

# Angular analysis of the decay $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$

---



## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** Angular distributions of the decay  $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$  are studied using events collected with the CMS detector in  $\sqrt{s} = 8 \text{ TeV}$  proton-proton collisions at the LHC, corresponding to an integrated luminosity of  $20.0 \text{ fb}^{-1}$ . The forward-backward asymmetry of the muons and the longitudinal polarization of the  $K^*(892)^+$  meson are determined as a function of the square of the dimuon invariant mass. These are the first results from this exclusive decay mode and are in agreement with a standard model prediction.

**KEYWORDS:**  $B$  physics, Hadron-Hadron scattering (experiments)

**ARXIV EPRINT:** [2010.13968](https://arxiv.org/abs/2010.13968)

---

**Contents**

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>The CMS detector</b>	<b>2</b>
<b>3</b>	<b>Event selection</b>	<b>2</b>
<b>4</b>	<b>Angular analysis</b>	<b>4</b>
<b>5</b>	<b>Systematic uncertainties</b>	<b>6</b>
<b>6</b>	<b>Results</b>	<b>7</b>
<b>7</b>	<b>Summary</b>	<b>8</b>
	<b>The CMS collaboration</b>	<b>14</b>

---

**1 Introduction**

The decays of heavy-flavor hadrons can be used to probe high mass scales by searching for effects caused by unknown heavy particles that modify the standard model (SM) description of the decay. Flavor changing neutral current decays, such as those involving  $b \rightarrow s\mu^+\mu^-$  transitions, are particularly promising as they are forbidden at tree level, and only occur via loop diagrams. The lack of a dominating tree-level process allows for a greater sensitivity to the effects of new particles. These effects can appear as differences in the overall decay rate or as modifications to the angular distributions of the decay products.

In this paper, an analysis of the  $B^+ \rightarrow K^{*+}\mu^+\mu^-$  decay is performed, where  $K^{*+}$  indicates the  $K^*(892)^+$  meson. Charge-conjugate states are implied throughout the paper. The theoretical description of this decay requires four independent kinematic variables, which are chosen by convention to be three angles plus the square of the dimuon invariant mass ( $q^2$ ). Two angular distributions are used to measure two decay observables, the muon forward-backward asymmetry,  $A_{FB}$ , and the  $K^{*+}$  longitudinal polarization fraction,  $F_L$ , in bins of  $q^2$ . The data for this analysis were collected in proton-proton (pp) collisions at a center-of-mass energy of 8 TeV by the CMS detector at the CERN LHC, and correspond to an integrated luminosity of  $20.0 \text{ fb}^{-1}$  [1]. Previous measurements of  $A_{FB}$  and  $F_L$  have been made in the exclusive mode  $B^0 \rightarrow K^*(892)^0\mu^+\mu^-$  [2–8] and in a combination of decays of the form  $B \rightarrow K^*(892)\ell^+\ell^-$  [9–11], where  $\ell$  refers to an electron or a muon and the combinations are of  $K^*(892)$  isospin states and/or lepton flavor states. The results are generally consistent with the SM predictions [12–22]. This paper reports the first measurement of  $A_{FB}$  and  $F_L$  in the exclusive decay  $B^+ \rightarrow K^{*+}\mu^+\mu^-$ , with the  $K^{*+}$  meson reconstructed in the  $K_S^0\pi^+$  decay mode and the  $K_S^0$  meson identified from its decay to a pair of charged pions.

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker measures charged particles within the pseudorapidity range  $|\eta| < 2.5$ . During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1440 silicon pixel and 15 148 silicon strip detector modules. For non-isolated particles of  $1 < p_T < 10$  GeV and  $|\eta| < 1.4$ , the track resolutions are typically 1.5% in  $p_T$  and 25–90 (45–150)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [23]. Muons with  $|\eta| < 2.4$  are measured with gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [24]. Distances that are measured with respect to the beamline are in the transverse plane.

Events of interest are selected using a two-tiered trigger system [25]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing.

## 3 Event selection

The events used in this analysis are selected by a trigger designed specifically for finding b hadron decays that include two muons. The trigger requires two oppositely charged muons, each with transverse momentum  $p_T > 3.5$  GeV and  $|\eta| < 2.2$ . The two muons are fitted to a common vertex and retained if the fit  $\chi^2$  probability is greater than 10% and the vertex is displaced from the beamline by at least three times the uncertainty in the distance. The dimuon system is further required to have  $p_T > 6.9$  GeV, invariant mass between 1 and 4.8 GeV, and a momentum vector whose angle  $\alpha$  with respect to the vector between the beamline and the dimuon vertex satisfies  $\cos \alpha > 0.9$ .

The offline reconstruction of the signal decay  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$  requires two oppositely charged muons and a  $K^{*+}$  meson, where the  $K^{*+}$  meson is reconstructed in the  $K_S^0 \pi^+$  decay mode, and the  $K_S^0$  meson is identified through its decay to  $\pi^+ \pi^-$ . The trigger requirements are reapplied to the corresponding offline quantities and the offline muon candidates must pass the soft muon criteria [26] and correspond to the muons that satisfied the trigger requirements. The  $K_S^0$  meson candidates are reconstructed by fitting pairs of oppositely charged tracks to a common vertex and selected using standard selection criteria. In particular, the tracks must have at least 6 hits in the silicon tracker, a  $\chi^2$  per degree of freedom (dof) less than 5, pass at a distance from the beamline at least 2 times its uncertainty, and have the closest distance between their trajectories be less than 1 cm. In addition, the fitted vertex must have a  $\chi^2/\text{dof} < 7$  and be located at a distance from the beamline that is at least 15 times the calculated uncertainty in the distance. The

two-track invariant mass must be within 17.3 MeV (three times the average resolution) of the  $K_S^0$  meson mass [27] when the tracks are assigned the charged pion mass. To remove  $\Lambda \rightarrow p\pi^-$  decays, the two-track combination is rejected if the invariant mass is in the range 1.11–1.125 GeV when the high and low momentum tracks are assigned the proton and charged pion mass, respectively. Each  $K_S^0$  candidate is combined with two oppositely charged muons and a non-muon track, assumed to be a pion, in a fit to a common vertex to form a  $B^+$  meson candidate. The  $K_S^0\pi^+$  invariant mass is required to be within 100 MeV of the world-average  $K^{*+}$  mass [27], and the invariant mass of the  $K_S^0\pi^+\mu^+\mu^-$  system,  $m$ , must be in the range  $4.76 < m < 5.8$  GeV.

The remaining selection criteria are obtained by maximizing  $S/\sqrt{S+B}$  for different event shape variables. The number of signal events,  $S$ , is obtained from the simulation (normalized to the data) and the number of background events,  $B$ , is obtained from the  $K_S^0\pi^+\mu^+\mu^-$  data sideband invariant mass regions 4.76–5.18 and 5.38–5.8 GeV. The  $K_S^0$  meson  $p_T$  must be greater than 1 GeV. The pion track from the  $K^{*+}$  decay must have  $p_T > 0.4$  GeV and an impact parameter with respect to the beamline of at least 0.4 times the uncertainty in this parameter found from the vertex fit. The  $B^+$  candidate vertex must have a fit  $\chi^2$  probability larger than 10% and a separation from the beamline of at least 12 times the calculated uncertainty in the separation. The angle  $\alpha$  between the vector from the beamline to the vertex location and the  $B^+$  candidate momentum vector (in the transverse plane) must satisfy  $\cos \alpha > 0.9994$ . In 0.3% of the events in which a candidate passes the selection criteria, a second candidate also passes the same criteria. In these cases, the candidate with the smaller vertex fit  $\chi^2$  value is chosen.

The decay modes  $B^+ \rightarrow K^{*+}J/\psi$  and  $B^+ \rightarrow K^{*+}\psi(2S)$ , followed by the dimuon decays of charmonium states  $J/\psi$  and  $\psi(2S)$ , have the same final-state particles as the signal mode. As described in section 4, the analysis is performed in bins of  $q^2$  that exclude candidates in the  $B^+ \rightarrow K^{*+}J/\psi$  and  $B^+ \rightarrow K^{*+}\psi(2S)$  regions, namely  $8.68 < q^2 < 10.09$  GeV<sup>2</sup> and  $12.86 < q^2 < 14.18$  GeV<sup>2</sup>. However, since events from charmonium decay are produced quite copiously, a significant contribution can still appear in the signal  $q^2$  regions. This primarily occurs through two effects: finite detector resolution resulting in a reconstructed dimuon mass different than the true value, and decays of the two charmonium states in which a low-energy photon is emitted in addition to the two muons. Two additional requirements are used to remove these contributions. First, candidates that satisfy either  $m_{J/\psi} - 5\sigma_q < q < m_{J/\psi} + 3\sigma_q$  or  $|q - m_{\psi(2S)}| < 3\sigma_q$  are removed, where  $m_{J/\psi}$  and  $m_{\psi(2S)}$  are the world-average  $J/\psi$  and  $\psi(2S)$  masses [27], respectively, and  $\sigma_q$  is the calculated uncertainty in  $q$  for each candidate. The second requirement specifically targets the radiative background by using the fact that the missing low-energy photon will shift  $q$  and  $m$  from their nominal values by a similar amount. Thus, these events are suppressed by requiring  $|(m - m_{B^+}) - (q - m_{J/\psi})| > 0.09$  GeV and  $|(m - m_{B^+}) - (q - m_{\psi(2S)})| > 0.03$  GeV. When the  $B^+ \rightarrow K^{*+}J/\psi$  decay mode is used as a control sample, the requirements in this paragraph are not applied.

The Monte Carlo (MC) samples corresponding to the signal and control channels are simulated using PYTHIA 6.426 [28], with the unstable particle decays modeled by EVTGEN [29]. The particles are then propagated through a detailed model of the CMS detector

with GEANT4 [30]. The reconstruction and selection of the MC generated events follow the same algorithms as for the collision data. The number and spatial distribution of additional pp collision vertices in the same or nearby beam crossings in the data are simulated by weighting the MC samples to match the distributions found in data. The signal MC samples are used to estimate the efficiency, which includes the detector acceptance, the trigger efficiency, and the efficiency for reconstructing and selecting the signal candidates.

#### 4 Angular analysis

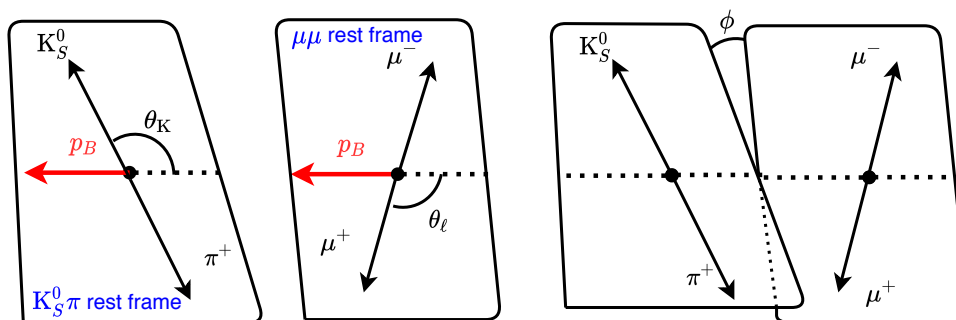
The measurement of  $A_{\text{FB}}$  and  $F_{\text{L}}$  is performed in three  $q^2$  regions:  $1 < q^2 < 8.68 \text{ GeV}^2$ ,  $10.09 < q^2 < 12.86 \text{ GeV}^2$ , and  $14.18 < q^2 < 19 \text{ GeV}^2$ . The angular distribution of the signal process,  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ , depends on three variables as shown in figure 1:  $\theta_{\text{K}}$  (the angle in the  $K^{*+}$  meson rest frame between the momentum of the  $K_{\text{S}}^0$  meson and the negative of the  $B^+$  meson momentum),  $\theta_{\ell}$  (the angle in the dimuon rest frame between the momentum of the positively charged muon and the negative of the  $B^+$  meson momentum), and  $\phi$  (the angle in the  $B^+$  meson rest frame between the plane containing the two muons and the plane containing the  $K_{\text{S}}^0$  and  $\pi^+$  mesons). Since the extracted angular observables  $A_{\text{FB}}$  and  $F_{\text{L}}$  do not depend on  $\phi$ , this angle is integrated out. While the  $K_{\text{S}}^0 \pi^+$  invariant mass is required to be consistent with coming from a  $K^{*+}$  resonance decay, there can still be  $S$ -wave  $K_{\text{S}}^0 \pi^+$  contributions [19, 31–33]. This is parameterized by two terms: the  $S$ -wave fraction,  $F_{\text{S}}$ , and the interference amplitude,  $A_{\text{S}}$ , between  $S$ - and  $P$ -wave decays. The parameters  $A_{\text{FB}}$ ,  $F_{\text{L}}$ ,  $F_{\text{S}}$ , and  $A_{\text{S}}$  are functions of  $q^2$ . The differential decay rate of the signal decay  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ , as a function of the angular variables and  $q^2$ , can be written [19, 33] as:

$$\begin{aligned} \frac{1}{\Gamma} \frac{d^3\Gamma}{d\cos\theta_{\text{K}} d\cos\theta_{\ell} dq^2} = & \frac{9}{16} \left\{ \frac{2}{3} [F_{\text{S}} + 2A_{\text{S}} \cos\theta_{\text{K}}] (1 - \cos^2\theta_{\ell}) \right. \\ & + (1 - F_{\text{S}}) [2F_{\text{L}} \cos^2\theta_{\text{K}} (1 - \cos^2\theta_{\ell}) \\ & + \frac{1}{2} (1 - F_{\text{L}}) (1 - \cos^2\theta_{\text{K}}) (1 + \cos^2\theta_{\ell}) \\ & \left. + \frac{4}{3} A_{\text{FB}} (1 - \cos^2\theta_{\text{K}}) \cos\theta_{\ell} \right\}. \end{aligned} \tag{4.1}$$

For each  $q^2$  bin, the observables  $A_{\text{FB}}$  and  $F_{\text{L}}$  are extracted by performing an unbinned extended maximum likelihood fit with three independent variables:  $m$ ,  $\cos\theta_{\text{K}}$ , and  $\cos\theta_{\ell}$ . The unnormalized probability density function (pdf) used to fit the data is:

$$\begin{aligned} \text{pdf}(m, \cos\theta_{\text{K}}, \cos\theta_{\ell}) = & Y_{\text{S}} S^m(m) S^a(\cos\theta_{\text{K}}, \cos\theta_{\ell}) \epsilon(\cos\theta_{\text{K}}, \cos\theta_{\ell}) \\ & + Y_{\text{B}} B^m(m) B^{\theta_{\text{K}}}(\cos\theta_{\text{K}}) B^{\theta_{\ell}}(\cos\theta_{\ell}). \end{aligned} \tag{4.2}$$

The parameters  $Y_{\text{S}}$  and  $Y_{\text{B}}$  are the signal and background yields, respectively, and are free parameters in the fit. The signal mass shape,  $S^m(m)$ , is modeled by the sum of two Gaussian functions with a common mean, and the shape parameters are fixed to the values obtained from fitting simulated signal events. The mass shape of the background,

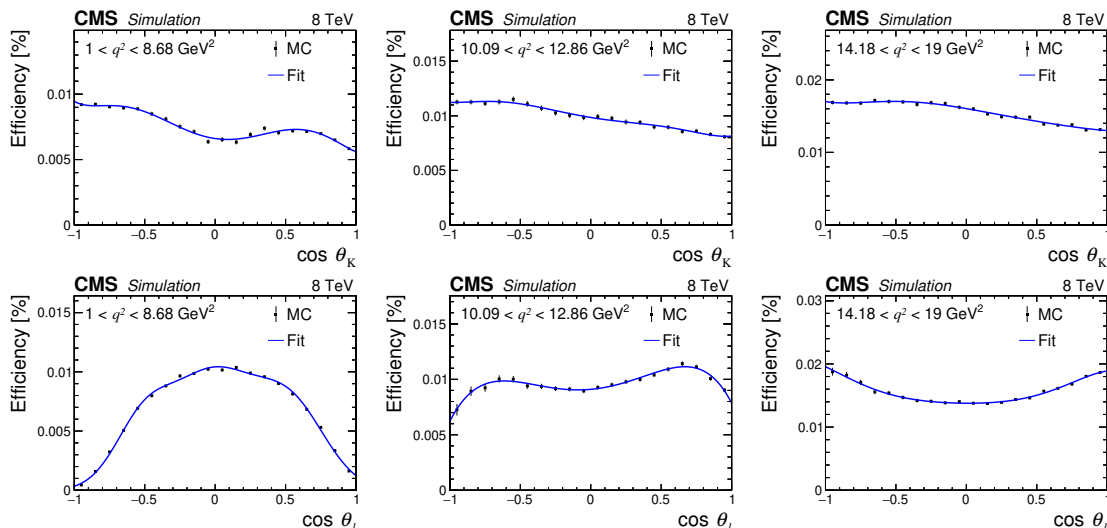


**Figure 1.** Definition of the angular observables  $\theta_K$  (left),  $\theta_\ell$  (middle), and  $\phi$  (right) for the decay  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ .

$B^m(m)$ , is an exponential function with the exponent as a free parameter. The function  $S^a(\cos \theta_K, \cos \theta_\ell)$  is obtained from eq. (4.1) to describe the signal event distribution in the  $(\cos \theta_K, \cos \theta_\ell)$  angular space. Since the  $S$ -wave contribution is found to be small,  $F_S$  and  $A_S$  are fixed to zero in the nominal fit. The functions  $B^{\theta_K}(\cos \theta_K)$  and  $B^{\theta_\ell}(\cos \theta_\ell)$  are the background shapes in the angular space. They are obtained by fitting the data events in the  $B^+$  invariant mass sideband regions and fixed in the final fit. The  $B^{\theta_K}(\cos \theta_K)$  distributions are fitted to a sum of two exponential functions, a fourth-degree polynomial, and a third-degree polynomial for the low, middle, and high  $q^2$  ranges, respectively. The  $B^{\theta_\ell}(\cos \theta_\ell)$  distributions are fitted to a sum of two Gaussian functions, a fourth-degree polynomial, and a linear function for the low, middle, and high  $q^2$  ranges, respectively.

The signal efficiency function in the two-dimensional angular spaces  $\epsilon(\cos \theta_K, \cos \theta_\ell)$  is obtained from the simulated samples using a two-step unbinned maximum likelihood fit process. In the first step, the efficiency in each  $q^2$  bin is fitted to a product of two one-dimensional functions, one for each angular variable, assuming there is no correlation between the variables. The one-dimensional functions are polynomials of degree six, except for the  $\cos \theta_\ell$  distribution of the first  $q^2$  bin, which is a sum of three Gaussian functions. In the second step, a two-dimensional fit is performed on both angular variables, where the results from the first step are fixed, and an additional function is added to account for correlations. This function is the product of the powers 0, 1, 2, and 3 for Legendre polynomials with  $\cos \theta_K$  as the argument and the powers 0, 1, 3, and 4 for ordinary polynomials with  $\cos \theta_\ell$  as the argument. This results in sixteen terms, each controlled by a free parameter in the fit. The signal efficiencies and the corresponding fits for each  $q^2$  bin are shown as projections on  $\cos \theta_K$  (upper plots) and  $\cos \theta_\ell$  (lower plots) in figure 2.

To test the fit, the reconstructed signal MC data set is split into 2000 random, disjoint samples, each with a similar number of signal events as the data sample. These are combined with background events generated using the appropriate pdf in eq. (4.2), with parameters taken from the fit to the data. Each sample is fitted in the same manner as the data and the resulting values for  $A_{FB}$  and  $F_L$  are found to have approximately Gaussian distributions with mean values close to the MC values. This indicates the fit is unbiased and accurate, even in the presence of background.



**Figure 2.** The signal efficiency as a function of  $\cos\theta_K$  (upper row) and  $\cos\theta_\ell$  (lower row) from simulation for the  $q^2$  ranges indicated. The vertical bars indicate the statistical uncertainty. The curves show the projection of the fitted result obtained from the two-dimensional fit, as described in the text.

The degree to which the simulation describes the data is examined by using the  $B^+ \rightarrow K^{*+} J/\psi$  MC sample to determine the efficiency, correcting the  $B^+ \rightarrow K^{*+} J/\psi$  data by this efficiency, and comparing the  $\cos\theta_K$  and  $\cos\theta_\ell$  distributions with the SM expectations. The residual discrepancies are found to have a negligible effect on the measured values of  $A_{FB}$  and  $F_L$ .

## 5 Systematic uncertainties

Several sources of systematic uncertainties are considered in this analysis. First, the statistical uncertainty associated with the finite number of signal MC events is evaluated by generating 200 alternative efficiency functions, varying the function parameters according to their uncertainties. Each of these efficiency functions is used to fit the data, and the standard deviations of the distributions of the fitted values for  $A_{FB}$  and  $F_L$  are taken as the systematic uncertainty in each quantity. The second source of systematic uncertainty is from the shape used to parameterize the efficiency. The difference between the values of  $A_{FB}$  and  $F_L$  obtained from fitting the generator-level MC signal events (with no efficiency function) and the reconstructed MC signal events (with the efficiency function) is taken as the estimate for this systematic uncertainty.

The third systematic uncertainty arises from modeling the angular distribution of the background events and is composed of three components. The first component is intended to check the functional form. Instead of fitting the sideband data with the functional forms described in section 4, the lower and upper sidebands are individually fit to a non-parametric function and the two pdfs are combined according to their relative yields. The difference between the results obtained with this alternative background pdf and the default



Source	$A_{\text{FB}} (10^{-3})$	$F_{\text{L}} (10^{-3})$
MC statistical uncertainty	12–29	18–38
Efficiency model	3–25	4–12
Background shape functional form	0–9	0–33
Background shape statistical uncertainty	16–73	20–87
Background shape sideband region	28–153	38–78
$S$ -wave contamination	4–22	5–12
Total systematic uncertainty	42–174	55–127

**Table 1.** Sources of systematic uncertainties and the effect on  $A_{\text{FB}}$  and  $F_{\text{L}}$ . The values given are absolute and the ranges indicate the variation over the  $q^2$  bins.

function is taken as a systematic uncertainty. The second component is intended to account for the uncertainty regarding how well the background in the sideband regions represents the background in the signal region. In the nominal fit, large  $B^+$  invariant mass sideband regions are used to determine the background shape in order to reduce the statistical uncertainty. As an alternate method, the background shape is determined from narrower sideband regions ( $4.96 < m < 5.18 \text{ GeV}$  and  $5.38 < m < 5.6 \text{ GeV}$ ), which are expected to be more representative of the signal region. Once the new background shape is determined, the fit is redone using all events (including the original sideband region), and the change in  $A_{\text{FB}}$  and  $F_{\text{L}}$  with respect to the nominal fit is used as the systematic uncertainty. Since the background shape parameters are fixed in the determination of  $A_{\text{FB}}$  and  $F_{\text{L}}$ , the third component accounts for the statistical uncertainty in the background shape. The data are fitted with 200 different background shapes obtained by varying the shape parameters by their uncertainties. The standard deviation of the distributions of the angular observables  $A_{\text{FB}}$  and  $F_{\text{L}}$  obtained from these 200 fits is included as a systematic uncertainty.

The fourth source of systematic uncertainty is the effect from  $S$ -wave contamination. The nominal fit does not include any  $S$ -wave contribution. We perform an alternative fit in which the  $S$ -wave fraction  $F_S$  is set to 5% and the  $S$ - $P$  interference term  $A_S$  is a free parameter. The change in  $A_{\text{FB}}$  and  $F_{\text{L}}$  from the default fit is taken as the systematic uncertainty from  $S$ -wave contamination. Since the analysis of the similar decay mode  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  did not find  $F_S$  above 3% in any  $q^2$  bin with many more signal events [5], an upper limit of 5% is a conservative choice.

The total systematic uncertainty is obtained by adding the individual contributions in quadrature for each  $q^2$  bin. The systematic uncertainties, all considered to be symmetric, are summarized in table 1.

## 6 Results

Fits to the data are performed in three independent  $q^2$  bins between 1 and  $19 \text{ GeV}^2$ . As described in section 4, the measured values for  $A_{\text{FB}}$  and  $F_{\text{L}}$  are obtained from an unbinned maximum likelihood fit in which both parameters are allowed to vary freely. The necessity of a nonnegative decay rate results in physical limits on  $A_{\text{FB}}$  and  $F_{\text{L}}$  that make it difficult



$q^2$ (GeV <sup>2</sup> )	$Y_S$	$A_{\text{FB}}$	$F_L$
1–8.68	$22.1 \pm 8.1$	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09–12.86	$25.9 \pm 6.3$	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18–19	$45.1 \pm 8.0$	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$

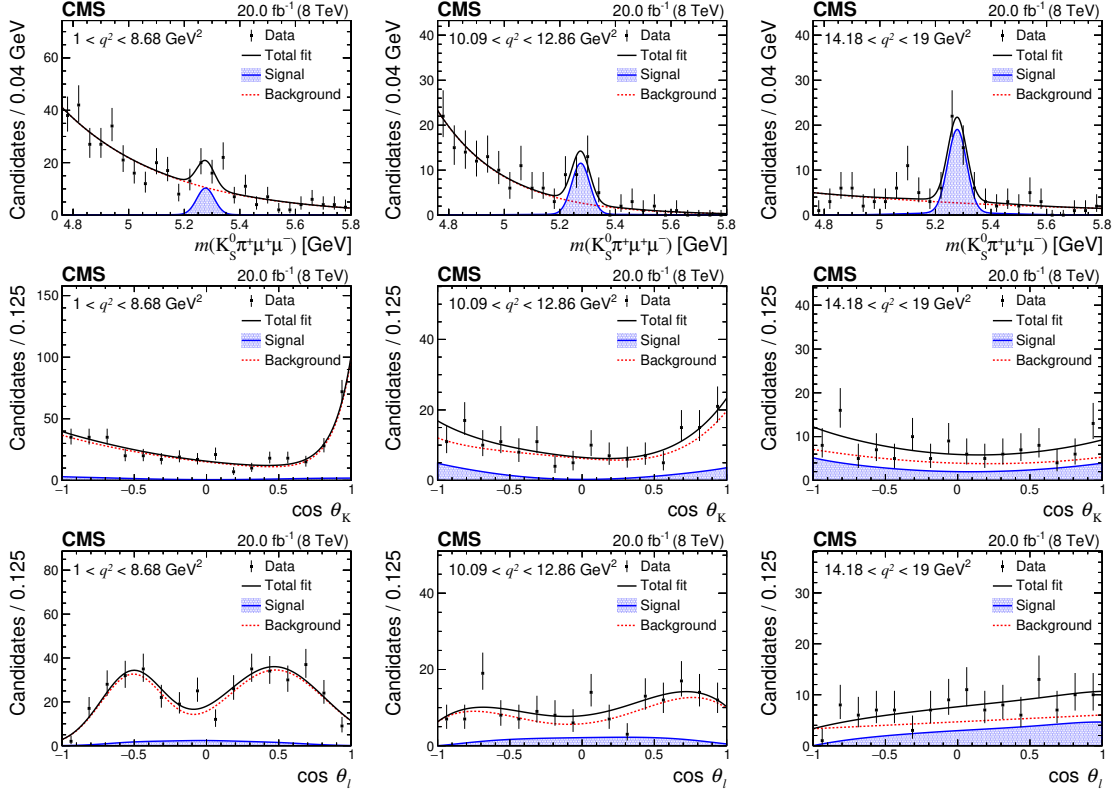
**Table 2.** The  $Y_S$ ,  $A_{\text{FB}}$ , and  $F_L$  values from the fit for each  $q^2$  range. The first uncertainty is statistical and the second is systematic.

to determine the statistical uncertainties from the likelihood function. Therefore, the one dimensional uncertainty for  $A_{\text{FB}}$ , and separately for  $F_L$ , are evaluated using Neyman constructions following the method of Feldman-Cousins [34], generalized to treat nuisance parameters in the test statistic by the profile likelihood method. In the construction for  $A_{\text{FB}}$ ,  $F_L$  is included in the nuisance parameters, and vice versa. In the Monte Carlo simulation of pseudo-experiments for obtaining the acceptance intervals in the construction, the nuisance parameters are treated by a parametric bootstrap procedure with profiling. That is, for each test value of the parameter of interest, the model including nuisance parameters is fit to the data to obtain the values of nuisance parameters that are used in the pseudo-experiments for constructing the acceptance intervals for that test value of the parameter of interest. The correlation coefficients between the two angular observables returned by MINUIT [35] are found to be 0.1 or less, depending on the  $q^2$  bin. Tests with pseudo-experiments are used to verify that the statistical uncertainties have a coverage exceeding 68.3% in all cases.

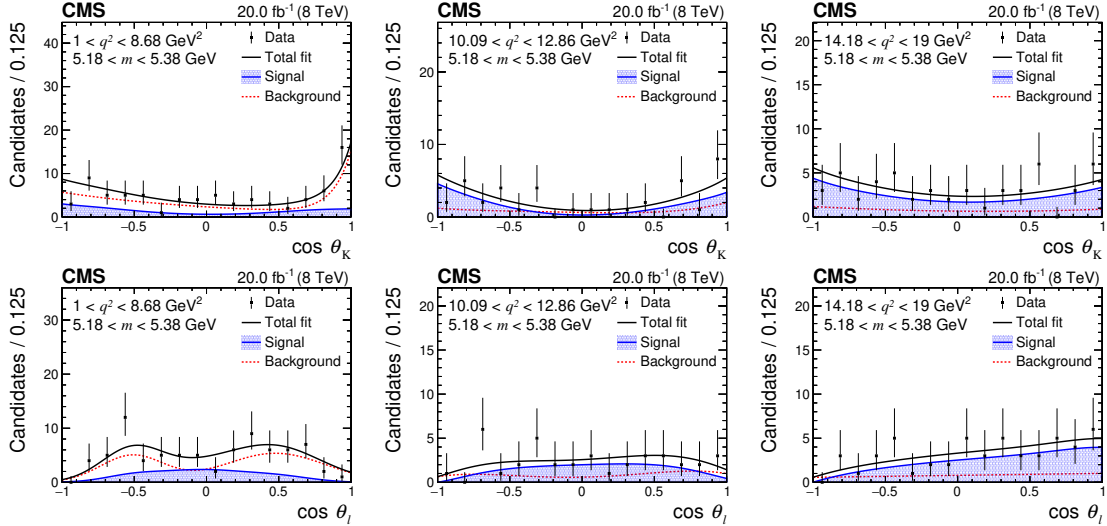
The results of the unbinned maximum likelihood fit are overlaid on the data in projections of  $m$  (upper plots),  $\cos \theta_K$  (middle plots), and  $\cos \theta_\ell$  (lower plots) for each  $q^2$  region in figure 3. The fitted values of  $Y_S$ ,  $A_{\text{FB}}$ , and  $F_L$ , along with their associated uncertainties, are given in table 2 for each of the  $q^2$  bins. In order to more clearly observe the signal features, the data and fit results are shown versus the two angular variables in the invariant mass signal region  $5.18 < m < 5.38$  GeV in figure 4. The fitted values of  $A_{\text{FB}}$  and  $F_L$  are shown as a function of  $q^2$  in figure 5, along with a SM prediction. This prediction combines quantum chromodynamic factorization and soft collinear effective theory at large recoil with heavy-quark effective theory and lattice gauge theory at small recoil to separate hard physics (around the b quark mass) from soft physics (around  $\Lambda_{\text{QCD}}$ ) [20, 36–38]. While theoretical predictions are unavailable for the region between the  $J/\psi$  and  $\psi(2S)$  meson masses ( $10.09 < q^2 < 12.86$  GeV<sup>2</sup>), the SM prediction agrees with the experimental results for the other  $q^2$  bins, indicating no evidence of contributions from physics beyond the SM.

## 7 Summary

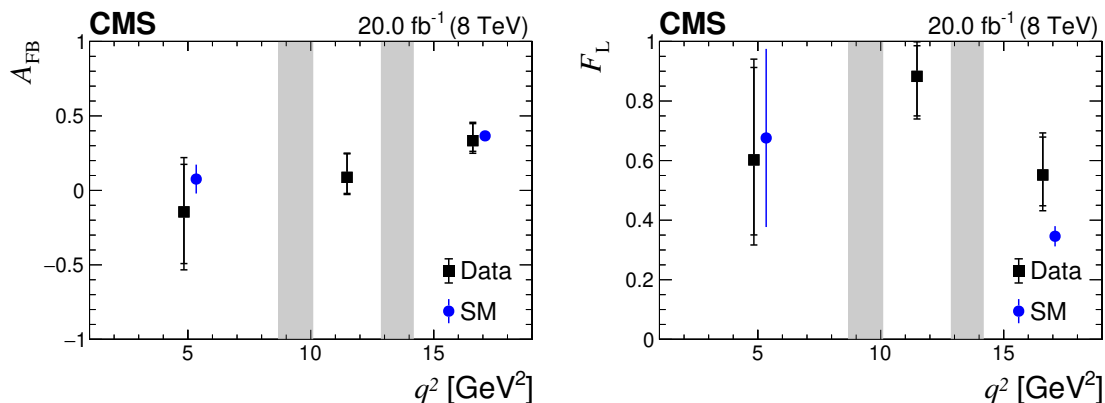
The first angular analysis of the exclusive decay  $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$ , including the charge-conjugate state, has been performed using a sample of proton-proton collisions at



**Figure 3.** The  $K_S^0 \pi^+ \mu^+ \mu^-$  invariant mass (upper row),  $\cos \theta_K$  (middle row), and  $\cos \theta_\ell$  (lower row) distributions for each  $q^2$  range is shown for data, along with the fit projections. The vertical bars on the data points indicate the statistical uncertainty. The filled areas, dashed lines, and solid lines represent the signal, background, and total contributions, respectively.



**Figure 4.** The  $\cos \theta_K$  (upper row) and  $\cos \theta_\ell$  (lower row) distributions for each  $q^2$  range is shown for data in the invariant mass region  $5.18 < m < 5.38 \text{ GeV}$ , along with the fit projections for the same region. The vertical bars on the data points indicate the statistical uncertainty. The filled areas, dashed lines, and solid lines represent the signal, background, and total contributions, respectively.



**Figure 5.** The measured values of  $A_{\text{FB}}$  (left) and  $F_L$  (right) versus  $q^2$  for  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$  decays are shown with filled squares, centered on the  $q^2$  bin. The statistical (total) uncertainty is shown by inner (outer) vertical bars. The vertical shaded regions correspond to the regions dominated by  $B^+ \rightarrow K^{*+} J/\psi$  and  $B^+ \rightarrow K^{*+} \psi(2S)$  decays. The SM predictions and associated uncertainties are shown by the filled circles and vertical bars, with the points slightly offset from the center of the  $q^2$  bin for clarity.

a center-of-mass energy of 8 TeV. The data were collected with the CMS detector in 2012 at the LHC, and correspond to an integrated luminosity of  $20.0 \text{ fb}^{-1}$ . For each bin of the dimuon invariant mass squared ( $q^2$ ), a three-dimensional unbinned maximum likelihood fit is performed on the distributions of the  $K^*(892)^+ \mu^+ \mu^-$  invariant mass and two decay angles. The muon forward-backward asymmetry,  $A_{\text{FB}}$ , and the  $K^*(892)^+$  longitudinal polarization fraction,  $F_L$ , are extracted from the fit in bins of  $q^2$  and found to be consistent with a standard model prediction.

### Acknowledgments

We thank J. Matias for providing the theoretical values of  $A_{\text{FB}}$  and  $F_L$  used for comparisons with our measurements.

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 centers 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: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP

and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (U.K.); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science — EOS” — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany’s Excellence Strategy — EXC 2121 “Quantum Universe” — 390833306; the Lendület (“Momentum”) Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] CMS collaboration, *CMS Luminosity Based on Pixel Cluster Counting — Summer 2013 Update*, [CMS-PAS-LUM-13-001](#) (2013) [[INSPIRE](#)].
- [2] CDF collaboration, *Measurements of the Angular Distributions in the Decays  $B \rightarrow K^{(*)}\mu^+\mu^-$  at CDF*, *Phys. Rev. Lett.* **108** (2012) 081807 [[arXiv:1108.0695](#)] [[INSPIRE](#)].
- [3] LHCb collaboration, *Differential branching fraction and angular analysis of the decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$* , *JHEP* **08** (2013) 131 [[arXiv:1304.6325](#)] [[INSPIRE](#)].
- [4] CMS collaboration, *Angular Analysis and Branching Fraction Measurement of the Decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$* , *Phys. Lett. B* **727** (2013) 77 [[arXiv:1308.3409](#)] [[INSPIRE](#)].
- [5] CMS collaboration, *Angular analysis of the decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  from pp collisions at  $\sqrt{s} = 8$  TeV*, *Phys. Lett. B* **753** (2016) 424 [[arXiv:1507.08126](#)] [[INSPIRE](#)].
- [6] LHCb collaboration, *Angular analysis of the  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  decay using  $3\text{fb}^{-1}$  of integrated luminosity*, *JHEP* **02** (2016) 104 [[arXiv:1512.04442](#)] [[INSPIRE](#)].
- [7] LHCb collaboration, *Measurement of CP-Averaged Observables in the  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  Decay*, *Phys. Rev. Lett.* **125** (2020) 011802 [[arXiv:2003.04831](#)] [[INSPIRE](#)].
- [8] ATLAS collaboration, *Angular analysis of  $B_d^0 \rightarrow K^{*}\mu^+\mu^-$  decays in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *JHEP* **10** (2018) 047 [[arXiv:1805.04000](#)] [[INSPIRE](#)].
- [9] BABAR collaboration, *Angular Distributions in the Decays  $B \rightarrow K^*\ell^+\ell^-$* , *Phys. Rev. D* **79** (2009) 031102 [[arXiv:0804.4412](#)] [[INSPIRE](#)].
- [10] BELLE collaboration, *Measurement of the Differential Branching Fraction and Forward-Backward Asymmetry for  $B \rightarrow K^{(*)}\ell^+\ell^-$* , *Phys. Rev. Lett.* **103** (2009) 171801 [[arXiv:0904.0770](#)] [[INSPIRE](#)].
- [11] BABAR collaboration, *Measurement of angular asymmetries in the decays  $B \rightarrow K^*\ell^+\ell^-$* , *Phys. Rev. D* **93** (2016) 052015 [[arXiv:1508.07960](#)] [[INSPIRE](#)].
- [12] C. Bobeth, G. Hiller and D. van Dyk, *The Benefits of  $\bar{B} \rightarrow \bar{K}^*l^+l^-$  Decays at Low Recoil*, *JHEP* **07** (2010) 098 [[arXiv:1006.5013](#)] [[INSPIRE](#)].
- [13] C. Bobeth, G. Hiller, D. van Dyk and C. Wacker, *The Decay  $B \rightarrow K\ell^+\ell^-$  at Low Hadronic Recoil and Model-Independent  $\Delta B = 1$  Constraints*, *JHEP* **01** (2012) 107 [[arXiv:1111.2558](#)] [[INSPIRE](#)].
- [14] 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** (2013) 034016 [[arXiv:1212.2321](#)] [[INSPIRE](#)].
- [15] A. Ali, G. Kramer and G. Zhu,  *$B \rightarrow K^+l^+l^-$  decay in soft-collinear effective theory*, *Eur. Phys. J. C* **47** (2006) 625 [[hep-ph/0601034](#)] [[INSPIRE](#)].
- [16] W. Altmannshofer, P. Ball, A. Bharucha, A.J. Buras, D.M. Straub and M. Wick, *Symmetries and Asymmetries of  $B \rightarrow K^*\mu^+\mu^-$  Decays in the Standard Model and Beyond*, *JHEP* **01** (2009) 019 [[arXiv:0811.1214](#)] [[INSPIRE](#)].
- [17] W. Altmannshofer, P. Paradisi and D.M. Straub, *Model-Independent Constraints on New Physics in  $b \rightarrow s$  Transitions*, *JHEP* **04** (2012) 008 [[arXiv:1111.1257](#)] [[INSPIRE](#)].
- [18] 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 [[arXiv:1212.2263](#)] [[INSPIRE](#)].
- [19] 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 [[arXiv:1303.5794](#)] [[INSPIRE](#)].

- [20] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, *On the impact of power corrections in the prediction of  $B \rightarrow K^* \mu^+ \mu^-$  observables*, *JHEP* **12** (2014) 125 [[arXiv:1407.8526](#)] [[INSPIRE](#)].
- [21] M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan and J. Matias, *Are we overlooking lepton flavour universal new physics in  $b \rightarrow s \ell \ell$ ?*, *Phys. Rev. D* **99** (2019) 075017 [[arXiv:1809.08447](#)] [[INSPIRE](#)].
- [22] M. Algueró et al., *Emerging patterns of New Physics with and without Lepton Flavour Universal contributions*, *Eur. Phys. J. C* **79** (2019) 714 [Addendum *ibid.* **80** (2020) 511] [[arXiv:1903.09578](#)] [[INSPIRE](#)].
- [23] CMS collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, *2014 JINST* **9** P10009 [[arXiv:1405.6569](#)] [[INSPIRE](#)].
- [24] CMS collaboration, *The CMS Experiment at the CERN LHC*, *2008 JINST* **3** S08004 [[INSPIRE](#)].
- [25] CMS collaboration, *The CMS trigger system*, *2017 JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [26] CMS collaboration, *Performance of CMS Muon Reconstruction in pp Collision Events at  $\sqrt{s} = 7$  TeV*, *2012 JINST* **7** P10002 [[arXiv:1206.4071](#)] [[INSPIRE](#)].
- [27] PARTICLE DATA collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01 [[INSPIRE](#)].
- [28] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [29] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [30] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [31] 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 [[arXiv:1207.4004](#)] [[INSPIRE](#)].
- [32] J. Matias, *On the S-wave pollution of  $B \rightarrow K^* \ell^+ \ell^-$  observables*, *Phys. Rev. D* **86** (2012) 094024 [[arXiv:1209.1525](#)] [[INSPIRE](#)].
- [33] 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 [[arXiv:1210.5279](#)] [[INSPIRE](#)].
- [34] G.J. Feldman and R.D. Cousins, *A Unified approach to the classical statistical analysis of small signals*, *Phys. Rev. D* **57** (1998) 3873 [[physics/9711021](#)] [[INSPIRE](#)].
- [35] 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 [[INSPIRE](#)].
- [36] 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 [[arXiv:1006.4945](#)] [[INSPIRE](#)].
- [37] 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 [[arXiv:1310.3722](#)] [[INSPIRE](#)].
- [38] R.R. Horgan, Z. Liu, S. Meinel and M. Wingate, *Rare B decays using lattice QCD form factors*, in proceedings of the *32nd International Symposium on Lattice Field Theory (LATTICE 2014)*, Brookhaven, NY, U.S.A., 23–28 June 2014, *PoS LATTICE 2014* (2015) 372 [[arXiv:1501.00367](#)] [[INSPIRE](#)].

**The CMS collaboration****Yerevan Physics Institute, Yerevan, Armenia**

A.M. Sirunyan<sup>†</sup>, A. Tumasyan

**Institut für Hochenergiephysik, Wien, Austria**

W. Adam, T. Bergauer, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, L. Lechner, D. Liko, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, S. Tempel, W. Waltenberger, C.-E. Wulz<sup>1</sup>, M. Zarucki

**Institute for Nuclear Problems, Minsk, Belarus**

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

**Universiteit Antwerpen, Antwerpen, Belgium**

M.R. Darwish<sup>2</sup>, E.A. De Wolf, X. Janssen, T. Kello<sup>3</sup>, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

**Vrije Universiteit Brussel, Brussel, Belgium**

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskiy, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, D. Müller, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

**Université Libre de Bruxelles, Bruxelles, Belgium**

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

**Ghent University, Ghent, Belgium**

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov<sup>4</sup>, G. Mestdach, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

**Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil**

G.A. Alves, C. Hensel, A. Moraes

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

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. Brandao Malbouisson, W. Carvalho, J. Chinellato<sup>5</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>6</sup>, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins<sup>7</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>8</sup>, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira



**Universidade Estadual Paulista<sup>a</sup>, Universidade Federal do ABC<sup>b</sup>, São Paulo, Brazil**

C.A. Bernardes<sup>a,a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>a,b</sup>, D.S. Lemos<sup>a</sup>, P.G. Mercadante<sup>a,b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**

A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

**Beihang University, Beijing, China**

T. Cheng, W. Fang<sup>3</sup>, Q. Guo, H. Wang, L. Yuan

**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad, G. Bauer, Z. Hu, Y. Wang, K. Yi<sup>9,10</sup>

**Institute of High Energy Physics, Beijing, China**

E. Chapon, G.M. Chen<sup>11</sup>, H.S. Chen<sup>11</sup>, M. Chen, T. Javaid<sup>11</sup>, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu<sup>11</sup>, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang<sup>11</sup>, J. Zhao

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

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

**Sun Yat-Sen University, Guangzhou, China**

Z. You

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China**

X. Gao<sup>3</sup>

**Zhejiang University, Hangzhou, China**

M. Xiao

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

**Universidad de Antioquia, Medellin, Colombia**

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac, T. Sculac

**Institute Rudjer Boskovic, Zagreb, Croatia**V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov<sup>12</sup>, T. Susa**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

**Charles University, Prague, Czech Republic**M. Finger<sup>13</sup>, M. Finger Jr.<sup>13</sup>, A. Kveton, J. Tomsa**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala

**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**S. Abu Zeid<sup>14</sup>, S. Khalil<sup>15</sup>, E. Salama<sup>16,14</sup>**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M.A. Mahmoud, Y. Mohammed<sup>17</sup>**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, J. Pata, M. Raidal, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

P. Luukka, T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>18</sup>, M. Titov, G.B. Yu**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher,

A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>19</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine<sup>19</sup>, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, K. Shchablo, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

A. Khvedelidze<sup>13</sup>, Z. Tsamalaidze<sup>13</sup>

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

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, J. Schulz, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad<sup>20</sup>, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>21</sup>, T. Ziemons

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>22</sup>, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defran-  
chis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo<sup>23</sup>, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari<sup>24</sup>, N.Z. Jomhari, H. Jung, A. Kasem<sup>22</sup>, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>25</sup>, T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Muss-  
giller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, A. Singh, R.E. Sosa Ri-  
cardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann,

A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann<sup>21</sup>, C. Heidecker, U. Husemann, I. Katkov<sup>26</sup>, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniowski

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

**National and Kapodistrian University of Athens, Athens, Greece**

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

**National Technical University of Athens, Athens, Greece**

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**

M. Bartók<sup>27</sup>, M. Csanad, M.M.A. Gadallah<sup>28</sup>, S. Lökös<sup>29</sup>, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>30</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

S. Czellar, J. Karancsi<sup>27</sup>, J. Molnar, Z. Szillasi, D. Teyssier

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

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

**Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary**

T. Csorgo<sup>32</sup>, F. Nemes<sup>32</sup>, T. Novak

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

**National Institute of Science Education and Research, HBNI, Bhubaneswar, India**

S. Bahinipati<sup>33</sup>, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>34</sup>, N. Sur, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra<sup>35</sup>, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

**University of Delhi, Delhi, India**

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

M. Bharti<sup>36</sup>, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>37</sup>, M. Maity<sup>38</sup>, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh<sup>36</sup>, S. Thakur<sup>36</sup>

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

**Bhabha Atomic Research Centre, Mumbai, India**

D. Dutta, V. Kumar, K. Naskar<sup>39</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, G.B. Mohanty, U. Sarkar

**Tata Institute of Fundamental Research-B, Mumbai, India**

S. Banerjee, S. Bhattacharya, S. Chatterjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

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

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

**Department of Physics, Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>40</sup>, M. Zeinali<sup>41</sup>

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

S. Chenarani<sup>42</sup>, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,43</sup>, C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, M. Gul<sup>a</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup>, J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, C. Ciocca<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, T. Diotallevi<sup>a,b</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Giommi<sup>a,b</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,44</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b,45</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,45</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, A. Cassese<sup>a</sup>, R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, F. Fiori<sup>a</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Lizzo<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, R. Seidita<sup>a,b</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**

M. Bozzo<sup>a,b</sup>, F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, F. Ceteorelli<sup>a,b</sup>, V. Ciriolo<sup>a,b,21</sup>, F. De Guio<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, A. Massironi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,21</sup>, D. Zuolo<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,21</sup>, P. Paolucci<sup>a,21</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, P. Bortignon<sup>a</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, S.Y. Hoh<sup>a,b</sup>, S. Lacaprara<sup>a</sup>, L. Layer<sup>a,46</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Presilla<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, G. Strong<sup>a</sup>, M. Tosi<sup>a,b</sup>, H. Yarar<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>

**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

C. Aimè<sup>a,b</sup>, A. Braghieri<sup>a</sup>, S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, F. Moscatelli<sup>a</sup>, A. Piccinelli<sup>a,b</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>, T. Tedeschi<sup>a,b</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, V. Bertacchi<sup>a,c</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, M.R. Di Domenico<sup>a,b</sup>, S. Donato<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, G. Ramirez-Sanchez<sup>a,c</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>, S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, N. Shafiei<sup>a,b</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini<sup>a</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Rome, Italy**

F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a</sup>, M. Diemoz<sup>a</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a,b</sup>, R. Tramontano<sup>a,b</sup>

**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy, Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, A. Bellora<sup>a,b</sup>, J. Berenguer Antequera<sup>a,b</sup>, C. Biino<sup>a</sup>, A. Cappati<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, S. Cometti<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, F. Legger<sup>a</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, G. Ortona<sup>a</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Salvatico<sup>a,b</sup>, F. Siviero<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>, M. Tornago<sup>a,b</sup>, D. Trocino<sup>a,b</sup>

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>, G. Della Ricca<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup>

**Kyungpook National University, Daegu, Korea**

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

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

H. Kim, D.H. Moon

**Hanyang University, Seoul, Korea**

B. Francois, T.J. Kim, J. Park

**Korea University, Seoul, Korea**

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo



**Kyung Hee University, Department of Physics, Seoul, Republic of Korea**

J. Goh, A. Gurtu

**Sejong University, Seoul, Korea**

H.S. Kim, Y. Kim

**Seoul National University, Seoul, Korea**

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

**University of Seoul, Seoul, Korea**

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

**Yonsei University, Department of Physics, Seoul, Korea**

H.D. Yoo

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

**College of Engineering and Technology, American University of the Middle East (AUM), Kuwait**

Y. Maghrbi

**Riga Technical University, Riga, Latvia**

V. Veckalns<sup>47</sup>

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

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

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

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

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>48</sup>, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

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

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

A. Morelos Pineda

**University of Montenegro, Podgorica, Montenegro**

J. Mijuskovic<sup>4</sup>, N. Raicevic

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P.H. Butler

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

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

**AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**

V. Avati, L. Grzanka, M. Malawski

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szeleper, P. Traczyk, P. Zalewski

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

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

A. Baginyan, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, I. Gorbunov, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev<sup>49,50</sup>, V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev<sup>51</sup>, A. Zarubin, I. Zhizhin

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

G. Gavrilo, V. Golovtcov, Y. Ivanov, V. Kim<sup>52</sup>, E. Kuznetsova<sup>53</sup>, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov<sup>†</sup>, A. Toropin

**Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia**

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko<sup>54</sup>, V. Popov, G. Safronov, A. Spiridonov, A. Steppenov, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev

**National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia**

R. Chistov<sup>55</sup>, M. Danilov<sup>56</sup>, P. Parygin, D. Philippov, S. Polikarpov<sup>56</sup>

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

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

A. Belyaev, E. Boos, M. Dubinin<sup>57</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>58</sup>, T. Dimova<sup>58</sup>, L. Kardapoltsev<sup>58</sup>, I. Ovtin<sup>58</sup>, Y. Skovpen<sup>58</sup>

**Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia**

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

**National Research Tomsk Polytechnic University, Tomsk, Russia**

A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

**Tomsk State University, Tomsk, Russia**

V. Borchsh, V. Ivanchenko, E. Tcherniaev

**University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>59</sup>, M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, L. Urda Gómez, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Camperros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

**University of Colombo, Colombo, Sri Lanka**

MK Jayananda, B. Kailasapathy<sup>60</sup>, D.U.J. Sonnadara, DDC Wickramarathna

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

T.K. Aarrestad, D. Abbaneo, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Bossini, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, L. Cristella, D. d’Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>61</sup>, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo<sup>21</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, T. Quast, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas<sup>62</sup>, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>63</sup>, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli, T. Rohe

**ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lusterhmann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann<sup>64</sup>, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

C. AMSLER<sup>65</sup>, C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring,

V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi

**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>66</sup>, C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>38</sup>, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

F. Boran, S. Damarsecin<sup>67</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>68</sup>, I. Dumanoglu<sup>69</sup>, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler<sup>70</sup>, I. Hos<sup>71</sup>, C. Isik, E.E. Kangal<sup>72</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>73</sup>, A. Polatoz, A.E. Simsek, B. Tali<sup>74</sup>, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

B. Isildak<sup>75</sup>, G. Karapinar<sup>76</sup>, K. Ocalan<sup>77</sup>, M. Yalvac<sup>78</sup>

**Bogazici University, Istanbul, Turkey**

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya<sup>79</sup>, O. Kaya<sup>80</sup>, Ö. Özçelik, S. Tekten<sup>81</sup>, E.A. Yetkin<sup>82</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>69</sup>, Y. Komurcu, S. Sen<sup>83</sup>

**Istanbul University, Istanbul, Turkey**

F. Aydogmus Sen, S. Cerci<sup>74</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>74</sup>

**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**

E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou<sup>84</sup>, J. Taylor, A. Titterton

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>85</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

**Imperial College, London, United Kingdom**

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal<sup>86</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash<sup>87</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee<sup>21</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

**Brunel University, Uxbridge, United Kingdom**

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, U.S.A.**

S. Abdullin, A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

**Catholic University of America, Washington, DC, U.S.A.**

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

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

A. Buccilli, O. Charaf, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio, C. West

**Boston University, Boston, U.S.A.**

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

**Brown University, Providence, U.S.A.**

G. Benelli, B. Burkle, X. Coubez<sup>22</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>88</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>89</sup>, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

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

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

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

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

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

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

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

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

**University of California, Santa Barbara — Department of Physics, Santa Barbara, U.S.A.**

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinman, J. Richman, U. Sarica, D. Stuart, S. Wang

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

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

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

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, I. Vorobiev

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

J.P. Cumalat, W.T. Ford, E. MacDonald, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

**Cornell University, Ithaca, U.S.A.**

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

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

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>57</sup>, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

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

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, X. Zuo



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

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

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

M.M. Baarmand, S. Butalla, T. Elkafrawy<sup>14</sup>, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

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

M. Alhuseini, K. Dilsiz<sup>90</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>91</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>92</sup>, Y. Onel, F. Ozok<sup>93</sup>, A. Penzo, C. Snyder, E. Tiras<sup>94</sup>, J. Wetzel

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

O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

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

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

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

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

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

F. Rebassoo, D. Wright

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

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

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

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

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

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

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

J.G. Acosta, S. Oliveros

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

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, J.E. Siado, G.R. Snow<sup>†</sup>, W. Tabb, F. Yan

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

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio

**Northeastern University, Boston, U.S.A.**

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, U.S.A.**

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

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

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko<sup>49</sup>, R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, L. Zygala

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

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

**Princeton University, Princeton, U.S.A.**

B. Bonham, P. Das, G. Dezoort, A. Dropulic, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

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

S. Malik, S. Norberg

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

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic<sup>18</sup>, N. Trevisani, F. Wang, A. Wildridge, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, U.S.A.**

J. Dolen, N. Parashar

**Rice University, Houston, U.S.A.**

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts<sup>†</sup>, J. Rorie, W. Shi, A.G. Stahl Leiton

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

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban<sup>25</sup>, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Spanier

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

O. Bouhali<sup>95</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>96</sup>, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

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

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

**Vanderbilt University, Nashville, U.S.A.**

E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

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

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, E. Wolfe

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

P.E. Karchin, N. Poudyal, P. Thapa

**University of Wisconsin — Madison, Madison, WI, U.S.A.**

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudan Sreekala, A. Mallampalli, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased

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

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

- 5: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 7: Also at UFMS, Nova Andradina, Brazil
- 8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 9: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 10: Now at The University of Iowa, Iowa City, U.S.A.
- 11: Also at University of Chinese Academy of Sciences, Beijing, China
- 12: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
- 13: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 14: Also at Ain Shams University, Cairo, Egypt
- 15: Also at Zewail City of Science and Technology, Zewail, Egypt
- 16: Also at British University in Egypt, Cairo, Egypt
- 17: Now at Fayoum University, El-Fayoum, Egypt
- 18: Also at Purdue University, West Lafayette, U.S.A.
- 19: Also at Université de Haute Alsace, Mulhouse, France
- 20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 23: Also at University of Hamburg, Hamburg, Germany
- 24: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
- 25: Also at Brandenburg University of Technology, Cottbus, Germany
- 26: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 28: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 29: Also at Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
- 30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 31: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 32: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 33: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 34: Also at Institute of Physics, Bhubaneswar, India
- 35: Also at G.H.G. Khalsa College, Punjab, India
- 36: Also at Shoolini University, Solan, India
- 37: Also at University of Hyderabad, Hyderabad, India
- 38: Also at University of Visva-Bharati, Santiniketan, India
- 39: Also at Indian Institute of Technology (IIT), Mumbai, India
- 40: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 41: Also at Sharif University of Technology, Tehran, Iran
- 42: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 43: Now at INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy
- 44: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 45: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 46: Also at Università di Napoli ‘Federico II’, NAPOLI, Italy
- 47: Also at Riga Technical University, Riga, Latvia, Riga, Latvia

- 48: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 49: Also at Institute for Nuclear Research, Moscow, Russia
- 50: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 51: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 52: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 53: Also at University of Florida, Gainesville, U.S.A.
- 54: Also at Imperial College, London, United Kingdom
- 55: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
- 56: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 57: Also at California Institute of Technology, Pasadena, U.S.A.
- 58: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 59: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 60: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- 61: Also at INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy, Pavia, Italy
- 62: Also at National and Kapodistrian University of Athens, Athens, Greece
- 63: Also at Universität Zürich, Zurich, Switzerland
- 64: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 65: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 66: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 67: Also at Şirnak University, Sirnak, Turkey
- 68: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
- 69: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 70: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 71: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
- 72: Also at Mersin University, Mersin, Turkey
- 73: Also at Piri Reis University, Istanbul, Turkey
- 74: Also at Adiyaman University, Adiyaman, Turkey
- 75: Also at Ozyegin University, Istanbul, Turkey
- 76: Also at Izmir Institute of Technology, Izmir, Turkey
- 77: Also at Necmettin Erbakan University, Konya, Turkey
- 78: Also at Bozok Universititesi Rektörlüğü, Yozgat, Turkey
- 79: Also at Marmara University, Istanbul, Turkey
- 80: Also at Milli Savunma University, Istanbul, Turkey
- 81: Also at Kafkas University, Kars, Turkey
- 82: Also at Istanbul Bilgi University, Istanbul, Turkey
- 83: Also at Hacettepe University, Ankara, Turkey
- 84: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 85: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 86: Also at IPPP Durham University, Durham, United Kingdom
- 87: Also at Monash University, Faculty of Science, Clayton, Australia
- 88: Also at Bethel University, St. Paul, Minneapolis, U.S.A., St. Paul, U.S.A.
- 89: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

- 90: Also at Bingol University, Bingol, Turkey
- 91: Also at Georgian Technical University, Tbilisi, Georgia
- 92: Also at Sinop University, Sinop, Turkey
- 93: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 94: Also at Erciyes University, KAYSERI, Turkey
- 95: Also at Texas A&M University at Qatar, Doha, Qatar
- 96: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea