Measurement of the $B^0_s \rightarrow \mu^+ \mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+ \mu^-$ with the CMS experiment

The CMS Collaboration

Abstract

Results are presented from a search for the rare decays $B^0_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV, with data samples corresponding to integrated luminosities of 5 and 20 fb$^{-1}$, respectively, collected by the CMS experiment at the LHC. An unbinned maximum-likelihood fit to the dimuon invariant mass distribution gives a branching fraction $\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$, where the uncertainty includes both statistical and systematic contributions. An excess of $B^0_s \rightarrow \mu^+ \mu^-$ events with respect to background is observed with a significance of 4.3 standard deviations. For the decay $B^0 \rightarrow \mu^+ \mu^-$ an upper limit of $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-9}$ at the 95% confidence level is determined. Both results are in agreement with the expectations from the standard model.

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In the standard model (SM) of particle physics, tree-level diagrams do not contribute to flavor-changing neutral-current (FCNC) decays. However, FCNC decays may proceed through higher-order loop diagrams, and this opens up the possibility for contributions from non-SM particles. In the SM, the rare FCNC decays $B^0_s \to \mu^+\mu^-$ have small branching fractions of $B(B^0_s \to \mu^+\mu^-) = (3.57 \pm 0.30) \times 10^{-9}$, corresponding to the decay-time integrated branching fraction, and $B(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$ [1, 2]. Charge conjugation is implied throughout this Letter. Several extensions of the SM, such as supersymmetric models with non-universal Higgs boson masses [3], specific models containing leptoquarks [4], and the minimal supersymmetric standard model with large tan $\beta$ [5, 6], predict enhancements to the branching fractions for these rare decays. The decay rates can also be suppressed for specific choices of model parameters [7]. Over the past 30 years, significant progress in sensitivity has been made, with exclusion limits on the branching fractions improving by five orders of magnitude. The ARGUS [8], UA1 [9], CLEO [10], Belle [11], BaBar [12], CDF [13], D0 [14], ATLAS [15], CMS [16], and LHCb [17] experiments have all published limits on these decays. The LHCb experiment has subsequently shown evidence, with 3.5 standard deviation significance, for the decay $B^0_s \to \mu^+\mu^-$ with $B(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ [18].

This Letter reports a measurement of $B(B^0_s \to \mu^+\mu^-)$ based on a simultaneous search for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays using a data sample of pp collisions corresponding to integrated luminosities of 5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20 fb$^{-1}$ at 8 TeV collected by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). For these data, the peak luminosity varied from $3.5 \times 10^{30}$ to $7.7 \times 10^{30}$ cm$^{-2}$s$^{-1}$. The average number of interactions per bunch crossing (pileup) was 9 (21) at $\sqrt{s} = 7(8)$ TeV.

The search for the $B \to \mu^+\mu^-$ signal, where $B$ denotes $B^0_s$ or $B^0$, is performed in the dimuon invariant mass regions around the $B^0_s$ and $B^0$ masses. To avoid possible biases, the signal region $5.20 < m_{\mu\mu} < 5.45$ GeV was kept blind until all selection criteria were established. For the 7 TeV data, this Letter reports a re-analysis of the data used in the previous result [16], where the data were re-blinded. The combinatorial dimuon background, mainly from semileptonic decays of separate $B$ mesons, is evaluated by extrapolating the data in nearby mass sidebands into the signal region. Monte Carlo (MC) simulations are used to account for backgrounds from $B$ and $\Lambda_b$ decays. These background samples consist of $B \to h h \nu$, $B \to h \mu \nu$, and $\Lambda_b \to p \mu \nu$ decays, as well as “peaking” decays of the type $B \to h h'$, where $h, h'$ are charged hadrons misidentified as muons, which give a dimuon invariant mass distribution that peaks in the signal region. The MC simulation event samples are generated using PYTHIA (version 6.424 for 7 TeV, version 6.26 for 8 TeV) [19], with the underlying event simulated with the Z2 tune [20], unstable particles decayed via EVTGEN [21], and the detector response simulated with GEANT4 [22].

A normalization sample of $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^-$ decays is used to minimize uncertainties related to the $b\bar{b}$ production cross section and the integrated luminosity. A control sample of $B^0_s \to J/\psi \phi \to \mu^+\mu^- K^+ K^-$ decays is used to validate the MC simulation and to evaluate potential effects from differences in fragmentation between $B^+$ and $B^0_s$. The efficiencies of all samples, including detector acceptances, are determined with MC simulation studies.

A detailed description of the CMS apparatus can be found in Ref. [23]. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the $x$ axis pointing to the center of the LHC ring, the $y$ axis pointing up, and the $z$ axis along the counterclockwise-beam direction. The polar angle $\theta$ is measured from the positive $z$ axis and the azimuthal angle $\phi$ is measured in the $x$-$y$ plane. The main subdetectors used in this analysis are the silicon tracker and the muon detectors. Muons are tracked within the pseudorapidity region $|\eta| < 2.4$, where $\eta = -\ln(\tan(\theta/2))$. A transverse momentum ($p_T$) resolution of about 1.5% is obtained for muons in this analysis [24].
The events are selected with a two-level trigger system. The first level only requires two muon candidates in the muon detectors. The high-level trigger (HLT) uses additional information from the silicon tracker to provide essentially a full event reconstruction. The dimuon invariant mass was required to satisfy $4.8 < m_{\mu\mu} < 6.0$ GeV. For the 7 TeV data set, the HLT selection required two muons, each with $p_T > 4.0$ GeV, and a dimuon $p_T^{\mu\mu} > 3.9$ GeV. For events having at least one muon with $|\eta| > 1.5$, $p_T^{\mu\mu} > 5.9$ GeV was required. For the 8 TeV data set, the $p_T$ criterion on the muon with lower $p_T$ was loosened to $p_T > 3.0$ GeV, with $p_T^{\mu\mu} > 4.9$ GeV. For events containing at least one muon with $|\eta| > 1.8$, the muons were each required to have $p_T > 4.0$ GeV, $p_T^{\mu\mu} > 7.0$ GeV, and the dimuon vertex fit $p$-value $> 0.5\%$.

For the normalization and control samples the HLT selection required the following: two muons, each with $p_T > 4$ GeV and $|\eta| < 2.2$; $p_T^{\mu\mu} > 6.9$ GeV; $2.9 < m_{\mu\mu} < 3.3$ GeV; and the dimuon vertex fit $p$-value $> 15\%$. Two additional requirements were imposed in the transverse plane: (i) the pointing angle $\alpha_{xy}$ between the dimuon momentum and the vector from the average interaction point to the dimuon vertex had to fulfill $\cos \alpha_{xy} > 0.9$, and (ii) the flight length significance $\ell_{xy}/\sigma(\ell_{xy})$ must be greater than 3, where $\ell_{xy}$ is the two-dimensional distance between the average interaction point and the dimuon vertex, and $\sigma(\ell_{xy})$ is its uncertainty. The signal, normalization, and control triggers required the three-dimensional (3D) distance of closest approach ($d_{ca}$) between the two muons to satisfy $d_{ca} < 0.5$ cm. The average trigger efficiency for events in the signal and normalization samples, as determined from MC simulation and calculated after all other selection criteria are applied, is in the range 39–85%, depending on the running period and detector region. The uncertainty in the ratio of trigger efficiencies (muon identification efficiencies) for the signal and normalization samples is estimated to be 3–6% (1–4%) by comparing simulation and data.

The $B \to \mu^+\mu^-$ candidates are constructed from two oppositely charged “tight” muons as described in Ref. [25]. Both muons must have $p_T > 4$ GeV and be consistent in direction and $p_T$ with the muons that triggered the event. A boosted decision tree (BDT) constructed within the TMVA framework [26] is trained to further separate genuine muons from those arising from misidentified charged hadrons. The variables used in the BDT can be divided into four classes: basic kinematic quantities, silicon-tracker fit information, combined silicon and muon track fit information, and muon detector information. The BDT is trained on MC simulation samples of B-meson decays to kaons and muons. Compared to the “tight” muons, the BDT working point used to select muons for this analysis reduces the hadron-to-muon misidentification probability by 50% while retaining 90% of true muons. The probability to misidentify a charged hadron as a muon because of decay in flight or detector punch-through is measured in data from samples of well-identified pions, kaons, and protons. This probability ranges from $(0.5–1.3) \times 10^{-3}$, $(0.8–2.2) \times 10^{-3}$, and $(0.4–1.5) \times 10^{-3}$, for pions, kaons, and protons, respectively, depending on whether the particle is in the barrel or endcap, the running period, and the momentum. Each of these probabilities is ascribed an uncertainty of 50%, based on differences between data and MC simulation.

Candidates are kept for further analysis if they have $4.9 < m_{\mu\mu} < 5.9$ GeV, after constraining the tracks to a common vertex. The B-candidate momentum and vertex position are used to choose a primary vertex based on the distance of closest approach along the beamline. Since the background level and mass resolution depend significantly on $\eta_{\mu\mu}$, where $\eta_{\mu\mu}$ is the pseudorapidity of the B-meson candidate, the events are separated into two categories: the “barrel channel” with candidates where both muons have $|\eta| < 1.4$, and the “endcap channel” containing those where at least one muon has $|\eta| > 1.4$. The $m_{\mu\mu}$ resolution, as determined from simulated signal events, ranges from 32 MeV for $\eta_{\mu\mu} \approx 0$ to 75 MeV for $|\eta_{\mu\mu}| > 1.8$. 

Four isolation variables are defined. (1) \( I = p_T^\mu / (p_T^\mu + \sum_{trk} p_T) \), where \( \sum_{trk} p_T \) is the sum of \( p_T \) of all tracks, other than muon candidates, satisfying \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.7 \), with \( \Delta \eta \) and \( \Delta \phi \) as the differences in \( \eta \) and \( \phi \) between a charged track and the direction of the B candidate. The sum includes all tracks with \( p_T > 0.9 \) GeV that are (i) consistent with originating from the same primary vertex as the B candidate or (ii) have a \( d_{ca} \) with respect to the B vertex <0.05 cm and are not associated with any other primary vertex. (2) \( I_\mu \) is the isolation variable of each muon, calculated as for the B candidate, but with respect to the muon track. A cone size of \( \Delta R = 0.5 \) around the muon and tracks with \( p_T > 0.5 \) GeV and \( d_{ca} < 0.1 \) cm from the muon are used. (3) \( N_{trk}^{\text{close}} \) is defined as the number of tracks with \( p_T > 0.5 \) GeV and \( d_{ca} \) with respect to the B vertex less than <0.03 cm. (4) \( d_{ca}^0 \) is defined as the smallest \( d_{ca} \) to the B vertex, considering all tracks in the event that are either associated with the same primary vertex as the B candidate or not associated with any primary vertex.

The final selection is performed with BDTs trained to distinguish between signal and background event candidates. For the training, \( B^0_s \to \mu^+\mu^- \) MC simulation samples are used for the signal, and candidates from the data dimuon mass sidebands after a loose preselection for the background. The preselection retains at least 10,000 events dominated by combinatorial background for each BDT. To avoid any selection bias, the data background events are randomly split into three sets, such that the training and testing of the BDT is performed on sets independent of its application. Studies with sideband events and signal MC simulation samples with shifted B mass show that the BDT response is independent of mass. Separate BDTs are trained for each of the four combinations of 7 and 8 TeV data and the barrel and endcap regions of the detector. For each BDT, a number of variables is considered and only those found to be effective are included. Each of the following twelve variables, shown to be independent of pileup, are used in at least one of the BDTs: \( I; I_\mu; N_{trk}^{\text{close}}; d_{ca}^0; p_T^\mu; \eta_{\mu\mu}; \) the B-vertex fit \( \chi^2 \) per degree of freedom (dof); the \( d_{ca} \) between the two muon tracks; the 3D pointing angle \( \alpha_{3D} \); the 3D flight length significance \( \ell_{3D}/\sigma(\ell_{3D}) \); the 3D impact parameter \( \delta_{3D} \) of the B candidate; and its significance \( \delta_{3D}/\sigma(\delta_{3D}) \), where \( \sigma(\delta_{3D}) \) is the uncertainty on \( \delta_{3D} \). The last four variables are computed with respect to the primary vertex. Good agreement between data and MC simulation is observed for these variables. In total, including the division into three sets, 12 BDTs are trained.

The output discriminant \( b \) of the BDT is used in two ways for further analysis. (1) In the 1D-BDT method, a minimum requirement on \( b \) per channel is used to define the final selection. The requirement on \( b \) is optimized for best \( S/\sqrt{S+B} \) (where \( S \) is the expected signal and \( B \) the background) on statistically independent data control samples. The optimization gives \( b > 0.29 \) for both barrel and endcap in the \( \sqrt{s} = 7 \) TeV data, and \( b > 0.36 \) (0.38) in the barrel (endcap) for the \( \sqrt{s} = 8 \) TeV sample. The 1D-BDT method is used for the determination of the upper limit on \( B(B^0 \to \mu^+\mu^-) \). The signal efficiencies \( \epsilon_{\text{tot}} \) for method (1) are provided in Table I together with the expected number of events (signal and signal plus background) for the \( B^0 \) signal region \( 5.20 < m < 5.30 \) GeV and the \( B^0_s \) signal region \( 5.30 < m < 5.45 \) GeV. (2) In the categorized-BDT method, the discriminant \( b \) is used to define twelve event categories with different signal-to-background ratios. For the \( \sqrt{s} = 7 \) TeV data in the barrel (endcap) channel, the two categories have boundaries of 0.10, 0.31, 1.00 (0.10, 0.26, 1.00). For the \( \sqrt{s} = 8 \) TeV sample in the barrel (endcap) channel, the corresponding boundaries for the four categories are 0.10, 0.23, 0.33, 0.44, 1.00 (0.10, 0.22, 0.33, 0.45, 1.00). This binning is chosen to give the same expected signal yield in each bin. The dimuon invariant mass distributions for the twelve categories of events are fitted simultaneously to obtain the final results. Method (2) has higher expected sensitivity and thus provides the main methodology for the extraction of \( B(B^0_s \to \mu^+\mu^-) \).
The B$^0 \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^-K^+$ (B$^0_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$) selection requires two oppositely charged muons with $3.0 < m_{\mu\mu} < 3.2$ GeV and $p_T^{\mu\mu} > 7$ GeV, combined with one or two tracks, assumed to be kaons, fulfilling $p_T > 0.5$ GeV and $|\eta| < 2.4$ (|$\eta$| < 2.1 in the 8 TeV data). The distance of closest approach between all pairs among the three (four) tracks is required to be less than 0.1 cm. For B$^0_s \rightarrow J/\psi\phi$ candidates the two assumed kaon tracks must have invariant mass $0.995 < m_{KK} < 1.045$ GeV and $\Delta R < 0.25$. The B vertex is fitted from the three (four) tracks; a candidate is accepted if the resulting invariant mass is in the range 4.8–6.0 GeV. The final selection is achieved using the same BDT as for the signal, with the following modifications: the B-vertex $\chi^2$/dof is determined from the dimuon vertex fit, and for the calculation of the isolation variables all B-candidate decay tracks are neglected.

The total efficiency to reconstruct with the 1D-BDT method a B$^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^-K^+$ decay, including the detector acceptance, is $\varepsilon_{\text{tot}}^{B^+} = (0.98 \pm 0.08) \times 10^{-3}$ and $(0.36 \pm 0.04) \times 10^{-3}$, respectively, for the barrel and endcap channels in the 7 TeV analysis, and $(0.82 \pm 0.07) \times 10^{-3}$ and $(0.21 \pm 0.03) \times 10^{-3}$ for the 8 TeV analysis, where statistical and systematic uncertainties are combined in quadrature. The distributions of $b$ for the normalization and control samples are found to agree well between data and MC simulation, with residual differences used to estimate systematic uncertainties. No dependence of the selection efficiency on pileup is observed. The systematic uncertainty in the acceptance is estimated by comparing the values obtained with different $b\bar{b}$ production mechanisms (gluon splitting, flavor excitation, and flavor creation). The uncertainty in the event selection efficiency for the $B^+ \rightarrow J/\psi K^+$ normalization sample is evaluated from differences between measured and simulated $B^+ \rightarrow J/\psi K^+$ events. The uncertainty in the $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ signal efficiencies (3–10%, depending on the channel and $\sqrt{s}$) is evaluated using the $B^0_s \rightarrow J/\psi\phi$ control sample.

The yields for the normalization (control) sample in each category are fitted with a double (single) Gaussian function. The backgrounds under the normalization and control sample peaks are described with an exponential (plus an error function for the normalization sample). Additional functions are included, with shape templates fixed from simulation, to account for backgrounds from $B^+ \rightarrow J/\psi\pi^+$ (Gaussian function) for the normalization sample, and $B^0 \rightarrow J/\psi K^0$ (Landau function) for the control sample. In the 7 TeV data, the observed number of $B^+ \rightarrow J/\psi K^+$ candidates in the barrel is $(71.2 \pm 4.1) \times 10^3$ and $(21.4 \pm 1.1) \times 10^3$ in the endcap channel. For the 8 TeV sample the corresponding yields are $(309 \pm 16) \times 10^3$ (barrel) and $(69.3 \pm 3.5) \times 10^3$ (endcap). The uncertainties include a systematic component estimated

| Channel   | $\varepsilon_{\text{tot}}^{B^+}$ | $N_{\text{signal}}^{\exp}$ | $N_{\text{total}}^{\exp}$ | $N_{\text{obs}}$ |
|-----------|-------------------------------|----------------------------|-----------------------------|-----------------|
| 7 TeV     |                               |                            |                             |                 |
| B$^0$ Bar | (0.33 ± 0.03)                 | 0.27 ± 0.03                | 1.3 ± 0.8                   | 3               |
| B$^0_s$ Bar | (0.30 ± 0.04)                | 2.97 ± 0.44                | 3.6 ± 0.6                   | 4               |
| B$^0$ Endcap | (0.20 ± 0.02)         | 0.11 ± 0.01                | 1.5 ± 0.6                   | 1               |
| B$^0_s$ Endcap | (0.20 ± 0.02)       | 1.28 ± 0.19                | 2.6 ± 0.5                   | 4               |
| 8 TeV     |                               |                            |                             |                 |
| B$^0$ Bar | (0.24 ± 0.02)                 | 1.00 ± 0.10                | 7.9 ± 3.0                   | 11              |
| B$^0_s$ Bar | (0.23 ± 0.03)                | 11.46 ± 1.72               | 17.9 ± 2.8                  | 16              |
| B$^0$ Endcap | (0.10 ± 0.01)            | 0.30 ± 0.03                | 2.2 ± 0.8                   | 3               |
| B$^0_s$ Endcap | (0.09 ± 0.01)        | 3.56 ± 0.53                | 5.1 ± 0.7                   | 4               |

The signal selection efficiencies $\varepsilon_{\text{tot}}$, the predicted number of SM signal events $N_{\text{signal}}^{\exp}$, and the expected number of signal and background events $N_{\text{total}}^{\exp}$ and the number of observed events $N_{\text{obs}}$ in the barrel and endcap channels for the 7 and 8 TeV data using the 1D-BDT method. The event numbers refer to the B$^0$ and B$^0_s$ signal regions, respectively.
from simulated events by considering alternative fitting functions.

The \( B^0_s \rightarrow \mu^+\mu^- \) branching fraction is measured using

\[
B(B^0_s \rightarrow \mu^+\mu^-) = \frac{N_S}{N^B_{\text{obs}}} \frac{f_u \epsilon^B_{\text{tot}}}{f_s \epsilon^B_{\text{tot}}} B(B^+),
\]

and analogously for the \( B^0 \rightarrow \mu^+\mu^- \) case, where \( N_S (N^B_{\text{obs}}) \) is the number of reconstructed \( B^0_s \rightarrow \mu^+\mu^- (B^+ \rightarrow J/\psi K^+) \) decays, \( \epsilon_{\text{tot}} (\epsilon^B_{\text{tot}}) \) is the total signal (\( B^+ \)) efficiency, \( B(B^+) = (6.0 \pm 0.2) \times 10^{-5} [27] \) is the branching fraction for \( B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^- K^+ \), and \( f_u/f_s \) is the ratio of the \( B^+ \) and \( B^0_s \) fragmentation fractions. The value \( f_u/f_s = 0.256 \pm 0.020 \), as measured by LHCb [28], is used and an additional systematic uncertainty of 5% is assigned to account for possible pseudorapidity and \( p_T^{\mu\mu} \) dependence of this ratio. Studies based on the \( B^+ \rightarrow J/\psi K \) and \( B^0_s \rightarrow J/\psi \phi \) control samples reveal no discernible pseudorapidity or \( p_T^{\mu\mu} \) dependence of this ratio in the kinematic region used in the analysis.

An unbinned maximum-likelihood fit to the \( m_{\mu\mu} \) distribution is used to extract the signal and background yields. Events in the signal window can result from genuine signal, combinatorial background, background from semileptonic b-hadron decays, and the peaking background. The probability density functions (PDFs) for the signal, semileptonic, and peaking backgrounds are obtained from fits to MC simulation. The \( B^0_s \) and \( B^0 \) signal shapes are modeled by Crystal Ball functions [29]. The peaking background is modeled with the sum of Gaussian and Crystal Ball functions (with a common mean). The semileptonic background is modeled with a Gaussian kernels method [30, 31]. The PDF for the combinatorial background is modeled with a first-degree polynomial. Since the dimuon mass resolution \( \sigma \), determined on an event-by-event basis from the dimuon mass fit, varies significantly, the PDFs described above are combined as a conditional product with the PDF for the per-event mass resolution, such that the Crystal Ball function width correctly reflects the resolution on a per-event basis. To avoid any effect of the correlation between \( \sigma \) and the candidate mass, we divide the invariant mass uncertainty by the mass to obtain a “reduced” mass uncertainty, \( \sigma_{\mu} = \sigma/m_{\mu\mu} \), which is used in the fit.

The dimuon mass distributions for the four channels (barrel and endcap in 7 and 8 TeV data), further divided into categories corresponding to different bins in the BDT parameter \( b_i \), are fitted simultaneously. The results are illustrated for the most sensitive categories in Fig. 1. The fits for all twelve categories are shown in Appendix A. Pseudo-experiments, done with MC simulated events, confirm the robustness and accuracy of the fitting procedure.

Systematic uncertainties are constrained with Gaussian PDFs with the standard deviations of the constraints set equal to the uncertainties. Sources of systematic uncertainty arise from the hadron-to-muon misidentification probability, the branching fraction uncertainty (dominated by 100% for \( \Lambda_b \rightarrow p\mu\nu \)), and the normalization of the peaking background. The \( B \rightarrow hh' \) and semileptonic backgrounds are estimated by normalizing to the observed \( B^+ \rightarrow J/\psi K^+ \) yield. The peaking background yield is constrained in the fit with log-normal PDFs with r.m.s. parameters set to the mean 1-standard-deviation uncertainties. The absolute level of peaking background has been studied on an independent data sample, obtained with single-muon triggers, and is found to agree with the expectation described above. The shape parameters for the peaking and the semileptonic backgrounds and for the signals are fixed to the expectation. The mass scale uncertainty at the B-meson mass is 6 MeV (7 MeV) for the barrel (endcap) channels, as determined with charmonium and bottomium decays to dimuon final states.

An excess of \( B^0_s \rightarrow \mu^+\mu^- \) decays is observed above the background predictions. The measured decay-time integrated branching fraction from the fit is \( B(B^0_s \rightarrow \mu^+\mu^-) = (3.0_{-0.9}^{+1.0}) \times 10^{-9} \).
Figure 1: Results from the categorized-BDT method of the fit to the dimuon invariant mass distributions for the $\sqrt{s} = 8$ TeV data in the barrel (top) and endcap (bottom) for the BDT bins with the highest (left) and second-highest (right) signal-to-background ratio.
Figure 2: Left, scan of the ratio of the joint likelihood for $B(B_s^0 \rightarrow \mu^+\mu^-)$ and $B(B^0 \rightarrow \mu^+\mu^-)$. As insets, the likelihood ratio scan for each of the branching fractions when the other is profiled together with other nuisance parameters; the significance at which the background-only hypothesis is rejected is also shown. Right, observed and expected $C_L$ for $B^0 \rightarrow \mu^+\mu^-$ as a function of the assumed branching fraction.

Figure 3: Plots illustrating the combination of all categories used in the categorized-BDT method (left) and the 1D-BDT method (right). For these plots, the individual categories are weighted with $S/(S+B)$, where $S$ ($B$) is the signal (background) determined at the $B_s^0$ peak position. The overall normalization is set such that the fitted $B_s^0$ signal corresponds to the total yield of the individual contributions. These distributions are for illustrative purposes only and were not used in obtaining the final results.
where the uncertainty includes both the statistical and systematic components, but is dominated by the statistical uncertainties. The observed (expected median) significance of the excess is 4.3 (4.8) standard deviations and is determined by evaluating the ratio of the likelihood value for the hypothesis with no signal, divided by the likelihood with $B(B^0 \rightarrow \mu^+\mu^-)$ floating. For this determination, $B(B^0 \rightarrow \mu^+\mu^-)$ is allowed to float and is treated as a nuisance parameter in the fit (see the left plot in Fig. 2). The measured branching fraction is consistent with the expectation from the SM. With the 1D-BDT method, the observed (expected median) significance is 4.8 (4.7) standard deviations. Figure 3 shows the combined mass distributions weighted by $S/(S+B)$ for the categorized-BDT (left) and the 1D-BDT (right) methods. However, these distributions are illustrative only and were not used to obtain the final results.

No significant excess is observed for $B^0 \rightarrow \mu^+\mu^-$, and the upper limit $B(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9} (9.2 \times 10^{-10})$ at 95% (90%) confidence level (CL) is determined with the CL$_S$ approach [32, 33], based on the observed numbers of events in the signal and sideband regions with the 1D-BDT method as summarized in Table 1. The expected 95% CL upper limit for $B(B^0 \rightarrow \mu^+\mu^-)$ in the presence of SM signal plus background (background only) is $6.3 \times 10^{-10} (5.4 \times 10^{-10})$, where the statistical and systematic uncertainties are considered. The right plot in Fig. 2 shows the observed and expected CL$_S$ curves versus the assumed $B(B^0 \rightarrow \mu^+\mu^-)$. From the fit, the branching fraction for this decay is determined to be $B(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$. The significance of this measurement is 2.0 standard deviations. The dimuon invariant mass distributions with the 1D-BDT method for the four channels are shown in Fig. 5 in the Appendix.

In summary, a search for the rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ has been performed on a data sample of pp collisions at $\sqrt{s} = 7$ and 8 TeV corresponding to integrated luminosities of 5 and 20 fb$^{-1}$, respectively. No significant evidence is observed for $B^0 \rightarrow \mu^+\mu^-$ and an upper limit of $B(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$ is established at 95% CL. For $B^0_s \rightarrow \mu^+\mu^-$, an excess of events with a significance of 4.3 standard deviations is observed, and a branching fraction of $B(B^0_s \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ is determined, in agreement with the standard model expectations.

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A Additional plots of mass fits
backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds. The points are the data, the solid line is the result of the fit, the shaded areas are the two B signals, and the different dotted lines are the backgrounds.

Figure 4. Results of the fit to the dimuon invariant mass distributions for all BDT bins in the data with the calibrated BDT method.

A Additional plots of mass fits
Figure 5: Results of the fit to the dimuon invariant mass distributions with the 1D-BDT method for the barrel (left) and endcap (right) from the 7 TeV (top) and 8 TeV (bottom) data samples. The points are the data, the solid line is the result of the fit, the shaded areas are the two $B$ signals, and the different dotted lines are the backgrounds.
A. Additional plots of mass fits
B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragnev, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünn, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, C. Rohringer, H. Rohringer, R. Schönbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

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

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D’Hondt, A. Kalogeropoulos, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

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

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Cerdá, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giannanco⁴, J. Hollar, P. Jez, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, A. Popov⁵, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Junior, W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
C.A. Bernardes⁶, F.A. Dias⁷, T.R. Fernandez Perez Tomei⁶, E.M. Gregores⁶, C. Lagana⁶, P.G. Mercadante b, S.F. Novaes⁶, Sandra S. Padula a

1 Present address:
2 On leave from:
3 Former CMS Collaboration member.
4 Current address:
5 Former CMS Collaboration member.
6 Former CMS Collaboration member.
7 Present address:
8 Former CMS Collaboration member.
Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev, P. Iaydjiev, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, X. Wang, Z. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, C.A. Carrillo Montoya, L.F. Chaparro Sierra, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina, D. Polic, I. Puljak

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgammal, A. Ellithi Kamel, A.M. Kuotb Awad, M.A. Mahmoud, A. Radi

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

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

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov
Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, M. Bliuj, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzyinski, A. Florent, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, J.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte, F. Drouhin, J.-C. Fontaine, D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, G. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann, A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, D. Horton, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krückner, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro
Cipriano, C. Riedl, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, R. Schmidt, T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
M. Aldaya Martin, V. Blobel, H. Enderle, J. Erfle, E. Garutti, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille, V. Sola, H. Stadie, G. Steinbrück, J. Tomesen, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff, F. Hartmann, T. Hauth, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov, J.R. Komaragiri, A. Kornmayer, P. Lobelle Pardo, D. Martschei, M.U. Mozer, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari, I. Topsis-giotis

University of Athens, Athens, Greece
L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, A. Sharma, J.B. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shrivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh
INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy
P. Azzi, N. Bacchetta, M. Biasotto, D. Bisello, A. Branca, R. Carlin, P. Checchia, T. Dorigo, U. Dosselli, M. Galanti, F. Gasparini, U. Gasparini, P. Giubilato, A. Gozzelino, K. Kanishchev, S. Lacapra, I. Lazzizzera, M. Margoni, A.T. Meneguzzo, M. Nespolo, J. Pazzini, N. Pozzobon, F. Ronchese, F. Simonetto, E. Torassa, M. Tosi, S. Vanini, P. Zotto, A. Zucchetta, G. Zumerle

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
M. Gabusi, S.P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
M. Biasini, G.M. Bilei, L. Fanè, P. Lariccia, G. Mantovani, M. Menichelli, A. Nappi, F. Romeo, A. Saha, A. Santocchia

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov, P. Azzurri, G. Bagliesi, T. Boccali, G. Broccoli, R. Castaldi, M.A. Ciocci, R.T. D’Agnolo, R. Dell’Orso, F. Fiori, L. Foà, A. Giassi, M.T. Grippi, A. Kraan, F. Ligabue, T. Lomtadze, L. Martini, A. Messineo, C.S. Moon, F. Palla, A. Rizzii, A. Savoy-Navarro, A.T. Serban, P. Spagnolo, P. Squillacioti, R. Tenchini, G. Tonelli, A. Venturi, P.G. Verdini, C. Vernieri

INFN Sezione di Roma, Università di Roma, Roma, Italy
L. Barone, F. Cavallari, D. Del Re, M. Diemoz, M. Grassi, E. Longo, F. Margaroli, P. Meridiani, F. Micheli, S. Nourbakhsh, G. Organtini, R. Paramatti, S. Rahatlou, C. Roselli, L. Soffi

INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale (Novara), Torino, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, R. Bellan, C. Biino, N. Cartiglia, S. Casasso, M. Costa, A. Deganolo, N. Demaria, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, M. Musich, M.M. Obertino, N. Pastrone, M. Pelliccioni, A. Potenza, A. Romero, M. Ruspa, R. Sacchi, A. Solano, A. Staiano, U. Tamponi

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, D. Montanino, A. Penzo, A. Schizzi, A. Zanetti

Kangwon National University, Chunchon, Korea
S. Chang, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

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

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu
Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
I. Grigelionis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada,
R. Lopez-Fernandez, J. Martinez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi,
M.A. Shah, M. Shoailb

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-
Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki,
J. Krolikowski, M. Misiura, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho,
M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin,
V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palchik, V. Perelygin,
S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov,
V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lyakhovskaya, V. Popov, G. Safronov, S. Semenov,
A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin
P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, M. Djordjevic, M. Ekmedzic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. García-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martin, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

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

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chung, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodriguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, J.F. Benitez, C. Bernet, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi, M. D’Alfonso, D. d’Enterría, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, A. Hinzmann, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimià, D. Piparo, M. Plagge, L. Quertenmont, A. Racz, W. Reece, G. Rolandi, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick,
S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas, D. Spiga, B. Stieger, M. Stoye, A. Tsirou, G.I. Veres, J.R. Vlimant, H.K. Wohri, S.D. Worm, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, F. Moortgat, C. Nágeli, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, M. Quittnat, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov, M. Takahashi, L. Tauscher, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

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

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, S. Cerci, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengü, K. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, H. Topakli, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, G. Karapinar, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalcin, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmaz, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar, E. Barlas, K. Çankocak, Y.O. Günaydın, F.I. Vardarlı, M. Yücel

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

University of Bristol, Bristol, United Kingdom
J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, C. Lucas, Z. Meng, S. Metson, D.M. Newbold, K. Nirunpong, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder,
S. Harper, J. Ilic, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

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

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

**Baylor University, Waco, USA**
J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

**The University of Alabama, Tuscaloosa, USA**
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

**Boston University, Boston, USA**
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazz, J. Rohlf, D. Sperka, J. St. John, L. Sulak

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

**University of California, Davis, Davis, USA**
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, J. Pilot, F. Ricci-Tam, B. Rutherford, M. Sarle, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

**University of California, Los Angeles, USA**
V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein, E. Takasugi, P. Traczyk, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**
J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

**University of California, San Diego, La Jolla, USA**
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech, F. Würthwein, A. Yagil, J. Yoo

**University of California, Santa Barbara, Santa Barbara, USA**
D. Barge, C. Campagnari, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, D. Kovalskyi, V. Krutelyov, R. Magaña Villalba, N. McColl, V. Pavlunin, J. Richman, R. Rossin, D. Stuart, W. To, C. West
California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H.B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, R.Y. Zhu

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

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

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

Fairfield University, Fairfield, USA
D. Winn

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

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

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D.H. Moon, C. O’Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas
The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo,
H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel,
F. Ozok, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic,
C. Martin, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer,
J.S. Wood

Kansas State University, Manhattan, USA
A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini,
S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, F. Rebassoo, D. Wright

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

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos,
M. Goncharov, D. Gulhan, Y. Kim, M. Klute, Y.S. Lai, A. Levin, P.D. Luckey, T. Ma, S. Nahn,
C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu,
R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. De Benedetti, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans,
N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, L.M. Cremaldi, R. Kroeger, S. Oliveros, L. Perera, R. Rahmat, D.A. Sanders,
D. Summers

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, R. Gonzalez Suarez,
J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash, T. Orimoto,
D. Trocino, D. Wood, J. Zhang

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

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

The Ohio State University, Columbus, USA
L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe

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

University of Puerto Rico, Mayaguez, USA
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA
E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumester, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
N. Parashar

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

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

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, S. Salur, S. Schnetzker, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, K. Rose, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
O. Bouhalii, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska
University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at California Institute of Technology, Pasadena, USA
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Suez Canal University, Suez, Egypt
10: Also at Zewail City of Science and Technology, Zewail, Egypt
11: Also at Cairo University, Cairo, Egypt
12: Also at Fayoum University, El-Fayoum, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at National Centre for Nuclear Research, Swierk, Poland
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Joint Institute for Nuclear Research, Dubna, Russia
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at The University of Kansas, Lawrence, USA
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at Tata Institute of Fundamental Research - EHEP, Mumbai, India
23: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
24: Now at King Abdulaziz University, Jeddah, Saudi Arabia
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Sharif University of Technology, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Laboratori Nazionali di Legnaro dell’ INFN, Legnaro, Italy
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
33: Also at Purdue University, West Lafayette, USA
34: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
35: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
36: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
37: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
38: Also at University of Athens, Athens, Greece
39: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
40: Also at Paul Scherrer Institut, Villigen, Switzerland
41: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
42: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
43: Also at Gaziosmanpasa University, Tokat, Turkey
44: Also at Adiyaman University, Adiyaman, Turkey
45: Also at Cag University, Mersin, Turkey
46: Also at Mersin University, Mersin, Turkey
47: Also at Izmir Institute of Technology, Izmir, Turkey
48: Also at Ozyegin University, Istanbul, Turkey
49: Also at Kafkas University, Kars, Turkey
50: Also at Süleyman Demirel University, Isparta, Turkey
51: Also at Ege University, Izmir, Turkey
52: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
53: Also at Kahramanmaras Sütçü İmam University, Kahramanmaras, Turkey
54: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
55: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
56: Also at Utah Valley University, Orem, USA
57: Also at Institute for Nuclear Research, Moscow, Russia
58: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
59: Also at Argonne National Laboratory, Argonne, USA
60: Also at Erzincan University, Erzincan, Turkey
61: Also at Yildiz Technical University, Istanbul, Turkey
62: Also at Texas A&M University at Qatar, Doha, Qatar
63: Also at Kyungpook National University, Daegu, Korea