Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration

Abstract

A study of proton-proton collisions in which two b hadrons are produced in association with a Z boson is reported. The collisions were recorded at a centre-of-mass energy of 7 TeV with the CMS detector at the LHC, for an integrated luminosity of 5.2 fb$^{-1}$. The b hadrons are identified by means of displaced secondary vertices, without the use of reconstructed jets, permitting the study of b-hadron pair production at small angular separation. Differential cross sections are presented as a function of the angular separation of the b hadrons and the Z boson. In addition, inclusive measurements are presented. For both the inclusive and differential studies, different ranges of Z boson momentum are considered, and each measurement is compared to the predictions from different event generators at leading-order and next-to-leading-order accuracy.

Submitted to the Journal of High Energy Physics
1 Introduction

The measurement of $Z/\gamma^*$ (henceforth denoted by “Z”) production in association with $b$ quarks at the Large Hadron Collider (LHC) is relevant for various experimental searches. In particular, the process constitutes one of the dominant backgrounds to standard model (SM) Higgs boson production associated with a Z boson, where the Higgs boson decays subsequently to a $b\bar{b}$ pair. The discovery by the ATLAS and Compact Muon Solenoid (CMS) experiments of a neutral boson with a mass of about 125 GeV [1, 2] motivates further studies to establish its nature and determine the coupling of the new boson to $b$ quarks. Furthermore, for models featuring an extended Higgs sector, such as two-Higgs-doublet models [3–6], an interesting discovery channel is $\phi_1 \to Z \phi_2$ with the subsequent decay $\phi_2 \to b\bar{b}$, where $\phi_{1,2}$ are neutral Higgs bosons.

Since the mass difference $m_{\phi_1} - m_{\phi_2}$ may be large, the Higgs decay would consist of a pair of collinear $b$ quarks produced in association with a Z boson.

Of particular interest is the measurement of angular correlations of $b$ hadrons, especially at small opening angles, where significant theoretical uncertainties in the description of the collinear production of $b$ quarks remain. Several theoretical predictions, obtained with different techniques and approximations, can be tested. Tree-level calculations allowing for large numbers of extra partons in the matrix elements (as initial- and final-state radiation) are available. These are provided by MadGraph [7, 8], ALPGEN [9], and SHERPA [10], in both the five- and four-flavour approaches, i.e. by considering the five or four lightest quark flavours in the proton parton distribution function (PDF) sets. Next-to-leading-order (NLO) calculations have been performed in both the five-flavour (MCFM) [11] and four-flavour [12, 13] approaches. A fully automated NLO computation matched to a parton shower simulation is implemented by the aMC@NLO event generator [14, 15]. A detailed discussion of $b$-quark production in the different calculation schemes is available in Ref. [16].

From the experimental point of view, the study of $b$-hadron pair production using the standard jet-based $b$-tagging methods [17] suffers from geometrical limitations due to the jet cone size. Hadronic cascades from $b$-quark pairs at small angular separation can merge into a single jet, making this region of phase space difficult to access using jet-based $b$-tagging techniques. To overcome this obstacle, an alternative method is used, consisting of the identification of $b$ hadrons from displaced secondary vertices, which are reconstructed from their charged decay products. This approach is implemented in the inclusive secondary vertex finder (IVF) [18]. The IVF exploits the excellent tracking capabilities of the CMS detector and, being independent of the jet reconstruction, extends the sensitivity to small angular separations and softer $b$-hadron transverse momenta ($p_T$).

Four variables are used to parametrise the angular correlations in the $Zb\bar{b}$ final state: $\Delta R_{BB}$, $\Delta \phi_{BB}$, min$\Delta R_{ZB}$, and $A_{ZBB}$. The angular correlation between the $b$ hadrons is described by two variables, $\Delta R_{BB}$ and $\Delta \phi_{BB}$, the angular separation between the flight directions of the two particles in $(\eta, \phi)$ and in the transverse plane, respectively. The variable $\Delta R_{BB}$ is defined as $\Delta R_{BB} = \sqrt{(\Delta \phi_{BB})^2 + (\Delta \eta_{BB})^2}$, where $\Delta \phi_{BB}$ and $\Delta \eta_{BB}$ are the azimuthal (in radians) and pseudorapidity separations. The pseudorapidity is defined as $\eta = -\ln[tan(\theta/2)]$, where $\theta$ is the polar angle relative to the anticlockwise beam direction. The $\Delta R_{BB}$ distribution constitutes a direct test of the modelling of the different $pp \to Zb\bar{b}X$ production modes. This quantity allows the identification of the contribution from the $q_i \to Zb\bar{b}X$ subprocesses (where $i = q, g$) for which the scattering amplitude modelling is based on Feynman diagrams with $g \to b\bar{b}$ splitting. Leading order diagrams for these subprocesses are shown in Figs. [1](a) and (b), together with diagrams representative of other $pp \to Zb\bar{b}$ production modes: emission of a Z boson from a $b$-quark line (c), and $b$-quark fusion $gg \to Zb\bar{b}$ (d).
Figure 1: Tree-level Feynman diagrams for (a,b) $q_i \rightarrow Z b\bar{b}X$ subprocesses (where $i = q, g$) involving $g \rightarrow b\bar{b}$ splitting; (c) $q\bar{q} \rightarrow Z b\bar{b}$ with the emission of a $Z$ boson from a $b$ quark; and (d) $gg \rightarrow Z b\bar{b}$.

A second variable, the angular separation between the $b$ hadrons in the transverse plane, $\Delta\phi_{BB}$, is also considered because it is a better observable for the back-to-back configuration. Since the relative fraction of quark- and gluon-initiated subprocesses is correlated with the $Z$-boson momentum $p^Z_T$, the differential $\Delta R_{BB}$ and $\Delta\phi_{BB}$ distributions are measured in different intervals of $p^Z_T$.

Two additional angular variables are considered: the angular separation between the $Z$ boson and the closest $b$ hadron in the $(\eta, \phi)$ plane, $\min\Delta R_{ZB}$, and the asymmetry between the $b$-hadron emission directions and the $Z$ production direction, $A_{ZBB}$, defined as

$$A_{ZBB} = \frac{\max\Delta R_{ZB} - \min\Delta R_{ZB}}{\max\Delta R_{ZB} + \min\Delta R_{ZB}},$$

where $\max\Delta R_{ZB}$ is the distance between the $Z$ boson and the further $b$ hadron. Configurations in which the two $b$ hadrons are emitted symmetrically with respect to the $Z$ direction yield a value of $A_{ZBB}$ close to zero. Emission of additional gluon radiation in the final state results in a nonzero value of $A_{ZBB}$. Hence, the $A_{ZBB}$ variable helps to indirectly test the validity of quantum chromodynamics (QCD) at higher orders of the perturbative series. The $\min\Delta R_{ZB}$ variable identifies events with the $Z$ boson in the vicinity of one of the two $b$ hadrons, and is therefore useful for testing NLO corrections involving $Z$ radiation from a quark [19].

The contribution of the $q_i \rightarrow Z b\bar{b}X$ subprocesses to the total production is illustrated in Fig. 2 as a function of each of the four variables described above. The distributions are shown for both the nonboosted (all $p^Z_T$) and the boosted ($p^Z_T > 50$ GeV) regions of the $Z$ transverse momentum. For all the variables, the contribution of the $q_i \rightarrow Z b\bar{b}X$ subprocesses differs from the contribution of $gg \rightarrow Z b\bar{b}X$. The $q_i \rightarrow Z b\bar{b}X$ subprocesses are dominant in the following regions: $\Delta R_{BB} < 1$, $\Delta\phi_{BB} < 0.75$, $\min\Delta R_{ZB} > 3.2$, and $A_{ZBB} < 0.05$.

In this analysis, the differential production cross sections for the process $pp \rightarrow Z b\bar{b}X$ (henceforth the processes are denoted by their final state, here “Zb$b$”) as functions of the four kinematic variables listed above are evaluated from CMS data. These cross sections are given at the hadron level and compared to the predictions provided by several of the Monte Carlo (MC) generators mentioned above. The total cross section is also measured. The results are given for different regions of $p^Z_T$. Because of the limited size of the available data sample, the differential measurements are calculated in the nonboosted and boosted regions. The total cross section is evaluated for $p^Z_T$ larger than 0, 40, 80, and 120 GeV. $Z$ bosons are reconstructed in the $e^+e^-$ and $\mu^+\mu^-$ decay modes. The analysis exploits the full 2011 data set recorded at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of $(5.2 \pm 0.1)$ fb$^{-1}$. Measurements of the $Z$-boson production cross section in association with one or two $b$-tagged jets at the LHC have been reported previously by the ATLAS and CMS Collaborations [20, 21].
Figure 2: Distribution of $\Delta R_{BB}$ (first row), $\Delta \phi_{BB}$ (second row), $\text{min}\Delta R_{ZB}$ (third row), and $A_{ZBB}$ (fourth row) as predicted by MADGRAPH in the four-flavour scheme, in the nonboosted (left) and boosted (right) regions of the $Z$' transverse momentum. The component from $gg \rightarrow Zb\bar{b}X$ is represented by the hatched histogram, while the contribution from $q_i \rightarrow Zb\bar{b}X$ subprocesses (where $i = q, g$) is represented by the shaded histogram. The unshaded histogram corresponds to the sum of the two components.
The paper is organised as follows: the description of the CMS experiment and simulated samples are given in Section 2; the event reconstruction and selection are presented in Section 3; the measurement technique is explained in Section 4; the systematic uncertainties are discussed in Section 5; the theoretical uncertainties associated with different models of $Zb\bar{b}$ production are summarized in Section 6; the results and conclusions are presented in Sections 7 and 8, respectively.

2 CMS detector and simulated samples

A detailed description of the CMS experiment can be found in Ref. [22]. The main subdetectors used in this analysis are the silicon tracker, the electromagnetic calorimeter (ECAL), and the muon system. The tracker consists of silicon pixel and strip detector modules and is immersed in a 3.8T magnetic field, which enables the measurement of charged particle momenta over the pseudorapidity range $|\eta| < 2.5$. The electromagnetic calorimeter consists of nearly 76000 lead tungstate crystals, which provide coverage for $|\eta| \leq 1.48$ in a cylindrical barrel region and $1.48 < |\eta| < 3.0$ in two endcap regions, except for an insensitive gap in the region $1.44 < |\eta| < 1.566$ between the ECAL barrel and endcap. Muons are identified in the range $|\eta| < 2.4$ by gas-ionisation detectors embedded in the steel return yoke. The first level of the CMS trigger system consists of custom hardware processors and uses information from the calorimeters and muon system to select the most interesting events in less than 1 $\mu$s. The high level trigger processor farm further decreases the event rate to less than 300 Hz before data storage.

Samples of signal and background events are produced using various event generators to estimate the signal purity, efficiency, and detector acceptance, with the CMS detector response modelled in extensive detail with GEANT4 [23].

The $Zb\bar{b}$ signal sample is produced with the MadGraph 1.4.8 generator in the four-flavour approach. No $b$ quarks are present in the initial state, while up to two additional light partons are produced in association with the $Z$ boson and the two $b$ quarks. The PDF set is CTEQ6L1 and the simulation of parton shower, hadronisation, and multiparton interactions is done with Pythia 6.4.2.4 [24]. The background samples are $Z$ plus jets, where the additional jets are from light quarks or gluons ($u, d, c, s, g$), top pair production (tt), and Z pair production. The $Z +$ jets sample is extracted from a Drell–Yan inclusive sample produced with MadGraph in the five-flavour approach and interfaced with Pythia. The tt sample is also produced with the MadGraph generator interfaced with Pythia, while the diboson ZZ sample is generated with Pythia. The tune considered in Pythia is Z2*, which is the Z1 tune [25] with the PDF set changed to CTEQ6L1 and minor modifications of the underlying event modelling, namely $\text{PARP}(90) = 0.227$ and $\text{PARP}(82) = 1.921$.

Additional interactions per bunch crossing (pileup) are included in the simulation with the distribution of pileup interactions matching that observed in data.

3 Event reconstruction and selection

The first step of the analysis is the online event selection with the loosest available dimuon and dielectron triggers in order to enrich the sample with $Z \rightarrow \mu^+\mu^-$ and $e^+e^-$ decays. The dielectron trigger line requires loose electron identification and isolation and imposes 17 and 8 GeV transverse momentum thresholds on the two electron candidates, respectively. The transverse momentum thresholds of the muon trigger line, which changed with time to cope with increasing instantaneous luminosity, were initially 7 GeV on both muon candidates, then 13 or 17 GeV
on one candidate and 8 GeV on the other.

Muon candidates are then required to pass tight selection requirements to ensure high purity [26]. Electron candidates are reconstructed from energy deposits in the ECAL, and must satisfy the standard CMS electron identification criteria [27]. Leptons are required to have $p_T > 20$ GeV, and to be within the pseudorapidity range $|\eta| < 2.4$. Prompt leptons are selected by requiring a distance of closest approach between the track and the primary pp interaction (identified as the vertex with the largest quadratic sum of its constituent tracks’ $p_T$) smaller than 200 $\mu$m. A requirement is applied on the lepton isolation, computed using the particle-flow technique [28], which exploits the information from all subdetectors to individually identify the particles produced in the collisions. The isolation, defined as the ratio between the scalar sum of the transverse momentum or transverse energy ($E_T$) of the particles within a $\Delta R < 0.4$ (0.3) cone around the muon (electron) and its transverse momentum, $(\sum_{\text{charged had.}} p_T + \sum_{\text{neutral had.}} E_T + \sum_{\text{photon}} E_T) / p_T$, must be at most 0.15. In order to ensure that the selection is stable regarding the large and varying number of primary interactions, the charged particle-flow candidates are required to be associated with the selected primary vertex (PV). In addition, a correction is applied to subtract the energy contribution of neutral hadrons and photons produced in pileup interactions. This correction is estimated event by event from the median of the energy density distribution and applied within the isolation cone [29].

Only events with two oppositely charged same-flavour lepton candidates with invariant mass between 60 and 150 GeV are selected. The signal region is then defined as the $81 < M_{\ell\ell} < 101$ GeV interval to reduce the contamination from $t\bar{t}$ events.

Events containing $b$ hadrons are selected by applying the inclusive vertex finder technique. The secondary vertex (SV) reconstruction on which the IVF is based is initiated by the identification of a set of “seed” tracks that are significantly displaced with respect to the primary vertex. Such tracks are selected by requiring their three-dimensional impact parameter to be larger than 50 $\mu$m, and their impact parameter (IP) significance $S_{IP} = IP / \sigma_{IP}$ larger than 1.2, where $\sigma_{IP}$ is defined from the uncertainties on both the PV position and the point of closest approach between the track and the PV. Additional tracks are clustered together with the seed tracks if they fulfill several requirements. First, the distance of closest approach of a track to the seed must not exceed 500 $\mu$m, and its significance must be smaller than 4.5. Second, the angle between the vector defined by the PV and the point of closest approach on the seed track and the seed track direction at the vertex has to be smaller than 45$^\circ$ so only forward tracks from $b$-hadron decays are retained. Secondary vertices are built from the seeds and clustered tracks [30].

The SV four-momentum is calculated as $p_{SV} = \sum p_i$ where the sum is over all tracks associated with that vertex. The pion mass hypothesis is used for every track to obtain its energy $E_i$. The vertex mass $m_{SV}$ is given by $m_{SV}^2 = E_{SV}^2 - p_{SV}^2$.

The IVF technique establishes a list of $b$-hadron (B) candidates from the reconstructed SVs. If two SVs are present, they can potentially be the signature of a $b \to cX$ decay chain and are merged into a single B candidate if the following conditions are fulfilled: i) $\Delta R(SV_1, SV_2) < 0.4$, ii) the sum of the invariant masses of track candidates associated with the vertices is smaller than 5.5 GeV, and iii) $\cos \delta > 0.99$, where $\delta$ is the angle between the vector from the position of the SV that is closer to the PV to the position of the other SV and the three-momentum of the vertex with larger decay length. The flight distance significance of a B candidate is calculated from the distance between the PV and SV divided by its uncertainty. More details of the SV and B candidate reconstruction can be found in Ref. [18].
Figure 3: Fit results for the dimuon (left) and dielectron (right) invariant mass distributions for events with two leptons and two B candidates selected as described in Section 3. The dashed line shows the fitted background component and the solid line the sum of the fitted signal and background components, which are described in the text. The vertical dashed lines indicate the boundaries of the signal region. The points with errors represent the data.

The flight distance $L$ is defined as the length of the three-dimensional vector connecting the primary and secondary vertices. Its significance $S_L$ is obtained by dividing $L$ by its uncertainty, calculated as quadratic sum of the PV and SV position uncertainties. A b hadron candidate is retained if $S_L > 5$, $|\eta| < 2$, $p_T > 8$ GeV, and invariant mass $m > 1.4$ GeV. The B candidate mass and flight distance significance cuts, along with the requirement of at least three tracks associated with the secondary vertex, are the most effective requirements for rejecting background events from $Z\tau\tau$ production.

Events that have exactly two B candidates are retained. The resulting dimuon and dielectron invariant masses are shown between 60 and 150 GeV in Fig. 3. In total, 330 (223) events pass all the selection requirements in the muon (electron) channel in the $81 < M_{\ell\ell} < 101$ GeV signal mass region. Thanks to the excellent performance of the CMS tracking system, the IVF angular resolution is approximately 0.02 for $\Delta R_{BB}$ and $\Delta \phi_{BB}$ and 0.03 for $\min \Delta R_{ZB}$ and $A_{ZBB}$.

The main source of background contamination in the final sample is top-quark pair production. The $t\bar{t}$ fraction is assessed from an unbinned maximum-likelihood fit to the measured dilepton invariant mass distribution as described in Section 4. The fit yields a $t\bar{t}$ contamination of approximately 30% in the inclusive event sample, and of about 23% for $p_T > 50$ GeV.

The measured and simulated distributions of the most significant event properties are compared at the detector level, as shown in Fig. 4. The measured distributions of mass and transverse momentum of the leading B candidate, i.e. that with the largest $p_T$, as well as $p_T^Z$, agree with MC predictions within uncertainties.

4 Cross section measurement

The differential and total cross sections are obtained by subtracting the background and correcting for detector acceptance, signal efficiency, and purity. The correction factors refer to the kinematic phase space for events with exactly two b hadrons and a lepton pair from a Z decay. The b hadrons have $p_T > 15$ GeV and pseudorapidity $|\eta| < 2$. Each lepton has $p_T > 20$ GeV, $|\eta| < 2.4$, and the dilepton invariant mass is $81 < M_{\ell\ell} < 101$ GeV. The differential cross sections are measured for $p_T^Z > 0$ GeV and $p_T^Z > 50$ GeV. In the former case, the bin sizes are 0.7, 0.53, 0.84, and 0.2 for $\Delta R_{BB}$, $\Delta \phi_{BB}$, $\min \Delta R_{ZB}$, and $A_{ZBB}$, respectively. In the latter, the corre-
The resulting yield is corrected for the b-hadron pair identification efficiency $\epsilon_{a,j}$, the b-hadron purity $\mathcal{P}_{a,j}$, and the integrated luminosity $\mathcal{L}$. The factor $\sigma^{\text{SB}}_{a,j}$ corrects for events with b hadrons with $p_T < 15$ GeV.

Figure 4: Distribution of the leading B candidate invariant mass (left), transverse momentum (centre), and $p_T^Z$ (right) for the muon and electron channels combined, in the signal region ($81 < M_{\ell\ell} < 101$ GeV). The CMS data are represented by solid points and the MC simulation by stacked histograms. The shaded region represents the statistical uncertainty in the MC prediction. The fraction of signal and top background in the simulation is extracted by means of fitting functions.

The two channels are combined into a single measurement $\mathcal{F}(n^\mu_{a,j}, n^e_{a,j})$ using the BLUE algorithm [31, 32], which performs a weighted average of the input values taking into account the respective uncertainties and their correlations.

The hadron-level differential cross section is calculated from

$$
\sigma_{a,j} = \mathcal{F}(n^\mu_{a,j}, n^e_{a,j}) \cdot \frac{S^B_{a,j}}{\epsilon^{2B}_{a,j}} \cdot \mathcal{P}_{a,j} \cdot \frac{1}{\mathcal{L}},
$$

where

$$
n_{a,j}^\ell = \frac{N_{a,j}^\ell}{\epsilon_{a,j}^\ell \cdot A_{a,j}^\ell},
$$

with $\ell = e, \mu$. For each bin $j$ of the angular variable $a$, indicating one of the four variables defined in Section 1, the number of signal events $N_{a,j}^\ell$ is extracted from an extended unbinned maximum-likelihood fit to the lepton pair invariant mass distribution. A Breit–Wigner distribution convolved with a Gaussian resolution function is used for the signal and a third-degree Chebychev polynomial distribution for the background, as shown in Fig. 3. The signal shape parameters are evaluated from data while the background parameters are obtained from simulation. $N_{a,j}^\ell$ is corrected for the dilepton reconstruction and selection efficiency $\epsilon_{a,j}^\ell$ and acceptance $A_{a,j}^\ell$. The corrected yields $n_{a,j}^\ell$ in the muon and electron channels are found to be in agreement, within statistical uncertainties.

The corresponding values are 0.84, 0.63, 1.0, and 0.25. Since the IVF angular resolution is significantly smaller than the bin size for all the measured distributions, no unfolding procedure is applied to measure the hadron-level differential cross sections.
The dilepton trigger efficiency is estimated from data with a tag-and-probe method, as a function of the lepton kinematics. It is approximately 93% for the dimuon and 98% for the dielectron trigger selections. The lepton offline reconstruction and selection efficiencies, around 80% for muon and 50% for electron pairs, are obtained from simulation and are rescaled to match the values measured in data with a tag-and-probe procedure, as a function of the lepton pseudorapidity.

The total b-hadron identification efficiency is estimated using multijet events containing semileptonic decays of b-hadrons and from events enriched with top quarks. In addition, a dedicated study is performed to verify that the efficiency measurements are valid for the inclusive vertex finding algorithm as well.

The efficiency for identifying b-hadron pairs, which ranges between 8% and 10%, is corrected by applying a factor of 0.88 to account for the discrepancy observed between the measured and simulated efficiency. This scale factor is measured from data, in the same way as it is done for the Simple Secondary Vertex method that identifies b hadrons inside jets [17]. This study requires the association of the vertices reconstructed with the IVF with jets and exploits the features of muons produced in semileptonic decays of the b hadrons, namely their high transverse momenta with respect to the jet axis. The purity $P_{b,j}$ and correction factor $S_{b,j}^B$ are evaluated to be about 85% and 97%, respectively, based on MC simulation.

The same method is used to derive the total cross section for different ranges of $p_T$. The extended maximum-likelihood fit and the procedure to extract the correction factors are applied to the corresponding event sample.

5 Systematic uncertainties

The following uncertainties on the differential cross sections are considered:

- **Uncertainty in combined dilepton signal**
  The procedure to combine the muon and electron channels takes into account the systematic uncertainties on the $N_{\alpha,j}^\ell$ yields and on the dilepton efficiency correction factors. The systematic uncertainty affecting the resulting combination is estimated by the BLUE algorithm, and is approximately ±2%. More details are given below.
    - **Uncertainty in the signal yield**
      The systematic uncertainty associated with the extraction of $N_{\alpha,j}^\ell$ from the extended unbinned maximum-likelihood fit is estimated by varying the shape parameters within their uncertainties. For the signal, the shape parameters are the Breit–Wigner mean and width, as well as the Gaussian standard deviation. For the background, the parameters of the Chebychev polynomial distribution are considered. A variation of these factors leads to a signal yield uncertainty below ±2%.
    - **Uncertainty in the trigger efficiency and the lepton efficiency scale factors**
      The lepton reconstruction and selection efficiency corrections are computed with the MC simulation, and rescaled to match the efficiency values measured from data with the tag-and-probe method. The corresponding systematic uncertainty is estimated by varying the scale factors and the trigger efficiency extracted from data within their systematic uncertainties, mostly due to the background shape parametrisation. The resulting variation is ±0.5% for the muon channel and ±1% for the electron channel.
- **Uncertainty in the efficiency scale factor**
  The scale factors between the b-hadron pair identification efficiency in data and simulation are determined as a function of the jet transverse momentum. The maximal deviation of the measured values from a constant leads to a ±12% systematic uncertainty assigned to the cross section.

- **Uncertainty in the purity correction factor**
  The purity correction factor accounts for the contamination from events with at least one reconstructed B candidate produced by a charm hadron decay or, more rarely, by a light jet. Three categories contribute to such impurity: Zb\bar{b} events with a charm hadron from a sequential c decay reconstructed as b hadron, Zc\bar{c} events, and Zb\bar{b}c events. The uncertainty in the purity originates essentially from the Zb\bar{b}c and Zc\bar{c} processes, where there is no measurement related to the production of one or two charm quarks produced in association with a Z boson. We therefore provide a conservative estimate of such uncertainty by varying the Zb\bar{b}c and Zc\bar{c} fractions by 50% in the simulation. The resulting uncertainty in $P_{α,j}$ is ±2.1%.

- **Bin-to-bin migrations**
  Possible migrations of events from one bin to the adjacent ones are accounted for as a source of systematic uncertainty. The effect varies between ±1–2% for $ΔR_{BB}$ and $\text{min}ΔR_{ZB}$, and ±3–4% for the $Δφ_{BB}$ and $A_{ZBB}$ variables. Such uncertainty does not affect the total cross section measurement.

- **Uncertainty in the luminosity**
  The luminosity $L$ is known with a systematic uncertainty of ±2.2% [33].

- **MC statistical uncertainty**
  The uncertainties on the efficiency and purity corrections are dominated by the limited size of the four-flavour Zb\bar{b} MADGRAPH sample. The effect is evaluated in each bin for the differential measurements, and globally for the total cross section determination, and is taken as an additional source of uncertainty that varies between ±2% and ±3.7%.

The systematic uncertainties are summarised in Table 1 for the differential cross sections and the total cross section measurements.

Table 1: Summary of systematic uncertainties assigned to the differential and total cross section measurements. The systematic uncertainties in $N_{α,j}$ and in the dilepton efficiency are used in the combination of the muon and electron channels, and are reported in the text.

| Source                              | Uncertainty (%) |
|-------------------------------------|-----------------|
| Dilepton channel combination        | 2               |
| IVF efficiency scale factors        | 12              |
| B purity                            | 2.1             |
| Bin-to-bin migrations ($ΔR_{BB}$, $\text{min}ΔR_{ZB}$) | 1–2            |
| Bin-to-bin migrations ($Δφ_{BB}$, $A_{ZBB}$) | 3–4            |
| MC statistics — Differential        | 2.0–3.7         |
| MC statistics — Total               | 1.0–3.5         |
| Integrated luminosity               | 2.2             |
Table 2: Summary of the central scale functional forms used in the different theoretical predictions for the factorisation ($\mu_F^2$) and renormalisation ($\mu_R^2$) scales. The label jets can be (u, d, s, c, b, g) for the MG5F production, while it is (u, d, c, s, g) for the MG4F one, for which the label b is mentioned explicitly to denote the b quark. $m_T$ denotes the transverse mass.

|        | $\mu_F^2$                                                                 | $\mu_R^2$                                                                 |
|--------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| MG5F   | $m_Z^2 + p_T^2$ (jets)                                                    | $k_T^2$ at each vertex splitting                                          |
| MG4F   | $m_{T,Z} \cdot m_T$ (b, b)                                                | $k_T^2$ at each vertex splitting (excl. b)                                |
| ALPGEN  | $m_Z^2 + \Sigma_{jets} (m_{jets}^2 + p_{T,jets}^2)$                       | $k_T^2$ at each vertex splitting (excl. b)                                |
| aMC@NLO | $m_{T\ell\ell'}^2 + p_{T\ell\ell'}^2 (\ell\ell') + \frac{m_b^2 + p_T^2 (b)}{2} + \frac{m_b'^2 + p_T^2 (b')}{2}$ | $\mu_F^2$                                                                  |

6 Theoretical predictions and uncertainties

The measured cross sections are compared at hadron level to the predictions by the MADGRAPH MC, in both the five- (MG5F) and four-flavour (MG4F) approaches, and by the ALPGEN generator in the four-flavour approach.

The MG5F prediction is based on a matrix-element calculation where up to four partons are produced in association with the Z boson, the b quarks are assumed massless, the proton PDF set is CTEQ6L1, and the jet matching is performed using the standard $k_T$-MLM scheme at a matching scale $Q_{\text{match}} = 20$ GeV \[34\]. Events with b-hadron pairs from a second partonic scattering are included.

The MG4F prediction considers massive b quarks in the matrix-element calculation with the mass set to $m_b = 4.7$ GeV. In the matrix element two additional light partons are produced in association with the Zb\bar{b} final state. The jet matching scheme is also the $k_T$-MLM with $Q_{\text{match}} = 30$ GeV.

The ALPGEN prediction adopts the four-flavour calculation scheme, with the MLM jet matching and CTEQ5L PDF set. The matching parameters are $\Delta R_{\text{match}}^{\text{parton-jet}} = 0.7$ and $p_T^{\text{match}} = 20$ GeV. In addition to the tree-level predictions mentioned above, the measurements are compared to the NLO expectations by aMC@NLO, which implements the four-flavour scheme with the MSTW2008 NLO PDF set.

The parton shower and hadronisation of all tree-level samples is obtained with PYTHIA, with $p_T$-ordered showers, while aMC@NLO is interfaced with HERWIG. The choices of factorisation and renormalisation scales are summarised in Table 2.

The MG5F prediction is rescaled by a $k$-factor of 1.23, corresponding to the ratio between the next-to-next-to-leading-order (NNLO) prediction of the inclusive Z production cross section, and the tree-level cross section from MADGRAPH. The tree-level cross section prediction for MG4F (ALPGEN) is rescaled by a $k$-factor obtained from the aMC@NLO cross section of 16 pb obtained for $M_{\ell\ell} > 30$ GeV divided by the corresponding MG4F (ALPGEN) prediction.

The following uncertainties on the theoretical predictions are considered and combined quadratically:

- The shape uncertainties associated with the b-quark mass, $m_b$, for the MADGRAPH 4F prediction are assessed by varying $m_b$ between 4.4 and 5.0 GeV. Each distribution is rescaled so that the normalisation matches the NLO cross section provided by aMC@NLO and the envelope is considered as the uncertainty band.
- The shape uncertainties due to the factorisation and renormalisation scales are as-
sessed for the MadGraph 4F and 5F predictions by varying their values simultaneously by a factor of two. The MadGraph 4F (5F) distributions are rescaled so that the normalisation matches the NLO (NNLO) cross section provided by aMC@NLO (FEWZ [35]) and the envelopes are considered as uncertainty bands.

- The uncertainties associated with the matching scale are assessed by varying it by ±15% for MadGraph 4F and by a factor of two for the 5F case.
- The shape uncertainties associated with the choice of PDF set are found to be negligible. The effect of PDF variations are included as normalisation uncertainties as described in the next item.
- For MadGraph 4F and Alpgen predictions the normalisation uncertainty is given by the corresponding aMC@NLO cross section uncertainty. The latter is obtained by varying the factorisation and renormalisation scales simultaneously by a factor of two, and by replacing the MSTW2008 PDF set with CT10. For MadGraph 5F the normalisation uncertainty is given by the corresponding NNLO cross section uncertainty [35].
- For aMC@NLO the uncertainty associated with the parton shower is assessed from the difference between Pythia (D6T tune) with virtuality-ordered showers and Herwig.
- The statistical uncertainty due to the finite size of the simulated sample is propagated for all theoretical predictions.

7 Results

The measured differential cross sections as a function of the three angular variables and the angular asymmetry variable are shown in Figs. 5 and 6 for all $p_T^Z$ and for $p_T^Z > 50$ GeV, respectively. Figure 5 shows that the $\Delta R_{BB}$ collinear region is better described by Alpgen, while the four- and five-flavour MadGraph as well as aMC@NLO predictions tend to underestimate the data. At large $\Delta R_{BB}$, all predictions are in good agreement with the data. The fraction of the cross section with collinear b hadrons increases for $p_T^Z > 50$ GeV and in this case Alpgen also gives the best description of the measured distributions.

Similar conclusions can be drawn from the $\Delta \phi_{BB}$ distribution. In the nonboosted case, data are above all MC predictions in the region of back-to-back b-hadron pairs by approximately one standard deviation. This discrepancy vanishes for $p_T^Z > 50$ GeV. The simulated min$\Delta R_{ZB}$ and $A_{ZBB}$ generally agree with the data. Some discrepancy is observed at min$\Delta R_{ZB} > 2$ in both ranges of $p_T^Z$, and at low $A_{ZBB}$. The data are found to be above the predictions primarily in the regions where the contributions from the $q_i \to Zb\bar{b}X$ subprocesses are expected to be dominant, as shown in Fig. 5.

The total hadron-level cross section is shown in Fig. 7 for four different regions of $p_T^Z$: for the inclusive spectrum, and for $p_T^Z > 40, 80, \text{ and } 120$ GeV. Data points are generally above all simulations by about 15%, apart from aMC@NLO for which the discrepancy can be as large as 50%. The shapes of the distributions predicted by MadGraph and Alpgen in the four-flavour approach agree with the data, while a discrepancy is observed in the comparison with MadGraph 5F and aMC@NLO, especially at large $p_T^Z$. 
8 Conclusions

The first measurement of angular correlations in the process $pp \rightarrow Zb\bar{b}X$ has been performed. The analysed data set corresponds to an integrated luminosity of $5.1 \text{ fb}^{-1}$ recorded by the CMS experiment in 2011 at a centre-of-mass energy of 7 TeV. $Z$ bosons are reconstructed in the $e^+e^-$ and $\mu^+\mu^-$ decay modes. The use of the inclusive vertex finder, which exploits the excellent CMS tracking performance, allows the full angular range to be probed, including configurations with collinear $b$ hadrons.
Figure 6: Differential cross sections for $p_T^Z > 50$ GeV, as a function of $\Delta R_{BB}$ (top left), $\Delta \phi_{BB}$ (top right), $\text{min} \Delta R_{ZB}$ (bottom left), and $A_{ZBB}$ (bottom right). The measured values are shown as black points. The dotted bands correspond to the quadratic sum of statistical and systematic uncertainties. Statistical uncertainties are shown separately as solid bands. The measurements are compared to the hadron-level predictions by MADGRAPH in the four- and five-flavour schemes, ALPGEN, and aMC@NLO. For each distribution the ratio between the Monte Carlo predictions and the measurements is also shown, with the total experimental uncertainty indicated by the dotted area.

The production cross sections are measured as functions of four angular variables: $\Delta R_{BB}$, $\Delta \phi_{BB}$, $\text{min} \Delta R_{ZB}$, and $A_{ZBB}$. The measurements are compared with tree-level predictions by the MADGRAPH and ALPGEN MC generators implementing different flavour number schemes. The variables most sensitive to the b-hadron production process, $\Delta R_{BB}$ and $\Delta \phi_{BB}$, show that the four-flavour prediction implemented in ALPGEN provides the best description of CMS data.

The MG5F MC generator has been one of the standard tools used to simulate backgrounds from associated production of vector bosons and heavy quarks for Higgs boson and new physics
searches as well as SM studies. The results reported here indicate that such a description may not be optimal for analyses sensitive to the production of collinear $b$ hadrons. This fact may be particularly important in the simulation of the $Wb\bar{b}$ process, where collinear $b$-hadron production is expected to be enhanced compared to the $Zb\bar{b}$ process.

This is the first time that aMC@NLO predictions, in which QCD contributions are computed to NLO, have been compared with data for the $Zb\bar{b}$ process. It is found that aMC@NLO underestimates the cross section at low $\Delta R_{BB}$ and $\Delta \phi_{BB}$, and at large $\text{min} \Delta R_{ZB}$. A comprehensive assessment of the aMC@NLO predictions requires further studies of the scale choices and parton shower modelling. It is worth noting that the use of NLO jet matching would also improve the precision of the prediction at small values of $\Delta R_{BB}$.

The total hadron-level cross section $\sigma_{\text{tot}} = \sigma(pp \rightarrow Zb\bar{b}X)B(Z \rightarrow \ell^+\ell^-)$ is also evaluated in different ranges of the $Z$ boson transverse momentum. For the case where no cut is applied on the $Z$ momentum, the total cross section is $\sigma_{\text{tot}} = 0.71 \pm 0.08$ pb; for $p_{T}^Z > 40$ GeV, $\sigma_{\text{tot}} = 0.44 \pm 0.05$ pb; for $p_{T}^Z > 80$ GeV, $\sigma_{\text{tot}} = 0.17 \pm 0.02$ pb; and for $p_{T}^Z > 120$ GeV, $\sigma_{\text{tot}} = 0.07 \pm 0.01$ pb. The measured values are systematically larger than MC predictions, partly because of the excess observed in the collinear $\Delta R_{BB}$ region. The shape of the measured integrated cross section as a function of the minimum transverse momentum of the $Z$ boson is in good agreement with the tree-level MG4F predictions, while slightly larger discrepancies are observed for MG5F and even more for aMC@NLO, particularly at large $p_{T}^Z$.

**Acknowledgements**

We thank Marco Zaro for his dedication in simulating aMC@NLO samples for this analysis.
We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science and Research and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education, Youth and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Recurrent financing contract SF0690030s09 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l’Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Office for Research and Technology, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Republic of Korea; the Lithuanian Academy of Sciences; the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Science and Innovation, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNSF, UniZH, Canton Zurich, and SER); the National Science Council, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (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 Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); the HOMING PLUS programme of Foundation for Polish Science, cofinanced by EU, Regional Development Fund; and the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF.
References

[1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. B 716 (2012) 1, doi:10.1016/j.physletb.2012.08.020

[2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. B 716 (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235

[3] J.-M. Gérard and M. Herquet, “Twisted Custodial Symmetry in Two-Higgs-Doublet Models”, Phys. Rev. Lett. 98 (2007) 251802, doi:10.1103/PhysRevLett.98.251802, arXiv:hep-ph/0703051.

[4] S. de Visscher et al., “Unconventional phenomenology of a minimal two-Higgs-doublet model”, JHEP 08 (2009) 042, doi:10.1088/1126-6708/2009/08/042, arXiv:0904.0705

[5] R. Dermisek, “Light CP-odd Higgs and Small tan beta Scenario in the MSSM and Beyond” (2008), arXiv:0806.0847

[6] R. Dermisek and J. F. Gunion, “Many light Higgs bosons in the next-to-minimal supersymmetric model”, Phys. Rev. D 79 (2009) 055014, doi:10.1103/PhysRevD.79.055014, arXiv:0811.3537

[7] J. Alwall et al., “MadGraph/MadEvent v4: the new web generation”, JHEP 09 (2007) 028, doi:10.1088/1126-6708/2007/09/028, arXiv:0706.2334

[8] J. Alwall et al., “MadGraph 5: going beyond”, JHEP 06 (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522

[9] M. L. Mangano et al., “ALPGEN, a generator for hard multiparton processes in hadronic collisions”, JHEP 07 (2003) 001, doi:10.1088/1126-6708/2003/07/001, arXiv:hep-ph/0206293

[10] T. Gleisberg et al., “Event generation with SHERPA 1.1”, JHEP 02 (2009) 007, doi:10.1088/1126-6708/2009/02/007, arXiv:0811.4622

[11] J. M. Campbell and R. K. Ellis, “Radiative corrections to Zb#bar{b} production”, Phys. Rev. D 62 (2000) 114012, doi:10.1103/PhysRevD.62.114012, arXiv:hep-ph/0006304

[12] F. Febres Cordero, L. Reina, and D. Wackeroth, “NLO QCD corrections to Zb#bar{b} production with massive bottom quarks at the Fermilab Tevatron”, Phys. Rev. D 78 (2008) 074014, doi:10.1103/PhysRevD.78.074014, arXiv:0806.0808

[13] F. Febres Cordero, L. Reina, and D. Wackeroth, “W- and Z-boson production with a massive bottom-quark pair at the Large Hadron Collider”, Phys. Rev. D 80 (2009) 034015, doi:10.1103/PhysRevD.80.034015, arXiv:0906.1923

[14] R. Frederix et al., “W and Z/γ* boson production in association with a bottom-antibottom pair”, JHEP 09 (2011) 061, doi:10.1007/JHEP09(2011)061, arXiv:1106.6019

[15] S. Frixione and B. R. Webber, “Matching NLO QCD computations and parton shower simulations”, JHEP 06 (2002) 029, doi:10.1088/1126-6708/2002/06/029, arXiv:hep-ph/0204244.
[16] F. Maltoni, G. Ridolfi, and M. Ubiali, “b-initiated processes at the LHC: a reappraisal”, *JHEP* **07** (2012) 022, doi:10.1007/JHEP04(2013)095, arXiv:1203.6393

[17] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462

[18] CMS Collaboration, “Measurement of B\bar{B} angular correlations based on secondary vertex reconstruction at $\sqrt{s} = 7$ TeV”, *JHEP* **03** (2011) 136, doi:10.1007/JHEP03(2011)136, arXiv:1102.3194

[19] M. Rubin, G. P. Salam, and S. Sapeta, “Giant QCD K-factors beyond NLO”, *JHEP* **09** (2010) 084, doi:10.1007/JHEP09(2010)084, arXiv:1006.2144

[20] ATLAS Collaboration, “Measurement of the cross-section for $b$–jets produced in association with a Z boson at $\sqrt{s} = 7$ TeV with the ATLAS detector”, *Phys. Lett. B* **706** (2012) 295, doi:10.1016/j.physletb.2011.11.059, arXiv:1109.1403

[21] CMS Collaboration, “Measurement of the $Z/\gamma^*+b$-jet cross section in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **06** (2012) 126, doi:10.1007/JHEP06(2012)126, arXiv:1204.1643

[22] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

[23] GEANT4 Collaboration, “GEANT 4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8

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

[25] R. Field, “Early LHC Underlying Event Data - Findings and Surprises”, (2010).

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

[27] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466

[28] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_T^{miss}$”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, (2009).

[29] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378

[30] W. Waltenberger, R. Frühwirth, and P. Vanlaer, “Adaptive vertex fitting”, *J. Phys. G* **34** (2007) N343, doi:10.1088/0954-3899/34/12/N01

[31] L. Lyons, D. Gibaut, and P. Clifford, “How to combine correlated estimates of a single physical quantity”, *Nucl. Instrum. Meth. A* **270** (1988) 110, doi:10.1016/0168-9002(88)90018-6

[32] A. Valassi, “Combining correlated measurements of several different physical quantities”, *Nucl. Instrum. Meth. A* **500** (2003) 391, doi:10.1016/S0168-9002(03)00329-2
[33] CMS Collaboration, “Absolute Calibration of the Luminosity Measurement at CMS: Winter 2012 Update”, CMS Physics Analysis Summary CMS-PAS-SMP-12-008, (2012).

[34] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, Eur. Phys. J. C 53 (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569

[35] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, “FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order”, Comput. Phys. Commun. 182 (2011) 2388, doi:10.1016/j.cpc.2011.06.008, arXiv:1011.3540
A The CMS Collaboration

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

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, V. Knünz, M. Krämer, D. Liko, I. Mikulec, D. Rabady, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz

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

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

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

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

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco, J. Hollar, A. Pin, K. Piotrzkowski, A. Popov, M. Selvaggi, J.M. Vizan Garcia

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

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

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

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
C.A. Bernardes, F.A. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores, C. Lagana, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev, P. Iaydjiev, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

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

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

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

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

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

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

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

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

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

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

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

Helsinki Institute of Physics, Helsinki, Finland
J. Harkonen, V. Karimaki, R. Kinnunen, M.J. Kortelainen, T. Lampen, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Maenpaa, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuominen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluji, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaier,
P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

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

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

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

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

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

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

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

University of Hamburg, Hamburg, Germany
V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine,
The CMS Collaboration

R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, D. Troendle, L. Vanelderen

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

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

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

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

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Béni, S. Czellar, J. Molnár, J. Palinkás, Z. Szillasi

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

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

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

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

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A.P. Singh

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, R.M. Chatterjee, S. Ganguly, S. Ghosh, M. Guha, A. Gurth, G. Kole,
S. Kumar, M. Maity, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

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

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, H. Resari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland

M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy

M. Abbrescia, L. Barbone, C. Calabria, S.S. Chhibra, A. Colaleo, D. Creanza, N. De Filippis, M. De Palma, L. Fiore, G. Iselli, G. Maggi, M. Maggi, B. Marangelli, S. My, N. Pacifico, A. Pompili, G. Pugliese, G. Selvaggi, L. Silvestris, G. Singh, R. Venditti, P. Verwilligen, G. Zito

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy

G. Abbiendi, A.C. Benvenuti, D. Bonacorsi, S. Braibant-Giacomelli, L. Brigliadori, R. Campanini, P. Capiluppi, A. Castorina, F.R. Cavallo, M. Cuffiani, G.M. Dallavalle, F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, A. Meneghelli, A. Montanari, F.L. Navarria, F. Odorici, A. Perrotta, F. Primavera, A.M. Rossi, S. Tosi, R. Travaglini

INFN Sezione di Catania, Università di Catania, Catania, Italy

S. Albergo, M. Chiorboli, S. Costa, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy

G. Barbaglini, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, S. Frosali, E. Gallo, S. Gonzi, V. Gorini, P. Lenzini, M. Meschini, S. Paolotti, G. Sguazzoni, A. Tropiano

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

INFN Sezione di Genova, Università di Genova, Genova, Italy

P. Fabbricatore, R. Musenich, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy

A. Benaglia, F. De Guio, L. Di Matteo, S. Fiorendi, S. Gennai, A. Ghezzi, P. Govoni, M.T. Lucchini, S. Malvezzi, R.A. Manzoni, A. Martelli, D. Menasce, L. Moroni, M. Paganoni, D. Pedrini, S. Ragazzi, N. Redaelli, T. Tabarelli de Fatis

INFN Sezione di Napoli, Università di Napoli Federico II, Università della Basilicata (Potenza), Università G. Marconi (Roma), Napoli, Italy

S. Buontempo, N. Cavallo, A. De Cosa, F. Fabozzi, A.O.M. Iorio, L. Lista, S. Meola, M. Merola, P. Paolucci

INFN Sezione di Padova, Università di Padova, Università di Trento, Padova, Italy

P. Azzi, N. Bacchetta, D. Bisello, A. Branca, R. Carlin, P. Checchia, T. Dorigo, U. Dosselli, S. Fantinel, F. Fanzago, M. Galanti, F. Gasparini, U. Gasparini, P. Giubilato, A. Gozzelino, K. Kanishchev, L. Lacaprara, I. Lazzizzera, M. Margoni, A. Naccari, A. Neri, A. Paccini, F. Pernici, S. Paoletti, S. Radici, A. Tropiano

2019-09-05
A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, E. Torassa\textsuperscript{a}, M. Tosi\textsuperscript{a,b}, S. Vanini\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, A. Zucchetta\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

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

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

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

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

INFN Sezione di Pisa \textsuperscript{a}, Università di Pisa \textsuperscript{b}, Scuola Normale Superiore di Pisa \textsuperscript{c}, Pisa, Italy

K. Androsov\textsuperscript{a,30}, P. Azzurri\textsuperscript{a}, G. Bagliesi\textsuperscript{a}, J. Bernardini\textsuperscript{a}, T. Boccali\textsuperscript{a}, G. Broccolo\textsuperscript{a,c}, R. Castaldi\textsuperscript{a}, R.T. D’Agnolo\textsuperscript{a,c,2}, R. Dell’Orso\textsuperscript{a}, F. Fiori\textsuperscript{a,c}, L. Foà\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a,30}, A. Kraan\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martini\textsuperscript{a,30}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, A.T. Serban\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, P. Squillacioti\textsuperscript{a}, T. Tschentscher\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}, C. Vernieri\textsuperscript{a,c}

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

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

INFN Sezione di Torino \textsuperscript{a}, Università di Torino \textsuperscript{b}, Università del Piemonte Orientale (Novara) \textsuperscript{c}, Torino, Italy

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

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

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

Kangwon National University, Chunchon, Korea

S. Chang, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

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

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

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

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

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

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

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

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

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

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

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

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

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

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

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

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilo, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin

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

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

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

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

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

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

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

Paul Scherrer Institut, Villigen, Switzerland
G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Gunaratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Illes, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp, A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

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

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

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

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

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

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

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

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, G. Hanson, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Parameswaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

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

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D’Alfonso, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutellyov, S. Lowette, R. Magana Villalba, N. Mccoll, V. Pavlinin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu
Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

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

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

Fairfield University, Fairfield, USA
D. Winn

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

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

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

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

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

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D.H. Moon, C. O’Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilk, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel, F. Ozok, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi
Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, M. Swartz, A. Whitbeck

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

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

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

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

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

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

University of Mississippi, Oxford, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

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

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

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

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

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

The Ohio State University, Columbus, USA
L. Antonelli, B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalvo, G. Williams, B.L. Winer, H. Wolfe
Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

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

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