$ and $K^- \mu^+ \mu^-$ possibilities in events with $5.41 - \sigma_m < m < m_{B^0} + 0.280$ GeV, but no evidence of such a peak is found. For the latter decay we search in data for an invariant mass peak around the Λ_b world-average mass after assigning the proton mass to the track previously identified as a pion. Also in this case, no evidence of a peak is found. Indeed, the simulation shows that less than one event is expected to pass our selection requirements.

4 Analysis method

This analysis measures the P_1 and P'_5 values in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays as a function of q^2 . Figure 1 illustrates the angular variables needed to describe the decay: θ_ℓ 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, θ_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 φ 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, 45–47]. This is parametrized with three terms: F_S , which is related to the S-wave fraction, and A_S and A_S^5 , which are the interference amplitudes between the S- and P-wave decays. Including these

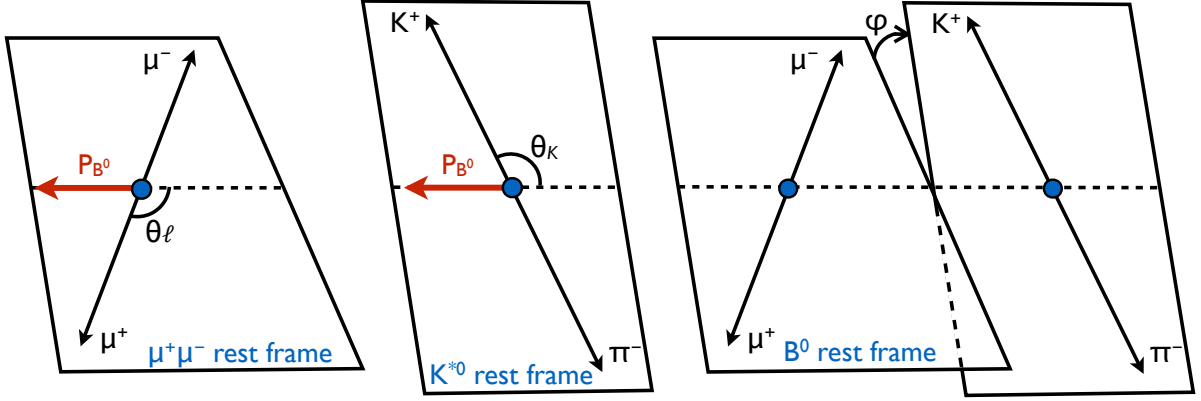


Figure 1: Illustration of the angular variables θ_ℓ (left), θ_K (middle), and φ (right) for the decay $B^0 \rightarrow K^{*0}(K^+ \pi^-) \mu^+ \mu^-$.

components, the angular distribution of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays can be written as [25]:

$$\begin{aligned}
 \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K d\varphi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[(F_S + A_S \cos\theta_K) (1 - \cos^2\theta_\ell) \right. \right. \\
 \left. \left. + A_S^5 \sqrt{1 - \cos^2\theta_K} \sqrt{1 - \cos^2\theta_\ell} \cos\varphi \right] \right. \\
 \left. + (1 - F_S) \left[2 F_L \cos^2\theta_K (1 - \cos^2\theta_\ell) \right. \right. \\
 \left. + \frac{1}{2} (1 - F_L) (1 - \cos^2\theta_K) (1 + \cos^2\theta_\ell) \right. \\
 \left. + \frac{1}{2} P_1 (1 - F_L) (1 - \cos^2\theta_K) (1 - \cos^2\theta_\ell) \cos 2\varphi \right. \\
 \left. \left. + 2 P'_5 \cos\theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2\theta_K} \sqrt{1 - \cos^2\theta_\ell} \cos\varphi \right] \right\}, \quad (1)
 \end{aligned}$$

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 φ and θ_ℓ angles about zero and $\pi/2$, respectively. Specifically, if $\varphi < 0$, then $\varphi \rightarrow -\varphi$, and the new φ domain is $[0, \pi]$. If $\theta_\ell > \pi/2$, then $\theta_\ell \rightarrow \pi - \theta_\ell$, and the new θ_ℓ 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 θ_ℓ , θ_K , and φ . The unnormalized probability density function (pdf) in each q^2 bin has the

following form:

$$\begin{aligned} \text{pdf}(m, \theta_K, \theta_\ell, \varphi) = & Y_S^C \left[S^C(m) S^a(\theta_K, \theta_\ell, \varphi) \epsilon^C(\theta_K, \theta_\ell, \varphi) \right. \\ & + \frac{f^M}{1 - f^M} S^M(m) S^a(-\theta_K, -\theta_\ell, \varphi) \epsilon^M(\theta_K, \theta_\ell, \varphi) \left. \right] \\ & + Y_B B^m(m) B^{\theta_K}(\theta_K) B^{\theta_\ell}(\theta_\ell) B^\varphi(\varphi), \end{aligned} \quad (2)$$

where the three terms on the righthand side correspond to correctly tagged signal events, mistagged signal events, and background events. The parameters Y_S^C 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 contribution of the two Gaussian functions in $S^C(m)$ and $S^M(m)$ are determined from simulation. The function $S^a(\theta_K, \theta_\ell, \varphi)$ describes the signal in the three-dimensional (3D) space of the angular variables and corresponds to Eq. (1). The combination $B^m(m) B^{\theta_K}(\theta_K) B^{\theta_\ell}(\theta_\ell) B^\varphi(\varphi)$ is obtained from the B^0 sideband data in m and describes the background in the space of $(m, \theta_K, \theta_\ell, \varphi)$, where $B^m(m)$ is an exponential function, $B^{\theta_K}(\theta_K)$ and $B^{\theta_\ell}(\theta_\ell)$ are second- to fourth-order polynomials, depending on the q^2 bin, and $B^\varphi(\varphi)$ is a first-order polynomial. The factorization assumption of the background pdf in Eq. (2) is validated by dividing the range of an angular variable into two at its center point and comparing the distributions of events from the two halves in the other angular variables.

The functions $\epsilon^C(\theta_K, \theta_\ell, \varphi)$ and $\epsilon^M(\theta_K, \theta_\ell, \varphi)$ are the efficiencies in the 3D space of $|\cos \theta_K| \leq 1$, $0 \leq \cos \theta_\ell \leq 1$, and $0 \leq \varphi \leq \pi$ for correctly tagged and mistagged signal events, respectively. The numerator and denominator of the efficiency are separately described with a nonparametric technique, which is implemented with a kernel density estimator [48, 49]. The final efficiency distributions used in the fit are obtained from the ratio of 3D histograms derived from the sampling of the kernel density estimators. The histograms have 40 bins in each dimension. A consistency check of the procedure used to determine the efficiency is performed by dividing the simulated data sample into two independent subsets, and extracting the angular parameters from the first subset using the efficiency computed from the second subset. The efficiencies for both correctly tagged and mistagged events peak at $\cos \theta_\ell \approx 0$, around which they are rather symmetric for $q^2 < 10 \text{ GeV}^2$, and are approximately flat in φ . The efficiency for correctly tagged events becomes relatively flat in $\cos \theta_\ell$ for larger values of q^2 , while it has a monotonic decrease for increasing $\cos \theta_K$ values for $q^2 < 14 \text{ GeV}^2$. For larger values of q^2 a decrease in the efficiency is also seen near $\cos \theta_K = -1$. The efficiency for mistagged 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 $B^m(m)$, $B^{\theta_K}(\theta_K)$, $B^{\theta_\ell}(\theta_\ell)$, and $B^\varphi(\varphi)$ 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_B . 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_5^5 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_5^5 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_5^5 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 $|A_5^5| < \sqrt{3F_S(1-F_S)(1-F_L)(1+P_1)}f$, 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 $B^0 \rightarrow J/\psi K^{*0}$ control sample contains 165 000 events, compared with 11 000 events for the $B^0 \rightarrow \psi' K^{*0}$ sample. Because of its greater statistical precision, we rely on the $B^0 \rightarrow J/\psi K^{*0}$ 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 $B^0 \rightarrow J/\psi K^{*0}$ decays. We find $F_L = 0.537 \pm 0.002$ (stat), compared with the world-average value 0.571 ± 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 overall efficiency is not affected by a q^2 -dependent offset, we measure the ratio of branching fractions $\mathcal{B}(B^0 \rightarrow \psi' K^{*0})/\mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) = 0.480 \pm 0.008$ (stat) ± 0.055 ($R_\psi^{\mu\mu}$), 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 $R_\psi^{\mu\mu}$ refers to the ratio $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)/\mathcal{B}(\psi' \rightarrow \mu^+\mu^-)$ of branching fractions. This is compared to the world-average value 0.484 ± 0.018 (stat) ± 0.011 (syst) ± 0.012 (R_ψ^{ee}) [40], where R_ψ^{ee} 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 $B^0 \rightarrow J/\psi K^{*0}$ control sample. We find $f^M = (14.5 \pm 0.5)\%$, compared to the result from simulation $(13.7 \pm 0.1)\%$. 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 distribution 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. Moreover, for the q^2 bin reported in Fig. 2, upper two rows, which shows an excess around $\cos \theta_\ell \approx 0.7$ that is also present in the sideband distribution (not shown in the figure), we refit the data using different descriptions of the background as a function of $\cos \theta_\ell$. The differences in the measurement of P_1 and P'_5 are within the systematic uncertainty quoted for the background distribution.

The low-mass sideband might contain partially reconstructed multibody B^0 decays. We test this possibility by refitting the data with a restricted range for the low-mass sideband, i.e., starting from ≈ 5.1 instead of ≈ 5 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/ψ (ψ') 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 properly propagate the uncertainty associated with the values of F_L , F_S , and A_S , taking into account possible correlations, 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 ρ of the statistical uncertainties in P_1 and P'_5 from the first fit to that in the second fit is used to compute this systematic uncertainty, which is proportional to the confidence interval determined from the Feldman–Cousins method through the coefficient $\sqrt{\rho^2 - 1}$. The stability of ρ as a function of the number of events of the pseudo-experiments is also verified. As cross-checks 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, obtaining the same value of F_L as in our previous study [31]. Moreover, we refit all the q^2 bins using only the P-wave contribution for the decay rate in Eq. (1) and leaving all three parameters, P_1 , P'_5 , and F_L , free to vary. The differences in the measured values of P_1 and P'_5 are within the systematic uncertainty quoted for the F_L , F_S , and A_S uncertainty propagation.

The effects of angular resolution on the reconstructed values of θ_K and θ_ℓ are estimated by performing 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 uncertainty 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.

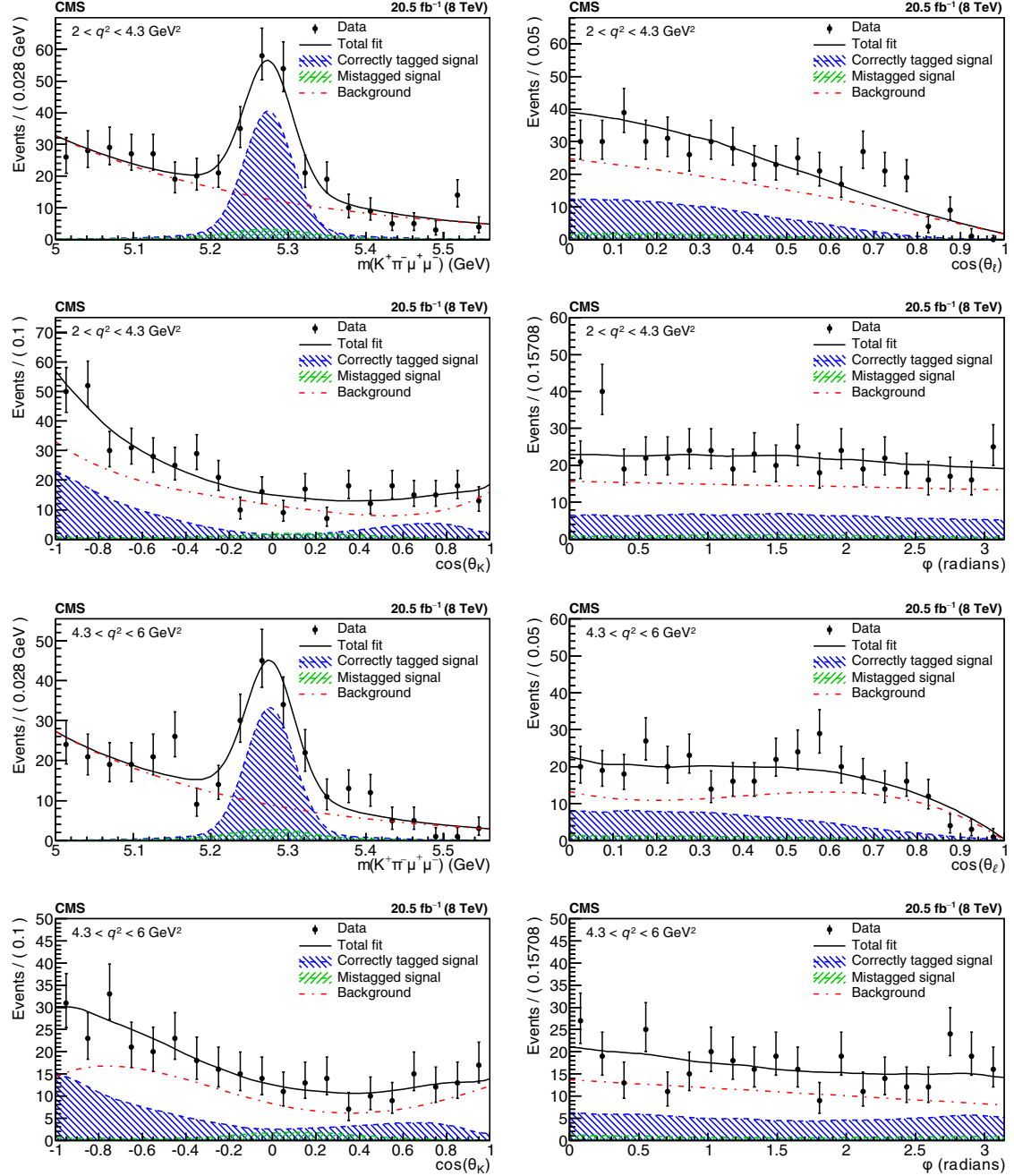


Figure 2: Invariant mass and angular distributions of $K^+\pi^-\mu^+\mu^-$ events for (upper two rows) $2 < q^2 < 4.3 \text{ GeV}^2$ and (lower two rows) $4.3 < q^2 < 6 \text{ GeV}^2$. The projection of the results from the total fit, as well as for correctly tagged signal events, mistagged signal events, and background events, are also shown. The vertical bars indicate the statistical uncertainties.

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_S^5 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	$+0.12^{+0.46}_{-0.47} \pm 0.10$	$+0.10^{+0.32}_{-0.31} \pm 0.07$	-0.0526
2.00–4.30	145 ± 16	$-0.69^{+0.58}_{-0.27} \pm 0.23$	$-0.57^{+0.34}_{-0.31} \pm 0.18$	-0.0452
4.30–6.00	119 ± 14	$+0.53^{+0.24}_{-0.33} \pm 0.19$	$-0.96^{+0.22}_{-0.21} \pm 0.25$	$+0.4715$
6.00–8.68	247 ± 21	$-0.47^{+0.27}_{-0.23} \pm 0.15$	$-0.64^{+0.15}_{-0.19} \pm 0.13$	$+0.0761$
10.09–12.86	354 ± 23	$-0.53^{+0.20}_{-0.14} \pm 0.15$	$-0.69^{+0.11}_{-0.14} \pm 0.13$	$+0.6077$
14.18–16.00	213 ± 17	$-0.33^{+0.24}_{-0.23} \pm 0.20$	$-0.66^{+0.13}_{-0.20} \pm 0.18$	$+0.4188$
16.00–19.00	239 ± 19	$-0.53 \pm 0.19 \pm 0.16$	$-0.56 \pm 0.12 \pm 0.07$	$+0.4621$

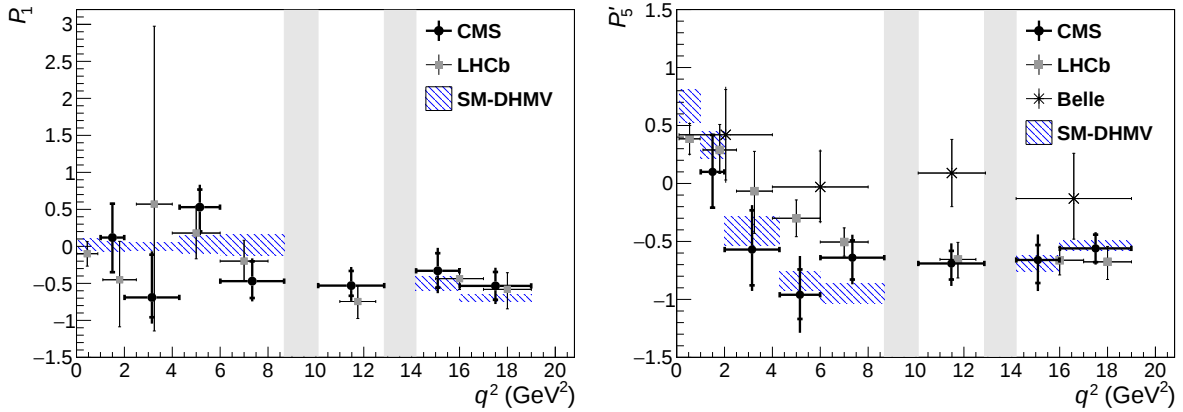


Figure 3: CMS measurements of the (left) P_1 and (right) P'_5 angular parameters versus q^2 for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays, in comparison to results from the LHCb [33] and Belle [34] Collaborations. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the J/ψ and ψ' resonances. The hatched region shows the prediction from SM calculations described in the text, averaged over each q^2 bin.

A SM prediction, denoted SM-DHNV, is available for comparison with the measured angular parameters. The SM-DHNV 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]. A reliable theoretical prediction is not available near the J/ψ and ψ' resonances. The SM prediction is shown in comparison to the data in Fig. 3 and it is seen to be in agreement with the CMS results. Thus, we do not obtain evidence for physics beyond the SM. Qualitatively, the CMS measure-

ments are compatible with the LHCb results. The Belle measurements lie systematically above both the CMS and LHCb results and the SM prediction.

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.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

- [1] W. Altmannshofer et al., “Symmetries and asymmetries of $B \rightarrow K^* \mu^+ \mu^-$ 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 $\bar{B}_d \rightarrow \bar{K}^{*0} (\rightarrow K\pi) \ell^+ \ell^-$ 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 $b \rightarrow s\ell\ell$ 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 $B \rightarrow K^*\ell^+\ell^-$ 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 $B \rightarrow (K, K^*)\ell^+\ell^-$ 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 $B \rightarrow (K, K^*)\ell^+\ell^-$ 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 $b \rightarrow s$ 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 $B \rightarrow K^*\ell^+\ell^-$ 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 $b \rightarrow s$ 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 $B^0 \rightarrow K^{*0}(\rightarrow K^-\pi^+)\ell^+\ell^-$ 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, “ $B \rightarrow K^*\ell^+\ell^-$ forward-backward asymmetry and new physics”, *Phys. Rev. D* **77** (2008) 014016, doi:10.1103/PhysRevD.77.014016, arXiv:hep-ph/0701046.
 - [12] U. Egede et al., “New observables in the decay mode $\bar{B}_d \rightarrow \bar{K}^{*0}\ell^+\ell^-$ ”, *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 $B \rightarrow K^*\mu^+\mu^-$ ”, *JHEP* **02** (2010) 053, doi:10.1007/JHEP02(2010)053, arXiv:0912.1382.
 - [15] A. K. Alok et al., “New physics in $b \rightarrow s\mu^+\mu^-$: 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, “ $B \rightarrow K^*\ell^+\ell^-, K\ell^+\ell^-$ 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 $B \rightarrow K^* \mu^+ \mu^-$ 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 $\bar{B} \rightarrow \bar{K}^* \ell^+ \ell^-$ 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 $\bar{B} \rightarrow \bar{K}^* \ell^+ \ell^-$ 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 $\bar{B} \rightarrow \bar{K}^{(*)} \ell^+ \ell^-$ 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, “ $B \rightarrow K^* \ell^+ \ell^-$ 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 $b \rightarrow s$ transitions”, *JHEP* **04** (2012) 008, doi:10.1007/JHEP04(2012)008, arXiv:1111.1257.
- [24] S. Jäger and J. Martin Camalich, “On $B \rightarrow V \ell \ell$ 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 $B \rightarrow K^* \ell^+ \ell^-$ 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 $B \rightarrow K^* \ell^+ \ell^-$ ”, *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 $B \rightarrow K^{(*)} \ell^+ \ell^-$ ”, *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 $B \rightarrow K^{(*)} \mu^+ \mu^-$ 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 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ ”, *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 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ ”, *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 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ from pp collisions at $\sqrt{s} = 8 \text{ TeV}$ ”, *Phys. Lett. B* **753** (2016) 424, doi:10.1016/j.physletb.2015.12.020, arXiv:1507.08126.
 - [32] LHCb Collaboration, “Measurement of form-factor-independent observables in the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ ”, *Phys. Rev. Lett.* **111** (2013) 191801, doi:10.1103/PhysRevLett.111.191801, arXiv:1308.1707.
 - [33] LHCb Collaboration, “Angular analysis of the $B^0 \rightarrow K^* \mu^+ \mu^-$ decay using 3 fb^{-1} of integrated luminosity”, *JHEP* **02** (2016) 104, doi:10.1007/JHEP02(2016)104, arXiv:1512.04442.
 - [34] Belle Collaboration, “Lepton-flavor-dependent angular analysis of $B \rightarrow K^* \ell^+ \ell^-$ ”, *Phys. Rev. Lett.* **118** (2017) 111801, doi:10.1103/PhysRevLett.118.111801, arXiv:1612.05014.
 - [35] CMS Collaboration, “CMS luminosity based on pixel cluster counting — Summer 2013 update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.
 - [36] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
 - [37] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
 - [38] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7 \text{ TeV}$ ”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
 - [39] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
 - [40] 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.
 - [41] 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.
 - [42] D. J. Lange, “The EvtGen particle decay simulation package”, *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.
 - [43] 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 $B \rightarrow K^{*0} \ell^+ \ell^-$ on the new physics search in $B \rightarrow K^* \ell^+ \ell^-$ 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 $B \rightarrow K^* \ell^+ \ell^-$ 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 $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ 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] G. J. Feldman and R. D. Cousins, “Unified approach to the classical statistical analysis of small signals”, *Phys. Rev. D* **57** (1998) 3873, doi:10.1103/PhysRevD.57.3873, arXiv:physics/9711021.
- [52] P. Ball and R. Zwicky, “ $B_{d,s} \rightarrow \rho, \omega, K^*, \phi$ decay form factors from light-cone sum rules reexamined”, *Phys. Rev. D* **71** (2005) 014029, doi:10.1103/PhysRevD.71.014029, arXiv:hep-ph/0412079.
- [53] A. Bharucha, D. M. Straub, and R. Zwicky, “ $b \rightarrow v \ell^+ \ell^-$ in the standard model from light-cone sum rules”, *JHEP* **08** (2016) 098, doi:10.1007/JHEP08(2016)098, arXiv:1503.05534.
- [54] R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate, “Lattice QCD calculation of form factors describing the rare decays $B \rightarrow K^* \ell^+ \ell^-$ and $B_s \rightarrow \phi \ell^+ \ell^-$ ”, *Phys. Rev. D* **89** (2014) 094501, doi:10.1103/PhysRevD.89.094501, arXiv:1310.3722.
- [55] A. Khodjamirian, T. Mannel, A. A. Pivovarov, and Y.-M. Wang, “Charm-loop effect in $B \rightarrow K^{(*)} \ell^+ \ell^-$ and $b \rightarrow K^* \gamma$ ”, *JHEP* **09** (2010) 089, doi:10.1007/JHEP09(2010)089, arXiv:1006.4945.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haeevermaet, 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. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

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. Piotrkowski, 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. Aldá 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 Silveira⁵, 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 ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

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. Fang⁶, X. Gao⁶, 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. Starodumov⁷, 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. Finger⁸, M. Finger Jr.⁸

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^{9,10}, S. Elgammal¹⁰, A. Mahrous¹¹

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. Heikkilä, 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. Besancon, 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.Ö. 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. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, 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. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁷, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁸, 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. Lohmann¹⁸, 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. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁵, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, 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. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, 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. Gerasis, 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. Surányi, G.I. Veres¹⁹

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók¹⁹, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²², S. Bhowmik, P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, Ashok Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁵, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁴, G. Majumder, K. Mazumdar, T. Sarkar²⁴, N. Wickramage²⁵

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁷, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,15}, R. Venditti^a, P. Verwilligen^a

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

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

INFN 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}

INFN 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. Viliani^{a,b,15}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁵

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

V. Calvelli^{a,b}, F. Ferro^a, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, A. Beschi^{a,b}, L. Brianza^{a,b}, 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^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{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 de Fatis^{a,b}

INFN Sezione di Napoli ^a, 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,15}, C. Sciacca^{a,b}, F. Thyssen^a

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

P. Azzi^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}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN 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}

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{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

INFN 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. Fedì^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. Martini^{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

INFN 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}

INFN 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^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy
S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^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 Ali³¹, F. Mohamad Idris³², W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, Ramirez-Sanchez, G., I. Heredia-De La Cruz³³, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, Reyes-Almanza, R, 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 Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, A. Byszuk³⁴, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, 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. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{35,36}, 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. Kim³⁷, E. Kuznetsova³⁸, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, 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. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁶

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

R. Chistov³⁹, M. Danilov³⁹, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan³⁶, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴⁰, 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. Blinov⁴¹, D. Shtol⁴¹, Y. Skovpen⁴¹

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, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic⁴², P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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. González 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 Virto, 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, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer¹, 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. Milenovic⁴³, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, T. Reis, G. Rolandi⁴⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁵, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁶, M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁴⁷, 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. Klijsma, W. Lustermann, B. Mangano, M. Marionneau, 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. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁸, 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

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Arun Kumar, 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. Bakirci⁴⁹, A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵⁰, E.E. Kangal⁵¹, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵², K. Ozdemir⁵³, S. Ozturk⁴⁹, B. Tali⁵⁴, U.G. Tok, H. Topakli⁴⁹, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, G. Karapinar⁵⁵, K. Ocalan⁵⁶, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁷, O. Kaya⁵⁸, S. Tekten, E.A. Yetkin⁵⁹

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. Newbold⁶⁰, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶¹, 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. Nikitenko⁷, 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 Acosta⁶², T. Virdee¹⁵, 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, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, 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. Derdzinski, 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. Wasserbaech⁶³, 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. Lawhorn, 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. Apyan, S. 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. Prokofyev, G. Rakness, L. Ristori, B. Schneider, 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. Bilki⁶⁴, W. Clarida, K. Dilsiz⁶⁵, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁷, Y. Onel, F. Ozok⁶⁸, 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. Skhirtladze, 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. Stephans, 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. Alverson, 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. Musienko³⁵, 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. Bouhali⁶⁹, A. Castaneda Hernandez⁶⁹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁰, 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. Duerdo, 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. Herndon, 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