

Search for a new neutral gauge boson produced in association with one or two b jets and decaying into a pair of muons in proton-proton collisions at $\sqrt{s} = 13$ TeV



The CMS collaboration

Full author list at the end of the paper

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: A search for a new neutral gauge boson, Z' , produced in association with one or two jets, including at least one b jet, and decaying into a pair of muons is presented. The analysis uses proton-proton collision data collected with the CMS detector at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1} . No significant deviation from background expectations is observed. Upper limits at 95% confidence level on the product of cross section, branching fraction to dimuons, acceptance, and efficiency, from 0.2 to 2 fb, are set for Z' boson masses between 125 and 350 GeV. Process-dependent products of acceptance and efficiency, and model-independent limits on the signal yield are provided. These are the only results to date in the 125–200 GeV mass range and the most stringent for b quark fusion production modes in the 200–350 GeV range, complementing inclusive Z' boson searches.

KEYWORDS: Beyond Standard Model, Hadron-Hadron Scattering

ARXIV EPRINT: [2511.11853](https://arxiv.org/abs/2511.11853)

Contents

1	Introduction	1
2	The CMS detector and event reconstruction	3
3	Data and simulated samples	6
4	Event selection and categorization	7
5	Background estimation	8
6	Systematic uncertainties	11
7	Results	15
8	Summary	21
	The CMS collaboration	28

1 Introduction

The standard model (SM) of particle physics describes a wide range of observed phenomena. However, it is not an ultimate theory of nature as, for example, the SM fails to explain neutrino masses, the matter-antimatter asymmetry of the universe, and the nature of dark matter [1]. In one of the simplest extensions, an additional $\mathcal{U}(1)$ symmetry group gives rise to a new neutral gauge boson, Z' , analogous to the SM Z boson. A Z' boson is proposed in various models of physics beyond the SM such as $\mathcal{U}(1)_X$ extensions [2, 3], Randall–Sundrum models [4–6], and grand unified theories [7, 8]. Such Z' bosons could be produced in proton-proton (pp) collisions at the CERN LHC.

In recent years, potential effects beyond the SM have been examined through precision measurements of B meson decay rates [9–19]. These effects can be roughly categorized into neutral-current anomalies $R(K^*)$ and charged-current anomalies $R(D^*)$, R being a branching fraction ratio between decay modes with different-flavored lepton daughters. These ratios measure the violation of lepton flavor universality in $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu_\ell$ transitions, respectively. These measurements have led to proposals of various theoretical models of heavy neutral and charged gauge bosons (Z' and W' , respectively) with nonuniversal fermion couplings. Anomalies in $R(K^*)$ motivate the search for a Z' boson that preferentially couples to third-generation fermions [20, 21]. Updated measurements from the LHCb experiment [18, 19] have removed tension originally observed in tests of lepton flavor universality in $b \rightarrow s\ell\ell$ transitions that motivated this low-mass Z' signal model. More recently, however, an additional spontaneously broken $\mathcal{U}(1)_X$ gauge group with family-dependent charges has been proposed that is consistent with the latest $R(K^*)$ measurements along with a TeV-scale Z' boson [3]. This motivates the current search (i.e., using the dimuon channel only).

Searches for a Z' boson inclusive in associated jet multiplicity have been performed by both the ATLAS and CMS Collaborations in dielectron and dimuon final states using data collected during the LHC Run 2 [22–24], which spanned the years 2015–2018. These searches assume flavor universality of the couplings to all quark and lepton generations,

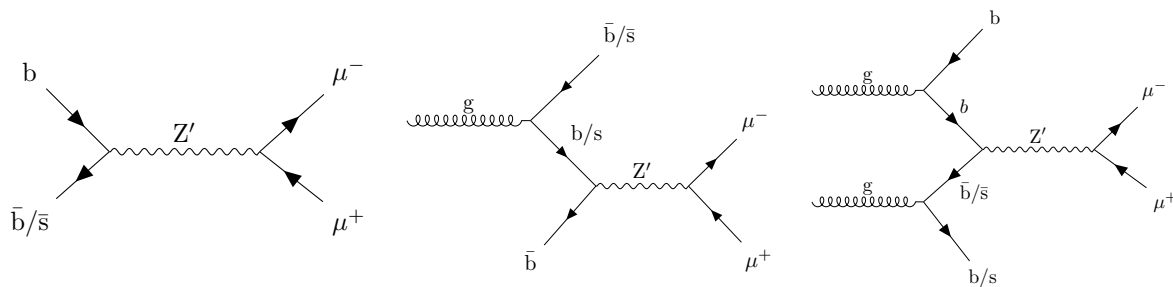


Figure 1. Representative Feynman diagrams of Z' boson production with bottom-bottom or bottom-strange quark fusion with decays into a dimuon final state. Production at tree level (left), single associated initial-state radiation (ISR) jet production (middle), and two associated ISR jet production (right) are shown.

and the leading order (LO) gauge boson production is driven by light-quark initial states. Assuming a Z' boson with the same couplings to the third-generation fermions as the SM Z boson, bounds on the Z' boson mass ($m_{Z'}$) are found for the $Z' \rightarrow \tau^+ \tau^-$ decay mode, excluding $m_{Z'}$ up to 2.42 (ATLAS) [25] and 3.5 TeV (CMS) [26], and for the $Z' \rightarrow b\bar{b}$ decay mode, excluding $m_{Z'}$ up to 2.7 (ATLAS) [27] and 2.4 TeV (CMS) [28]. Models that prefer third-generation quark production modes, such as those in ref. [20], which proposes a Z' boson decaying to muons that could accommodate flavor anomalies and be detected at the LHC. We probe the decay to muons of a Z' boson (with no coupling to electrons) produced via bottom-bottom or bottom-strange quark fusion as a benchmark model. A Z' decay into a tau lepton pair is not considered. Consequently, models in refs. [29–31], which propose Z' bosons decaying to tau leptons, are not directly excluded. Diagrams for the Z' boson production and decay are shown in figure 1.

The search presented here for a Z' boson in the mass range of 125–350 GeV complements the search of ref. [32], which explored Z' boson masses in the range of 350 GeV to 2 TeV. The present study is optimized for a Z' boson scenario with exclusive bottom quark couplings in the quark sector and possible flavor-changing neutral current (FCNC) bottom-strange couplings (δ_{bs}). The presence of the δ_{bs} coupling adds diagrams directly accessing the strange quark PDF of the proton for Z' boson production, as well as 2-jet diagrams where one of the outgoing jets is a strange quark jet. Increasing δ_{bs} enhances the production cross section and increases the fraction of events with associated light jets.

In this benchmark scenario, the hypothetical spin-1 narrow Z' resonance couples exclusively to muons and muon neutrinos in the lepton sector. We therefore search for a narrow resonance, i.e., with the width less than 1% of its mass. It is produced in association with one or more jets where at least one is b tagged, and decays into a pair of muons. Dielectron events are treated as a control region (CR).

The search does retain some sensitivity to flavor-universal models. For a sequential-SM [33] Z' boson with flavor-universal quark couplings most of the parameter space has already been excluded for masses ranging from 150 GeV to 5.15 TeV [22, 24, 34]. The sensitivity of the search reported here for flavor-universal lepton couplings is reduced because of the use of dielectron CRs for the background prediction. This limitation will be described in section 7.

The analysis is performed on LHC Run 2 pp collision data at a center-of-mass energy of 13 TeV collected during 2016–2018, and corresponding to an integrated luminosity of 138 fb^{-1} . As cross section measurements of Drell–Yan (DY) plus single or double b jet processes have found significant deviations from simulation predictions [35, 36], the background estimation strategy is fully based on control samples in data. Results are presented in a model-independent manner, covering a range of hypothetical Z' boson production with different final states for both pure bottom and FCNC bottom-strange quark couplings. The processes are grouped into seven categories for the interpretation of our results according to the matrix element (ME) calculation of the process. For the left diagram in figure 1, 0b (b-s) and 0b (b-b) denote b-s and b-b fusion, respectively, with no associated partons. For the middle diagram, 1b denotes a single associated b parton, and 1s denotes a single associated s parton. For the right diagram, 1b + 1s denotes associated b and s partons, 2b denotes two associated b partons, and 2s denotes two associated s partons arising from a similar diagram where an ISR gluon splits into an $s\bar{s}$ parton pair.

This paper is structured as follows: Section 2 describes the CMS detector and the event reconstruction. Section 3 introduces the data used and the simulated samples generated. Section 4 deals with the event selection and categorization. Section 5 describes the background estimation, while section 6 lists all systematic uncertainties considered. Results are shown in section 7, with a summary provided in section 8. Tabulated results can be found in the HEPData record for this analysis [37].

2 The CMS detector and event reconstruction

The CMS apparatus [38, 39] is a multipurpose, nearly hermetic detector, designed to trigger on [40–42] and identify electrons, muons, photons, and (charged and neutral) hadrons [43–45]. Its central feature 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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in refs. [38, 39].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about $4 \mu\text{s}$ [40]. 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, and reduces the event rate to around 1 kHz before data storage [41]. Events are selected using either (i) a trigger requiring a single muon, with a minimum p_T threshold of 50 GeV, updated in 2017 and 2018 to use a slightly different reconstruction method better optimized for high- p_T muons, or (ii) a double-electron trigger with a p_T requirement of 33 GeV per electron, which was lowered to 25 GeV during 2017 and 2018. Single-muon triggers are used instead of double-muon

triggers because they offer higher acceptance, and the primary advantage of double muon triggers, the lower p_T threshold, is not required.

The global event reconstruction, also called particle-flow (PF) event reconstruction [46], aims to reconstruct and identify each individual particle in an event, with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged hadron, neutral hadron) plays an important role in the determination of the particle direction and energy. Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL. Electrons are identified as a primary charged-particle track and potentially many ECAL energy clusters corresponding to this track extrapolation and to possible bremsstrahlung photons. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Charged hadrons are identified as charged-particle tracks neither identified as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged-hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged-hadron energy deposit.

Hadronic jets are clustered from reconstructed PF particles using the anti- k_T algorithm [47, 48] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true particle-level momentum. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged-particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average, and in situ measurements of the momentum balance in dijets, multijets, and Z+jets events are used to account for any residual differences in the jet energy scale between data and simulation [49]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [49]. We refer to the group of either type of lepton (e or μ) or jet, irrespective of b tagging, as an object, from hereon out. A tight lepton veto is applied to ensure jets are not misreconstructed leptons and a $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ requirement is applied to the nearest electron or muon, where $\Delta\eta$ and $\Delta\phi$ are the differences in the pseudorapidity and azimuthal angle, respectively, between the two objects. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [50].

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [51]. The $\vec{p}_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

Jets containing b quarks can be identified utilizing the relatively long b quark lifetime and identifying a secondary vertex within the jet, as well as using jet shape variables [52]. We utilize the medium working point of the DEEPJET algorithm [53, 54] defined by a 1% misidentification probability for jets originated from light-quarks or gluons, yielding an

efficiency of $\approx 90\%$ to identify jets originated from b quarks as b-tagged. All jets are required to fulfill $|\eta| < 2.4$, a tight jet identification selection to suppress detector noise, and for jet $p_T < 50$ GeV, a boosted decision tree discriminator is used to reject pileup jets if the score passes a certain threshold (tight working point) [50, 55]. The b-tagged jets are subject to a requirement of $p_T > 20$ GeV, while non-b-tagged jets must satisfy $p_T > 30$ GeV. The lower p_T requirement for b jets allows for greater acceptance of the soft associated b jet production and is possible since the b-tagged jet selection retains purity at lower p_T . Lastly, all jets must be separated from any identified isolated electron or muon by at least $\Delta R > 0.4$. Scale factors to correct for the differences between data and simulation are applied to pileup and b tagging criteria [52].

The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The relative energy resolution for electrons with $p_T \approx 45$ GeV from $Z \rightarrow ee$ decays ranges from 1.4 to 3%. It is generally better in the barrel region than in the endcaps, depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL, and the data-taking year [43, 56]. This results in a dielectron mass resolution for $Z \rightarrow ee$ decays in the ranges 1.2–2.0% or 2.2–3.2% when both electrons are in the ECAL barrel or in the ECAL endcaps, respectively

Muons are measured in the pseudorapidity range $|\eta| < 2.4$. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [44].

Electrons and muons in this analysis are required to fulfill $p_T > 53$ GeV and $|\eta| < 2.4$, slightly above the 50 GeV muon trigger threshold. We require tight quality criteria with misidentification probabilities of 1% for electrons, using high-energy electron pair (HEEP) identification [43], and 0.1% for muons, using the cutoff-based high- p_T identification [44]. Moreover, both types of leptons are required to be isolated, where the relative isolation is measured by the p_T sum of all additional PF candidates in a cone around the lepton relative to the lepton p_T [44, 57]. The cone size is $\Delta R < 0.3$ for electrons and < 0.4 for muons. The isolation is part of a multivariate analysis (MVA) discriminant for electrons with the aforementioned misidentification rate and a total efficiency of reconstruction, identification, and the isolation requirement of 85–90% [43]. For muons, relative isolation is evaluated independently of the identification working point and is required to be less than 0.1. Lepton isolation is corrected for neutral-hadron contributions from pileup [43, 44]. This selection is synchronized with the CMS dilepton final-state search [24] and utilizes the high- p_T identification developed for that analysis. Muon and electron momentum scale factors are applied to amend differences in momentum reconstruction between data and simulation. Both lepton types are corrected in simulation with scale factors for differences in identification, isolation, and reconstruction efficiencies to data.

An additional loose selection of electrons or muons is used to veto events with extra leptons. A loose set of quality criteria is applied, using the MVA identification for electrons [43], as the HEEP identification [43] does not allow for selecting sufficiently low- p_T electrons, and the

Object	Identification	Minimum p_T [GeV]
μ	Tight	53
e	Tight	53
Veto μ	Loose	10
Veto e	Loose	10
b jet	Pass medium b tag	20
Non-b jet	Fail medium b tag	30

Table 1. Summary of object selection requirements on leptons, veto leptons, and jets passing and failing b jet identification. All objects have a maximum $|\eta|$ of 2.4. The efficiencies of the respective identification working points are detailed in the text of section 2.

cutoff-based high- p_T identification for the muons along with the requirements $p_T > 10$ GeV and $|\eta| < 2.4$ [44].

Table 1 summarizes these selection requirements.

3 Data and simulated samples

Signal Monte Carlo (MC) samples were prepared with MADGRAPH5_aMC@NLO [58] version 2.4.2 (2.6.0) for 2016 (2017 and 2018) at leading order (LO) with the NNPDF3.1 [59] parton distribution functions (PDFs) in the five flavor scheme. The MLM technique [60] is used to eliminate the double counting between jets from the matrix element calculations and parton shower. The signal process is generated with up to two additional partons. The Universal FeynRules Output (UFO) [61] configuration file for the signal process was privately prepared and can be found in the HEPData record for this analysis [37]. Signals are generated at Z' boson masses of 125, 150, 175, 200, 250, 300, and 350 GeV, and with δ_{bs} values of 0.04, 0.5, and 1.0, with resonance widths of less than 1% of the Z' boson mass. This is lower than the reconstructed dimuon mass resolution, which ranges from 1.7 GeV at 125 GeV to 7.2 GeV at 350 GeV. Different δ_{bs} samples change the proportion of different production categories, each with its unique product of acceptance and efficiency, but not the dimuon mass shape. The δ_{bs} values were chosen to cover different production categories [20].

DY + jets processes are simulated at next-to-leading order (NLO) using MADGRAPH5_aMC@NLO version 2.4.2 (2.6.5) for 2016 (2017 and 2018) data taking, with jets from the matrix element calculations and from parton shower matched using the FxFx scheme [62]. Single top quark, top quark pair production (tt), and diboson ($VV = WW, WZ, ZZ$) samples are simulated at NLO using the POWHEG v2.0 generator. Additional NLO DY samples generated with POWHEG are used to increase the event count of the MADGRAPH5_aMC@NLO samples in the low-mass regions where the selections are most stringent. In the POWHEG samples, the jet matching is handled internally.

The NNPDF3.0 [63] parton distribution functions (PDFs) are used for 2016, while NNPDF3.1 [59] is used for the 2017 and 2018 data taking. The matrix element generators are interfaced with PYTHIA 8.226 (8.230) [64] for parton showering and underlying event description using the CUETP8M1 tune [65] (CP5 tune [66]) for 2016 (2017 and 2018) samples.

Pileup is included in the simulation, as generated with PYTHIA, with its multiplicity distribution adjusted to match that observed in data. All simulated events are processed by a GEANT4-based [67] simulation of the CMS detector, in the same version of the CMS software as used in data reconstruction.

4 Event selection and categorization

After selecting events that pass the single muon or double-electron triggers, we retain only events with exactly two opposite-sign same-flavor leptons with selection criteria that ensure high purity and veto any event with any further loosely selected leptons of any flavor, as detailed in the object selections described in section 2. To search for a Z' boson that decays to muons, with associated b jets, we create dimuon signal regions (SRs) containing at least one b-tagged jet and CRs enhanced with either events containing either electrons, or light-quark, or gluon, jets.

We select events with exactly one or two jets. These two jet multiplicity categories are handled separately to distinguish the two types of leading diagrams in their respective jet multiplicity categories for the targeted signal: a quark-gluon initiated diagram with one final-state b quark in the 1-jet category, and a gluon-gluon initiated diagram with an sb or bb quark pair in the final state for the 2-jet category. The presence of a flavor-violating δ_{bs} coupling adds diagrams directly accessing the strange quark PDF of the proton for Z' boson production, as well as 2-jet diagrams where one of the outgoing jets is a strange quark jet. Therefore, the strength of such a coupling changes both the branching fraction between the 1- and 2-jet categories, and their acceptances. Higher jet multiplicities are not included due to of minimal signal acceptance and larger additional background. The SRs and the dielectron b jet enriched CRs require at least one jet to be b tagged, while the light-jet regions require no b-tagged jets. In the labeling of SRs and CRs, dimuon and dielectron regions are denoted with a $\mu\mu$ or ee superscript, respectively, and a “j”, “b”, “2j” or “b + j/b” subscript indicates that the region is a single/double light-quark jet or b jet region. Table 2 lists the resulting SRs and CRs.

Further requirements to suppress backgrounds beyond the selections introduced in section 2 depend on the dilepton invariant mass $m_{\ell\ell}$ and the jet multiplicity. Consequently, two-dimensional Bottom Quark Fusion (BQF) variable selections are applied to optimize the analysis as a function of the reconstructed dilepton mass. These are upper bounds on $p_T^{\text{miss}}/m_{\mu\mu}$ and on the difference between the scalar sum of jet transverse momenta (H_T) and lepton transverse momenta (L_T), denoted as $H_T - L_T$. Distributions of these BQF variables, proposed in ref. [20], for backgrounds and signals in $\text{SR}_b^{\mu\mu}$ and $\text{SR}_{b+j/b}^{\mu\mu}$ are shown in figure 2. The signal distributions for the $H_T - L_T$ and $p_T^{\text{miss}}/m_{\mu\mu}$ variables shift as a function of the Z' boson mass.

We optimize the selections on each BQF variable to maximize the expected significance, defined as the signal counts divided by the square root of the sum of signal and expected background counts, for a range of signal mass hypotheses between 125 and 350 GeV. The reconstructed Z' boson mass is used as a proxy of the generated Z' boson mass to create two-dimensional selections tuned for optimal performance as a function of the mass. The results of the optimization are shown in table 3.

N_b	$N_{\text{jets}}^{\text{all}}$	$\mu^+\mu^-$	e^+e^-
≥ 1	2	$\text{SR}_{b+j/b}^{\mu\mu}$	$\text{CR}_{b+j/b}^{ee}$
0	2	$\text{CR}_{2j}^{\mu\mu}$	CR_{2j}^{ee}
1	1	$\text{SR}_b^{\mu\mu}$	CR_b^{ee}
0	1	$\text{CR}_j^{\mu\mu}$	CR_j^{ee}

Table 2. Number of jet requirements for the SRs and CRs based on opposite-sign dilepton pair flavor, number of b-tagged jets (N_b), and the overall number of jets ($N_{\text{jets}}^{\text{all}}$). Events with more than two leptons passing veto lepton selections of any flavor are discarded. In the chosen benchmark model, the Z' boson does not decay into electrons, hence the use of the dielectron CRs.

BQF variable	Jet multiplicity	
	1	2
$p_T^{\text{miss}}/m_{\ell\ell} <$	$223(m_{\ell\ell}/\text{GeV})^{-0.23}$	$67(m_{\ell\ell}/\text{GeV})^{-0.04}$
$H_T - L_T <$	$-0.43m_{\ell\ell} + 47 \text{ GeV}$	$-0.56m_{\ell\ell} + 124 \text{ GeV}$

Table 3. Summary of additional $m_{\ell\ell}$ -dependent event selection requirements on p_T^{miss} and $H_T - L_T$ BQF variables to suppress backgrounds. The jet multiplicity column indicates the maximum value the BQF variables can have to pass the selection for the respective number of jets.

At the lowest dimuon masses in our search range, the background suppression is less effective, as both $H_T - L_T$ and $p_T^{\text{miss}}/m_{\mu\mu}$ better separate signal from background for high- p_T dimuons. Additionally, the decay products of a low-mass Z' boson are generally more similar to those of SM processes, reducing the efficacy of the BQF selections. Conversely, with increasing mass, the background rejection power of the BQF variables improves.

Compared to the variables used for masses above 350 GeV in the high-mass analysis [32], the BQF variables offer less stringent background rejection but higher acceptance. For dilepton masses between 125 and 350 GeV, background events are reduced to 78–42% of their pre-BQF-variable selection values in $\text{SR}_b^{\mu\mu}$ and to 43–21% in $\text{SR}_{b+j/b}^{\mu\mu}$. Signal events are reduced to 95–84% in $\text{SR}_b^{\mu\mu}$ and 76–67% in $\text{SR}_{b+j/b}^{\mu\mu}$ relative to their pre-BQF-variable selection values.

We analyze the dilepton mass range 122–391 GeV so as to cover a Z' boson mass range of 125–350 GeV, by expanding the mass window by 3 times the dimuon mass resolution in each direction.

5 Background estimation

In this search, we use an ABCD (matrix) background estimation technique based on parametric fits to the CRs to smooth statistical fluctuations. All previous selections, including the BQF ones, are applied before performing the fits. Jet and electron selections are used to construct the CRs, which are then used to predict the backgrounds in the muon-enriched and b jet enriched SRs.

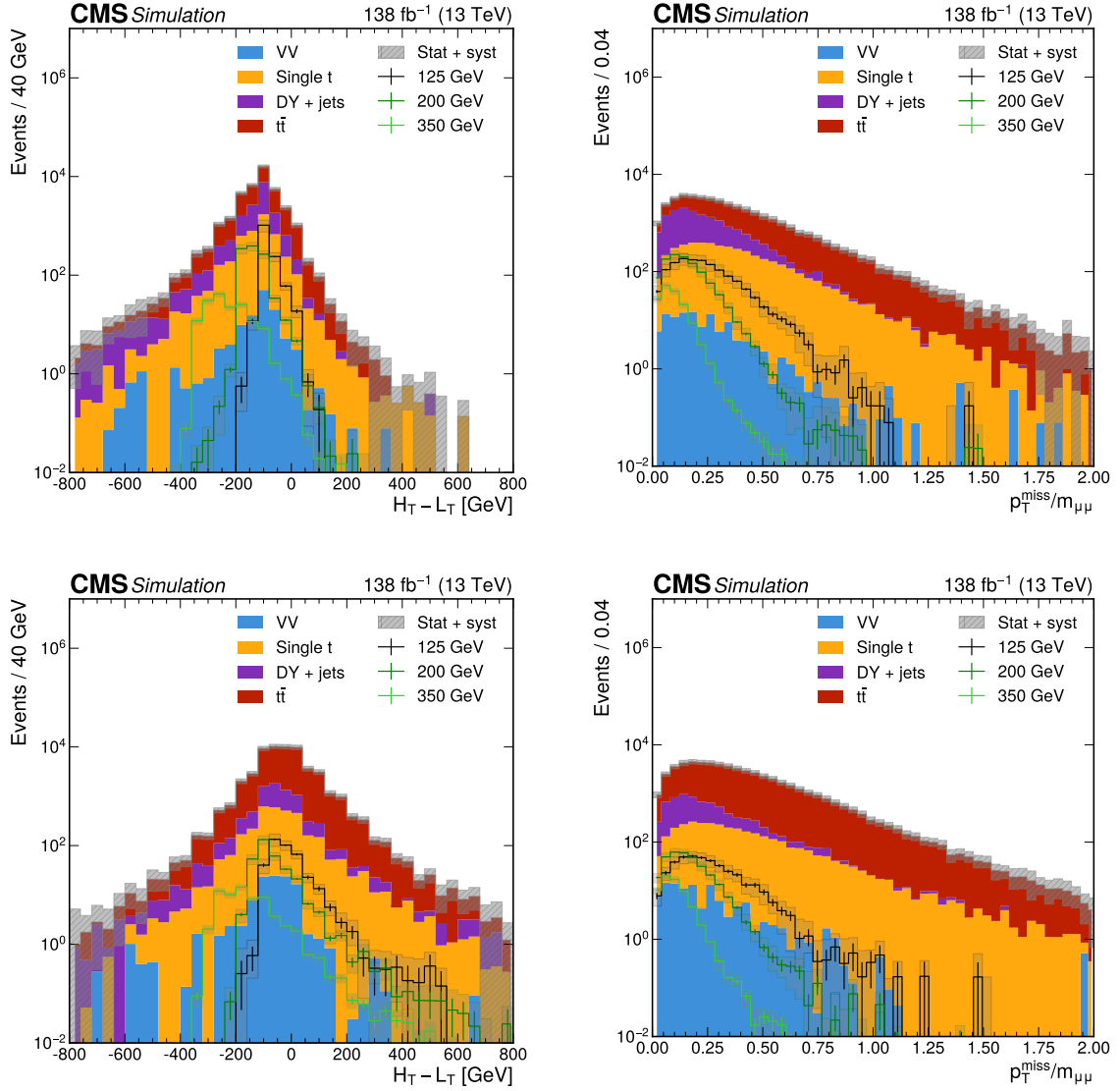


Figure 2. Distributions of the search-specific variables from simulated backgrounds and signals for Z' boson masses of 125, 200, and 350 GeV after object selections including a single-muon requirement and categorization into both jet multiplicities. The left column shows the $H_T - L_T$ distributions, and the right column shows the $p_T^{\text{miss}}/m_{\ell\ell}$ distributions. The upper row shows the 1-jet category distributions, and the lower row shows the 2-jet category distributions. Overflow events are not shown.

Figure 3 shows a visualization of the ABCD method. Here, the symbols A, B, C, and D refer to four regions constructed from two uncorrelated selection based on leptons and jets. One of the regions (A) is dominated by signal while the other three CRs (B, C, D) are background-dominated. The background yield in the SR is estimated from the yields in the three CRs with the expression: $N_A = N_B N_C / N_D$, where N_X is the number of events in region X.

For this analysis, as the benchmark model predicts no decays to electrons, the background shape is extracted from a dielectron CR with at least one b-tagged jet for both the one

	muon	electron
b jet	A $SR_b^{\mu\mu}$ Signal Region	B CR_b^{ee}
Non-b jet	C $CR_j^{\mu\mu}$	D CR_j^{ee}

Figure 3. A visualization of the ABCD SRs and CRs. For example, $SR_b^{\mu\mu}$ represents the dimuon b jet enriched SRs ($SR_b^{\mu\mu}$ or $SR_{b+j/b}^{\mu\mu}$) and CR_b^{ee} represents the dielectron b jet enriched CRs (CR_b^{ee} or $CR_{b+j/b}^{ee}$).

(CR_b^{ee}) and two ($CR_{b+j/b}^{ee}$) jet regions, as also indicated in table 2. To correct for differences in the dilepton mass shape and normalization arising from acceptance, resolution, and other differences between electrons and muons, a multiplicative transfer factor per bin in the dilepton mass distribution is determined from functional fits, described below, in non-b-tagged regions: $CR_j^{\mu\mu}/CR_j^{ee}$ and $CR_{2j}^{\mu\mu}/CR_{2j}^{ee}$ for the one- and two-jet regions, respectively. These per-bin transfer factors are then multiplied per bin by fit values in the dielectron b-tagged regions CR_b^{ee} and $CR_{b+j/b}^{ee}$ to create the predictions for backgrounds in $SR_b^{\mu\mu}$ and $SR_{b+j/b}^{\mu\mu}$. Thus, the ABCD background prediction equations are given by:

$$SR_b^{\mu\mu} = CR_b^{ee} \frac{CR_j^{\mu\mu}}{CR_j^{ee}}, \quad SR_{b+j/b}^{\mu\mu} = CR_{b+j/b}^{ee} \frac{CR_{2j}^{\mu\mu}}{CR_{2j}^{ee}}. \quad (5.1)$$

This method assumes that there is no signal in the CRs. In the benchmark model, signal contamination in the dimuon non-b-tagged regions has been tested and found to be negligible even with a signal ten times the expected exclusion cross section, because of the far higher background rates and lower signal acceptance, even for production with additional associated strange jets. Furthermore, any initial/final-state radiation or PDF effects cancel in the ratio of the regions of different lepton flavors by construction. In addition, a signal injection test into the dielectron b jet enriched CRs was conducted to demonstrate robustness against signal contamination for Z' scenarios with electron couplings (as discussed in section 7).

The main backgrounds depend on the associated jet multiplicity and dilepton mass. In general, $t\bar{t}$ is the most relevant background at higher dilepton masses, while in the lower range, DY processes are dominant. A subdominant contribution from single top quark production is always present at either multiplicity, and rarer backgrounds, such as VV, contribute at the sub-percent level. Most of the DY background is in the 1-jet regions ($\approx 50\%$ DY, $\approx 40\%$ $t\bar{t}$, $\approx 10\%$ single top quark), while $t\bar{t}$ background aggregates preferably in the 2-jet regions ($\approx 20\%$ DY, $\approx 75\%$ $t\bar{t}$, $\approx 5\%$ single top quark).

All backgrounds are estimated directly from data using the ABCD method rather than from simulations. This is motivated because (i) in cross section measurements of DY production with one or two associated b jets, discrepancies between simulations and data have been observed [35], and (ii) uncertainties in the bottom and strange quark PDF contributions would affect predictions for the relative rate of background processes, and thereby the background acceptance in regions with one to two associated b jets.

We utilize two types of $m_{\ell\ell}$ binning in this analysis. We use a flat 1 GeV binning for the background estimation based on CRs in data to improve the fit stability in the CRs. For the SRs, we use a binning scheme that progressively widens in 1 GeV steps, starting from 1 GeV and ending at 9 GeV, to match the width of the Z' boson mass resonance peak. This ensures sufficient resolution for limit setting while avoiding low counts per bin. The dilepton mass distribution is plotted as the number of events normalized by the bin width (figures 4–9). The bin widths are rounded down to the closest integer of the reconstructed Z' boson width in GeV for a resonance at the corresponding $m_{\ell\ell}$. The $m_{\ell\ell}$ locations at which the binning widens are: 136, 182, 224, 264, 299, 335, 363, and 395 GeV.

All shapes and normalizations are extracted using a log-normal function:

$$f(m_{\ell\ell}, \sigma, \mu, n) = \frac{n}{m_{\ell\ell} \sigma \sqrt{2\pi}} \exp \left[-\frac{(\ln(m_{\ell\ell}) - \mu)^2}{2\sigma^2} \right], \quad (5.2)$$

where σ is the turn-on width, μ is the mean, and n the normalization.

The comparisons of simulated backgrounds, including all systematic uncertainties, with the ABCD SR background predictions derived from fits to the simulated CRs are shown in figure 4. The respective ratios of the ABCD predictions derived on simulated CRs to the actual simulated prediction in each SR are also shown.

Discrepancies are observed between data and simulation in the CRs, as shown in figures 5 and 6, which motivated us not to use a simulated background prediction in favor of a background prediction based solely on data. Figure 7 presents the ABCD prediction compared to the data, illustrating the accuracy of the background estimation technique based on the CRs in data. Between the ABCD background estimation and the observed background in data, we calculate a χ^2 of 83.0, 67.1, 124.0 (42.7, 71.9, 77.4) over 84 bins for 2016, 2017, 2018 $\text{SR}_{\text{b}}^{\mu\mu}$ ($\text{SR}_{\text{b+j/b}}^{\mu\mu}$), respectively.

6 Systematic uncertainties

Systematic uncertainties of both theoretical and experimental origin that affect signal simulation are listed in table 4. Background uncertainties in this analysis are not subject to simulation uncertainties, but rather uncertainties in the closure of the ABCD method. These uncertainties affect both the signal and background acceptance, as well as the dilepton mass distribution, which is the primary search variable. As we aim to provide model-independent results, we factorize the results into signal acceptances for different final-states. Template shapes for the nominal dilepton mass resonance and each of its systematic variations are used to set limits on the shape prior to applying the acceptances for each final-state jet multiplicity. It is important to note that the addition of initial-state b jet production does not change the mass shape of the resonance.

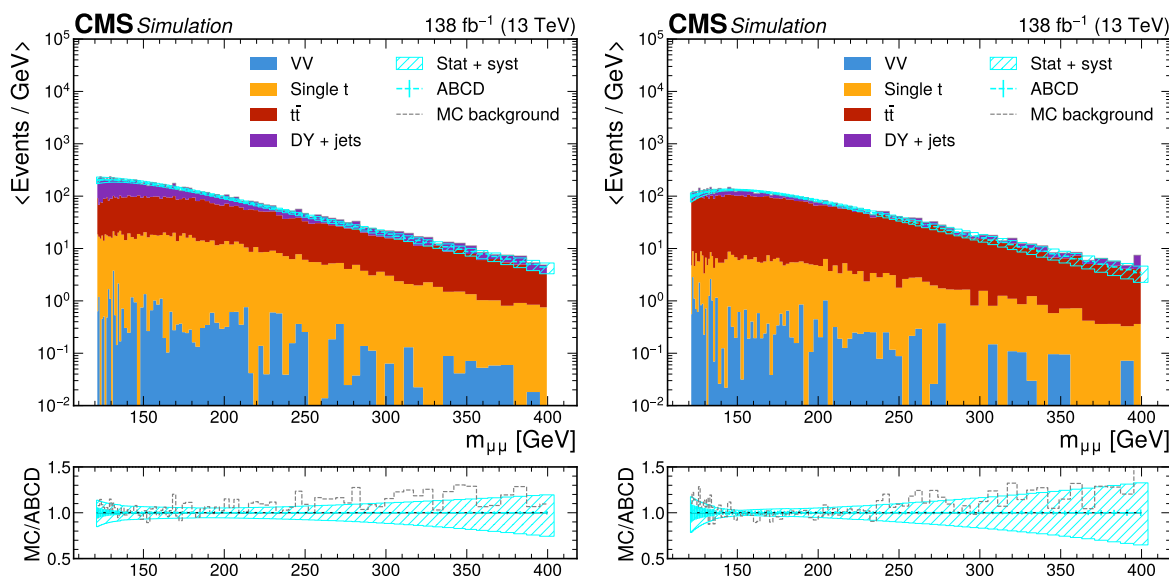


Figure 4. Comparison between the predictions of the $\text{SR}_b^{\mu\mu}$ background from simulation (gray) and the ABCD method (teal) from MC simulation. Events are divided by the bin width. The statistical and systematic uncertainties using the ABCD method are shown around it in a teal hashed area. The ratio of the nominal MC background values (dashed line) to the ABCD prediction is shown as a dashed line in the ratio plot. The MC background uncertainties are not shown for visual clarity. Left: $\text{SR}_b^{\mu\mu}$. Right: $\text{SR}_{b+j}^{\mu\mu}$.

The integrated luminosities for the 2016, 2017, and 2018 data-taking periods have 1.2–2.5% individual uncertainties [68–70], while the overall uncertainty for the 2016–2018 period is 1.6%.

Mismodeling of pileup is evaluated by varying the total inelastic pp cross section used to predict the pileup distribution in the data by $\pm 4.6\%$ [71]. This affects the signal normalization in the range of 0.30–2.44%, correlated across years.

Simulated jet four-momenta are varied according to the jet energy scale and resolution uncertainties, resulting in a systematic uncertainty in the transverse momentum of 2.4–4.4% for the jet energy scale and 2.6–7.2% for the jet energy resolution per jet. The misidentification rate of genuine jets in the pileup identification between data and simulation is also varied within its uncertainty, contributing 0.7–1.7% uncertainty in the event yield. Finally, the uncertainty in the p_T - and $|\eta|$ -dependent b tagging efficiency for b , c , and light-flavor quarks or gluons is evaluated by varying data-to-simulation scale factors applied to simulation by their uncertainties. These variations yield a change in normalization and shape of 0.6–1.6%.

In June of 2018, the HCAL experienced a readout loss covering approximately a $\Delta\phi = 40^\circ$ arc in the region $1.3 < |\eta| < 3.0$ [39]. In MC simulations, jets in this region are assigned an additional 0.20–0.22% HCAL jet energy scale uncertainty to account for uncertainties in the modeling of this issue.

The fit function used for the mass distribution in each CR is subject to correlations by which fluctuations in low-mass bins can inversely affect the fit predictions in the high-mass range, and vice versa. For example, an upward fluctuation in the lower part of the CR_b^{ee} mass range could cause the fitted function to underestimate the data in the higher part

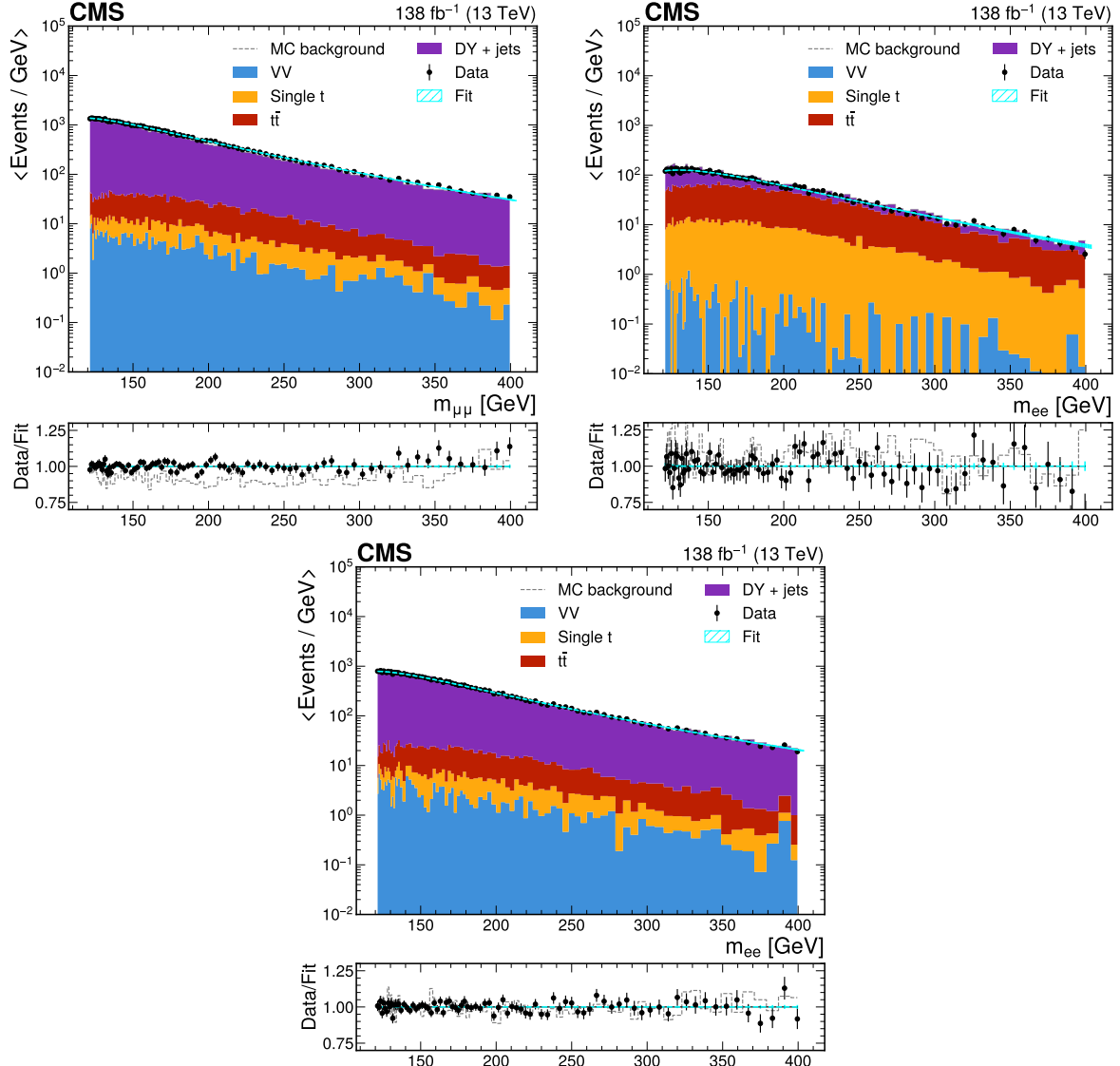


Figure 5. The 1-jet CRs with data fits used for the $SR_b^{\mu\mu}$ background prediction. Upper left: $CR_j^{\mu\mu}$. Upper right: CR_b^{ee} . Lower: CR_j^{ee} . Events are divided by the bin width. We observe a shape difference between data and simulation in $CR_j^{\mu\mu}$. The ratio of the nominal MC background values (dashed line) and data to the ABCD prediction is shown as a dashed line in the ratio plot. The MC background is included as a comparison, and is not used for predictions.

of the CR_b^{ee} mass range. These effects lead to nontrivial and varied changes in the fit prediction, depending on the bin where the fluctuation occurs, which are not adequately accounted for by taking the envelope of the covariance matrix. As such, the variations in the fit from fluctuations at each bin are introduced as a systematic uncertainty. Because CR_b^{ee} and $CR_{b+j/b}^{ee}$ are the least populated regions, and therefore the most sensitive to statistical fluctuations in any bin, we use these CRs to estimate the correlations in the fit function across bins caused by such fluctuations. The central prediction of the fit is used as a baseline for the per-bin estimated yield. The Poissonian uncertainty in that estimated yield is taken

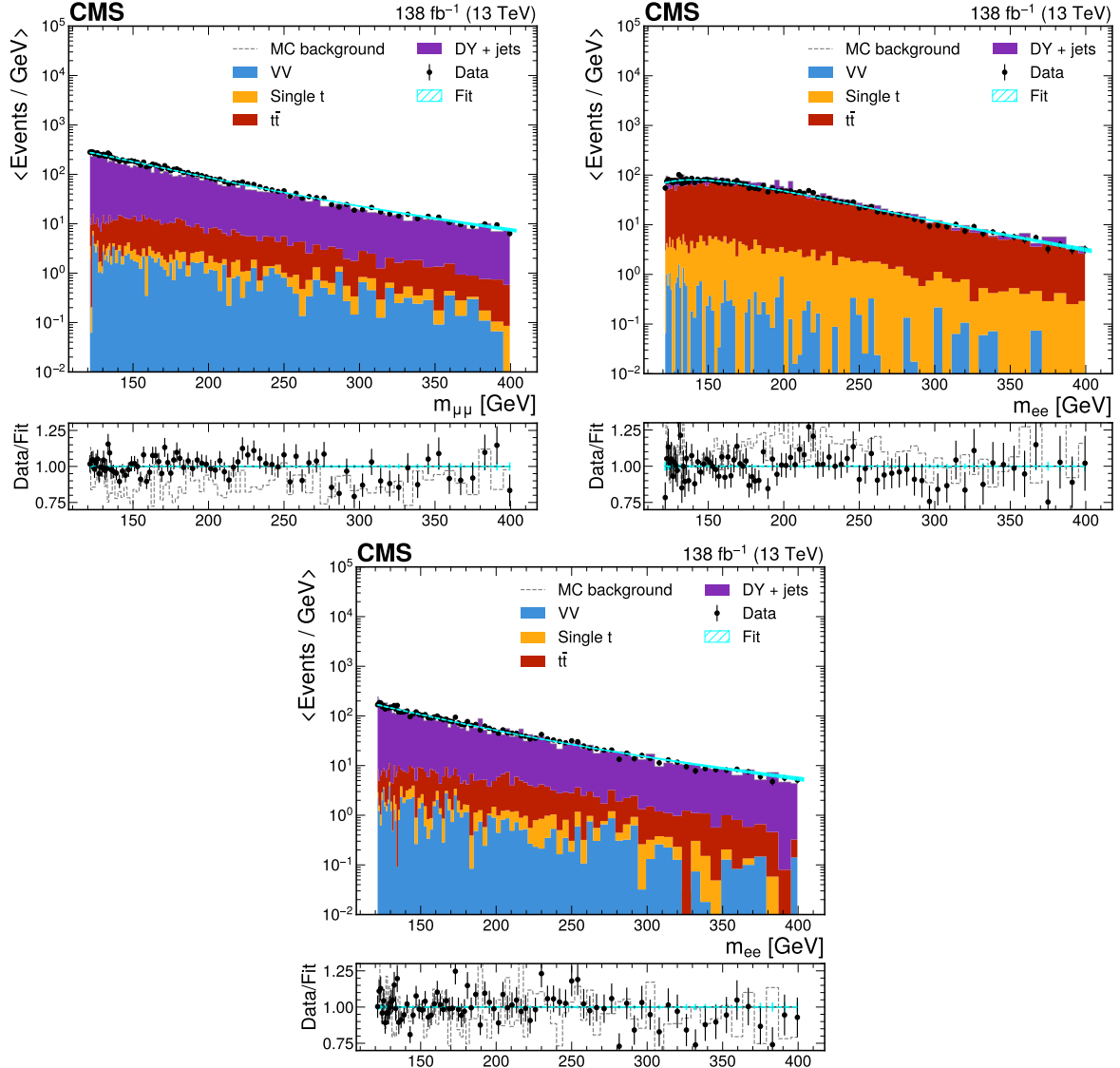


Figure 6. The 2-jet CRs with data fits used for the $\text{SR}_{b+j/b}^{\mu\mu}$ background prediction. Upper left: $\text{CR}_{2j}^{\mu\mu}$. Upper right: $\text{CR}_{b+j/b}^{\text{ee}}$. Lower: $\text{CR}_{2j}^{\text{ee}}$. Events are divided by the bin width. We observe a shape difference between the MC and data in $\text{CR}_{2j}^{\mu\mu}$. The ratio of the nominal MC background values (dashed line) and data to the ABCD prediction is shown as a dashed line in the ratio plot. The MC background is included as a comparison, and is not used for predictions.

as the bin's fluctuation value. For each bin, we vary the number of events up and down by its fluctuation value and refit the distribution for each variation. The resulting changes to the fit prediction based on the fit variations are assigned as shape uncertainties over the dilepton mass range. This method preserves the correlations between the bins along the entire fit prediction curve. To demonstrate the size of the fit variations, the envelope of all these variations adds an effective uncertainty that we refer to as the background fit uncertainty of 2 to 16% (2 to 17%) in $\text{SR}_b^{\mu\mu}$ ($\text{SR}_{b+j/b}^{\mu\mu}$).

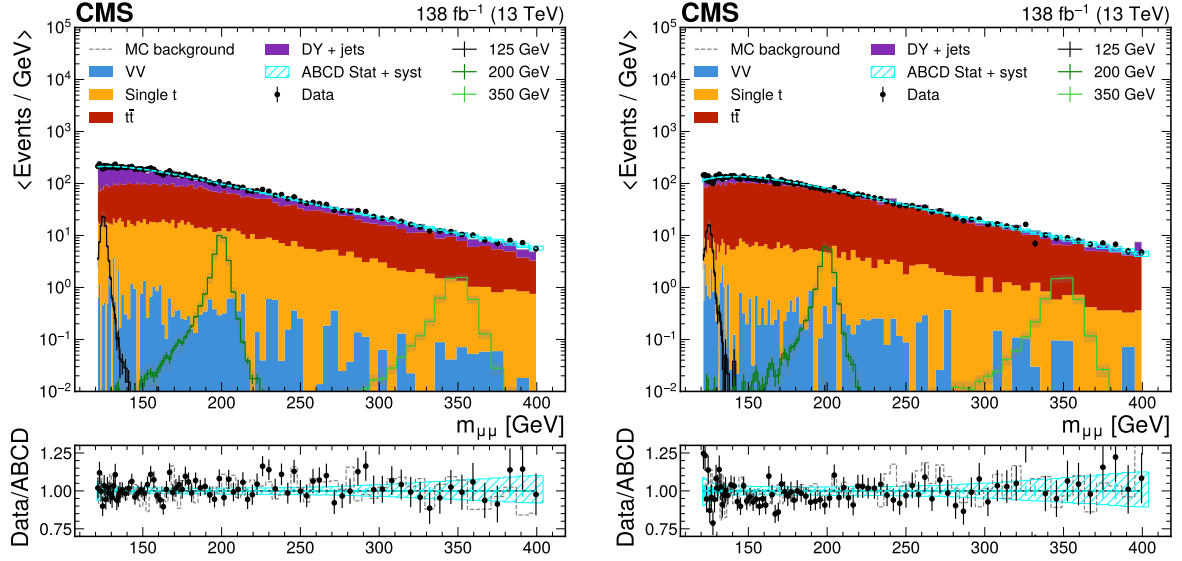


Figure 7. Distributions of $m_{\ell\ell}$ in the $\text{SR}_b^{\mu\mu}$ (left) and $\text{SR}_{b+j/b}^{\mu\mu}$ (right) SRs. Events are divided by the bin width. Simulated signal shapes for Z' boson masses of 125, 200, and 350 GeV are shown. The “Stat + syst” band shows the envelope of the fit variations with statistical uncertainties. The ratio of the nominal MC background values (dashed line) and data to the ABCD prediction is shown as a dashed line in the ratio plot. The MC background uncertainties are not shown for visual clarity.

For the signal acceptances of different jet multiplicities, we take into account the PDF, factorization, and renormalization scale uncertainties of each. The PDF uncertainties are evaluated by reweighting the signal and background events using the 68% envelopes of the NNPDF 3.0 or 3.1 set of eigenvector variations as per the recommendation of the PDF4LHC working group [72]. The PDF uncertainties result in a $< 0.1\%$ uncertainty in the acceptance, correlated across the data-taking years. Factorization and renormalization scales, μ_F and μ_R , impact within each matrix element diagram the presence of further associated soft jets. The associated soft jets mostly affect the acceptance of final states with no inherent outgoing bottom quark. Uncertainties in this are estimated for each final states’s acceptance by halving or doubling each scale independently and choosing the largest deviations from nominal in each direction among all permutations as the total uncertainty, excluding the two extreme variations. The scale variations introduce a relative variation of up to 7%, with a mean value of 2%. An overview of all uncertainties considered for the dilepton mass shape of the Z' boson resonance and the background and which part of the analysis they affect, as well as whether there are correlations across the data-taking years, are summarized in table 4.

7 Results

The SR data agree with the background predictions within the uncertainties.

We report limits on the product of inclusive cross section and branching fraction. Acceptance times efficiency for individual production processes, primarily based on the flavors and multiplicities (b and s) of the initial-state radiation (ISR), are listed in tables 5–11, such that the limits can be reinterpreted for any model based on these processes. Contributions from

Uncertainty source	Type	Processes	Range	
			$\text{SR}_b^{\mu\mu}$	$\text{SR}_{b+j/b}^{\mu\mu}$
Trigger eff.	Per event	Signal	2.2–4.7%	
Background fit	Per event	Backgr. est.	2–16%	2–17%
Integrated luminosity	Per event	Signal	1.2–2.5%	
Muon reco., ident., and iso. eff.	Per muon	Signal	0.2–0.6%	
Muon energy scale	Per muon (p_T)	Signal	0.1–0.2%	
Jet energy scale	Per jet (p_T)	Signal	2.4–4.4%	
Jet energy resolution	Per jet (p_T)	Signal	2.6–7.2%	
HCAL inefficiency*	Per jet (p_T)	Signal	0.20–0.22%	
b tagging efficiency*	Per jet	Signal	0.6–1.6%	
Pileup*	Per event	Signal	0.30–2.44%	
Pileup jet ident.	Per jet	Signal	0.7–1.7%	
PDF	Per event	Signal	<0.02%	<0.2%
Factorization/renormalization scales	Per event	Signal	<0.2%	<0.4%

Table 4. Overview of systematic uncertainty sources and their ranges. Systematic uncertainties that are treated as fully or partially correlated across the data-taking years are labeled with an asterisk.

other jet flavors (light-flavor and charm quarks) are not considered for the categorization, as they do not couple to the Z' boson in the model considered.

The $m_{\ell\ell}$ distributions corresponding to the reconstructed dilepton masses in the 1- and 2-jet categories, combined over all three data-taking years, are shown in figure 7, along with a few simulated Z' boson signal masses. Limits are based on the background estimation from control samples in data. The dominant background in the low-mass range of $\text{SR}_b^{\mu\mu}$ is DY production, while in all other areas of the $m_{\ell\ell}$ distribution $t\bar{t}$ dominates, for either SR. Single top quark background contributes at the 5 to 10% level and rarer diboson backgrounds have sub-percent contributions.

The total background shape and normalization have been estimated based on CRs in data, as described in section 5. Asymptotic limits at 95% confidence level (CL) [73] are set for Z' boson masses between 125 and 350 GeV, with corresponding reconstructed mass peak widths ranging from 1.7 to 7.2 GeV. The data compared to the ABCD method background predictions are shown in figures 8 and 9 for $\text{SR}_b^{\mu\mu}$ and $\text{SR}_{b+j/b}^{\mu\mu}$, and for each data taking year separately.

A simultaneous maximum likelihood fit across data-taking years is performed in each jet multiplicity category separately to extract any potential signal contributions from the 0–2 parton signal processes shown in figure 1. It has been shown that the dilepton mass shape is the same in our chosen benchmark model for all evaluated signal processes with the same Z' boson mass, regardless of the production diagram. Systematic uncertainties as described in section 6 are treated as nuisance parameters following log-normal probability density functions for purely rate-affecting cases, while systematic uncertainties affecting the $m_{\ell\ell}$ shape are assumed to follow a Gaussian probability density function instead. Asymptotic limits at 95% CL are set on the product of cross section, branching fraction, and acceptance for Z' boson masses between 125 and 350 GeV in steps equal to the reconstructed dimuon

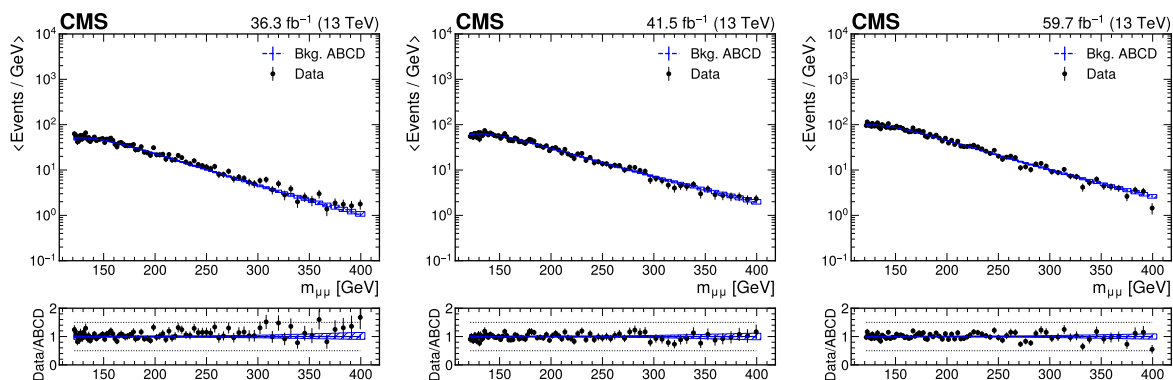


Figure 8. Data (black) vs. the ABCD method background prediction (blue) for 2016 (left), 2017 (middle), and 2018 (right) data-taking years in $\text{SR}_b^{\mu\mu}$. Events are divided by the bin width. Error bars show statistical uncertainties of data. The blue band shows the propagated uncertainty of all individual fit variations in a given bin, which we consider to be uncorrelated. The lower panels show the ratio of the observed data to the background estimation.

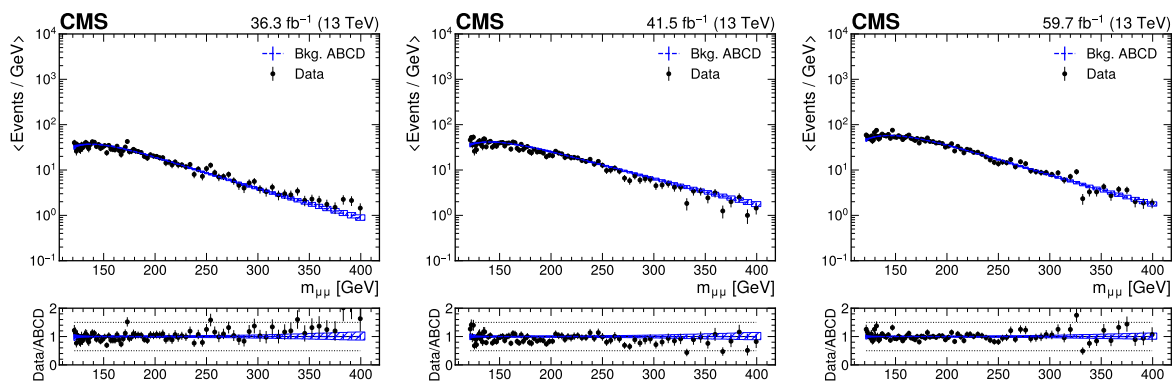


Figure 9. Data (black) vs. the ABCD method background prediction (blue) for 2016 (left), 2017 (middle), and 2018 (right) data-taking years in $\text{SR}_{b+j/b}^{\mu\mu}$. Events are divided by the bin width. Error bars show statistical uncertainties of data. The blue band shows the propagated uncertainty of all individual fit variations in a given bin, which we consider to be uncorrelated. The lower panels show the ratio of the observed data to the background estimation.

mass width. The limits are computed using the CMS statistical analysis tool COMBINE [74] which is based on the ROOFIT [75] and ROOSTATS [76] frameworks. The generator width for Z' boson masses of 125, 250, and 300 GeV is 0.6, 0.65, and 0.72 GeV, respectively. Limits are also set on the presence of a signal for $\text{SR}_b^{\mu\mu}$ and $\text{SR}_{b+j/b}^{\mu\mu}$ separately, as shown in figure 10. No evidence of a statistically significant signal contribution is found from the fit to the data. The most notable deviation from the expected limits occurs in $\text{SR}_b^{\mu\mu}$ at 230 GeV with a 3.1 standard deviations local significance; however, the global significance, computed using MC pseudo-experiments and accounting for both SRs, is only at 0.5 standard deviations due to the look-elsewhere effect [77]. Since we aim to provide model-independent limits corresponding to different signal process diagrams, we do not combine the two SRs in this paper, to avoid assumptions on the mix of processes involved.

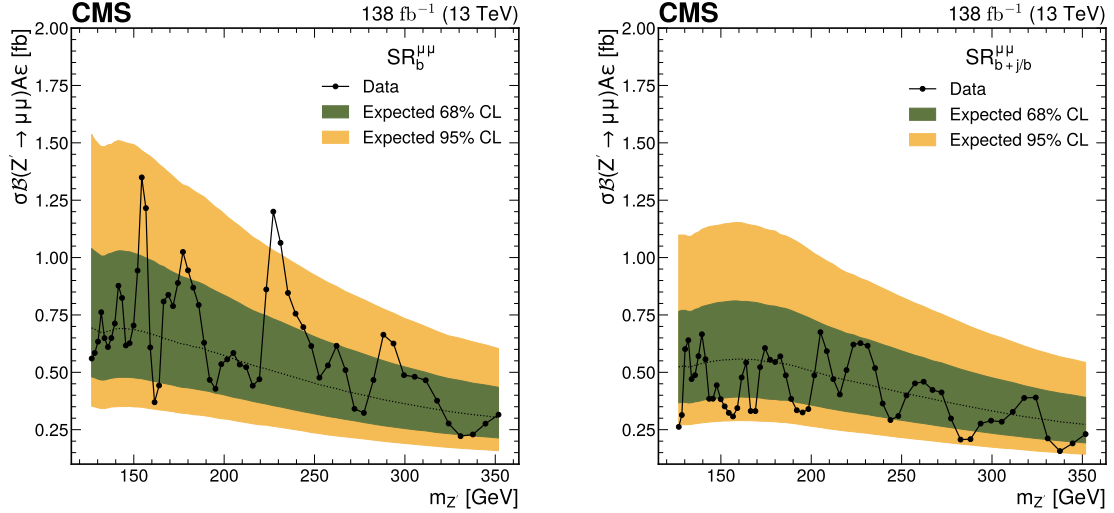


Figure 10. The asymptotic 95% CL limits on the product of cross section(σ), branching fraction into a pair of muons ($\mathcal{B}$), acceptance (A), and efficiency (ϵ). Left is $SR_b^{\mu\mu}$, right is $SR_{b+j/b}^{\mu\mu}$. A combination of both limits depends on the relative acceptance contributions in each region and is omitted here.

Production process categories we consider are based on matrix element level generator selections after hadronization and jet matching with the MLM prescription [60], as described in section 3. The primary concern of this categorization is the number of ISR jets and their flavor (bottom or strange), whilst a secondary concern is, for events with no hard matrix element ISR jets, the production of the Z' boson via one or two associated bottom quarks. The multiplicity of b jets depends on the soft b hadrons from hadronization in the underlying event, and therefore affects the acceptance.

Contributions from other jet flavors, gluons or light and charm quarks, are not considered for the categorization, as they do not couple to the Z' boson in the model considered. The processes are grouped into the following categories, in the order shown in figure 1:

- 0b (b-s): No associated final-state s or b jet production, where the initial state involved a single bottom quark (first diagram of figure 1, tree level).
- 0b (b-b): No associated final-state s or b jet production, where the initial state involved two different bottom quarks (first diagram of figure 1, tree level).
- 1b: A single associated final-state b jet (second diagram of figure 1).
- 1s: A single associated final-state s jet (second diagram of figure 1).
- 1b + 1s: A pair of associated final-state s and b jets (third diagram of figure 1).
- 2b: Two associated final-state b jets (third diagram of figure 1).
- 2s: Two associated final-state s jets (originating from an ISR gluon that splits into an $s\bar{s}$ pair).

$m_{Z'}$ [GeV]	$A\epsilon(\text{SR}_b^{\mu\mu})$ [%]	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu})$ [%]
125	$1.09 \pm 0.01^{+0.02}_{-0.01}$	$0.12 \pm 0.00^{+0.01}_{-0.01}$
150	$2.71 \pm 0.02^{+0.03}_{-0.02}$	$0.29 \pm 0.00^{+0.01}_{-0.01}$
175	$3.80 \pm 0.02^{+0.05}_{-0.03}$	$0.46 \pm 0.01^{+0.02}_{-0.01}$
200	$4.45 \pm 0.02^{+0.06}_{-0.04}$	$0.56 \pm 0.01^{+0.02}_{-0.01}$
250	$4.73 \pm 0.28^{+0.09}_{-0.06}$	$0.76 \pm 0.11^{+0.04}_{-0.02}$
300	$5.44 \pm 0.27^{+0.08}_{-0.06}$	$1.01 \pm 0.12^{+0.04}_{-0.03}$
350	$5.44 \pm 0.02^{+0.04}_{-0.04}$	$0.98 \pm 0.01^{+0.01}_{-0.01}$

Table 5. Acceptance times efficiency by the SR for events with no generator-level matrix element ISR jets of strange or bottom flavor. Exactly one bottom quark contributes directly to the Z' boson production vertex. Statistical and systematic uncertainties for this 0b (b-s) category are listed.

$m_{Z'}$ [GeV]	$A\epsilon(\text{SR}_b^{\mu\mu})$ [%]	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu})$ [%]
125	$1.87 \pm 0.01^{+0.06}_{-0.03}$	$0.23 \pm 0.00^{+0.02}_{-0.01}$
150	$4.78 \pm 0.02^{+0.06}_{-0.03}$	$0.59 \pm 0.01^{+0.04}_{-0.02}$
175	$6.71 \pm 0.03^{+0.10}_{-0.03}$	$0.89 \pm 0.01^{+0.05}_{-0.02}$
200	$7.80 \pm 0.03^{+0.11}_{-0.10}$	$1.12 \pm 0.01^{+0.05}_{-0.04}$
250	$9.09 \pm 0.03^{+0.15}_{-0.10}$	$1.48 \pm 0.01^{+0.06}_{-0.04}$
300	$9.58 \pm 0.03^{+0.15}_{-0.11}$	$1.73 \pm 0.01^{+0.06}_{-0.04}$
350	$9.63 \pm 0.03^{+0.09}_{-0.08}$	$1.86 \pm 0.01^{+0.03}_{-0.03}$

Table 6. Acceptance times efficiency by the SR for events with no generator-level matrix element ISR jets of strange or bottom flavor. Exactly two bottom quarks contribute directly to the Z' boson production vertex. Statistical and systematic uncertainties for this 0b (b-b) category are listed.

The acceptances times efficiency for each production category are given separately in tables 5–11 for each SR, including all relevant event selections. We note that the acceptances are not derived from a single b-tag efficiency; in addition to jets originating from b quarks in the hard process, additional b-tagged jets from gluon splitting or initial- and final-state radiation are also included, as well as effects from other object efficiencies and event selections. However, any realistic model interpretation will have to take into account not only the contribution of each diagram, its acceptance, and the uncertainty in the acceptance, but also the uncertainty in the relative contribution of each category among all categories with ISR and final-state radiation (FSR), and PDF uncertainties. The ISR/FSR and PDF uncertainties can be large in comparison to the systematic uncertainties in the background estimation and the acceptance.

The 95% exclusion limits are derived assuming that the Z' boson decays solely to muons. Since the Z' boson could also decay to electrons, contributions of this process to the dielectron

$m_{Z'} [\text{GeV}]$	$A\epsilon(\text{SR}_b^{\mu\mu}) [\%]$	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu}) [\%]$
125	$6.34 \pm 0.06^{+0.17}_{-0.09}$	$2.59 \pm 0.04^{+0.22}_{-0.12}$
150	$10.95 \pm 0.07^{+0.14}_{-0.07}$	$4.23 \pm 0.04^{+0.24}_{-0.14}$
175	$15.78 \pm 0.08^{+0.22}_{-0.09}$	$5.95 \pm 0.05^{+0.29}_{-0.13}$
200	$18.97 \pm 0.09^{+0.25}_{-0.20}$	$7.30 \pm 0.05^{+0.29}_{-0.21}$
250	$21.42 \pm 0.11^{+0.37}_{-0.24}$	$9.50 \pm 0.07^{+0.41}_{-0.28}$
300	$21.60 \pm 0.09^{+0.34}_{-0.25}$	$9.99 \pm 0.06^{+0.35}_{-0.26}$
350	$21.41 \pm 0.07^{+0.20}_{-0.17}$	$9.38 \pm 0.04^{+0.13}_{-0.13}$

Table 7. Acceptance times efficiency by the SR for events with exactly one generator-level matrix element ISR jets of bottom flavor. Statistical and systematic uncertainties for this 1b category are listed.

$m_{Z'} [\text{GeV}]$	$A\epsilon(\text{SR}_b^{\mu\mu}) [\%]$	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu}) [\%]$
125	$0.28 \pm 0.04^{+0.01}_{-0.00}$	$1.10 \pm 0.08^{+0.08}_{-0.05}$
150	$0.57 \pm 0.04^{+0.01}_{-0.00}$	$1.69 \pm 0.07^{+0.09}_{-0.05}$
175	$0.87 \pm 0.05^{+0.01}_{-0.01}$	$2.41 \pm 0.08^{+0.11}_{-0.07}$
200	$0.94 \pm 0.05^{+0.01}_{-0.01}$	$2.87 \pm 0.09^{+0.11}_{-0.08}$
250	$1.36 \pm 0.83^{+0.00}_{-0.01}$	$5.61 \pm 1.41^{+0.30}_{-0.19}$
300	$1.47 \pm 0.53^{+0.02}_{-0.01}$	$3.52 \pm 0.82^{+0.11}_{-0.08}$
350	$1.15 \pm 0.04^{+0.01}_{-0.01}$	$3.65 \pm 0.07^{+0.04}_{-0.05}$

Table 8. Acceptance times efficiency by the SR for events with exactly one generator-level matrix element ISR jets of strange flavor. Statistical and systematic uncertainties for this 1s category are listed.

$m_{Z'} [\text{GeV}]$	$A\epsilon(\text{SR}_b^{\mu\mu}) [\%]$	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu}) [\%]$
125	$0.68 \pm 0.21^{+0.02}_{-0.01}$	$4.52 \pm 0.50^{+0.32}_{-0.20}$
150	$1.09 \pm 0.17^{+0.01}_{-0.01}$	$7.67 \pm 0.44^{+0.40}_{-0.24}$
175	$2.09 \pm 0.21^{+0.02}_{-0.01}$	$10.01 \pm 0.48^{+0.46}_{-0.30}$
200	$2.57 \pm 0.26^{+0.03}_{-0.02}$	$10.23 \pm 0.47^{+0.36}_{-0.26}$
250	$1.60 \pm 1.60^{+0.01}_{-0.01}$	$11.39 \pm 4.71^{+0.62}_{-0.38}$
300	$3.46 \pm 2.04^{+0.06}_{-0.04}$	$12.45 \pm 3.82^{+0.40}_{-0.31}$
350	$2.88 \pm 0.16^{+0.02}_{-0.02}$	$12.82 \pm 0.34^{+0.13}_{-0.15}$

Table 9. Acceptance times efficiency by the SR for events with exactly two generator-level matrix element ISR jets, one of which has strange, the other bottom flavor. Statistical and systematic uncertainties for this 1b +1s category are listed.

$m_{Z'}$ [GeV]	$A\epsilon(\text{SR}_b^{\mu\mu})$ [%]	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu})$ [%]
125	$1.84 \pm 0.17^{+0.06}_{-0.03}$	$5.24 \pm 0.28^{+0.48}_{-0.26}$
150	$2.74 \pm 0.19^{+0.04}_{-0.02}$	$8.48 \pm 0.34^{+0.51}_{-0.30}$
175	$3.74 \pm 0.20^{+0.04}_{-0.01}$	$11.21 \pm 0.36^{+0.59}_{-0.20}$
200	$4.40 \pm 0.19^{+0.06}_{-0.05}$	$12.47 \pm 0.32^{+0.50}_{-0.39}$
250	$4.65 \pm 0.20^{+0.07}_{-0.05}$	$14.68 \pm 0.36^{+0.60}_{-0.42}$
300	$5.27 \pm 0.16^{+0.07}_{-0.05}$	$14.87 \pm 0.28^{+0.45}_{-0.35}$
350	$4.97 \pm 0.14^{+0.04}_{-0.04}$	$15.55 \pm 0.26^{+0.24}_{-0.23}$

Table 10. Acceptance times efficiency by the SR for events with exactly two generator-level matrix element ISR jets of bottom flavor. Statistical and systematic uncertainties for this 2b category are listed.

$m_{Z'}$ [GeV]	$A\epsilon(\text{SR}_b^{\mu\mu})$ [%]	$A\epsilon(\text{SR}_{b+j/b}^{\mu\mu})$ [%]
125	$0.93 \pm 0.34^{+0.02}_{-0.01}$	$2.05 \pm 0.51^{+0.17}_{-0.09}$
150	$1.55 \pm 0.42^{+0.01}_{-0.00}$	$5.09 \pm 0.83^{+0.31}_{-0.17}$
175	$2.45 \pm 0.50^{+0.02}_{-0.02}$	$5.85 \pm 0.79^{+0.29}_{-0.13}$
200	$2.74 \pm 0.48^{+0.01}_{-0.01}$	$7.96 \pm 0.87^{+0.29}_{-0.22}$
250	$4.66 \pm 0.71^{+0.11}_{-0.06}$	$10.00 \pm 1.12^{+0.43}_{-0.30}$
300	$5.00 \pm 0.66^{+0.06}_{-0.05}$	$9.92 \pm 0.94^{+0.34}_{-0.25}$
350	$2.84 \pm 0.37^{+0.01}_{-0.01}$	$7.54 \pm 0.60^{+0.10}_{-0.10}$

Table 11. Acceptance times efficiency by the SR for events with exactly two generator-level matrix element ISR jets of strange flavor. Statistical and systematic uncertainties for this 2s category are listed.

CRs could modify the background estimation. To test this, we assume an equal contribution to the dimuon signal in size and in shape to the b-quark-rich dielectron CRs. Then, the ABCD background estimation is rerun as described in section 5, including the systematic calculations. Thus modified background predictions are used to recompute exclusion limits. At 200 and 350 GeV, these exclusion limits remain unchanged. However, at the 125 GeV mass point, the observed exclusion limit would degrade by 10%.

8 Summary

A search for a new neutral Z' gauge boson with nonuniversal couplings, decaying into a pair of muons and produced with one or two associated jets, where at least one is b tagged, has been presented. The analysis is based on LHC proton-proton collision data at $\sqrt{s} = 13$ TeV, collected by the CMS experiment during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . Exclusion bounds prior to this analysis predominantly

focused on Z' boson production with universal couplings through light-quark fusion, leading to less stringent constraints on this signature. This analysis provides a complementary approach by targeting Z' boson production through bottom quark fusion, improving the sensitivity to this less-constrained region.

The presented results set the first specific limits on the product of cross section, branching fraction to dimuons, acceptance, and efficiency for bZ' and $b\bar{b}Z'$ production with Z' decays into a pair of muons. The data are consistent with the background-only hypothesis, showing no evidence of a signal. Limits at 95% confidence level on the product of cross section, branching fraction to dimuons, acceptance, and efficiency, ranging from 0.2 to 2 fb, are set for Z' boson masses between 125 and 350 GeV. Process-dependent products of acceptance and efficiency, and model-independent limits on the signal yield are provided. These limits are presently the only results in the mass range of 125–200 GeV. In the mass range of 200–350 GeV, these results provide the most stringent constraints on the specified set of bottom quark fusion production modes, serving as a complementary approach to inclusive Z' boson searches.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); 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, 758316, 765710, 824093, 101115353, 101002207, 101001205, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA) and Fonds voor Wetenschappelijk Onderzoek contract No. 1228724N (Belgium); the Beijing Municipal Science

& Technology Commission, No. Z191100007219010, the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of China under Grant No. 2023YFA1605804, the Natural Science Foundation of China under Grant No. 12061141002, 12535004, and USTC Research Funds of the Double First-Class Initiative No. YD2030002017 (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany’s Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306, and under project number 400140256 – GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program – ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, TKP2021-NKTA-64, and 2021-4.1.2-NEMZ_KI-2024-00036 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, FAIR – Future Artificial Intelligence Research, and CUP I53D23001070006 (Mission 4 Component 1), funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369, 2021/43/B/ST2/01552, 2023/49/B/ST2/03273, and the NAWA contract BPN/PPO/2021/1/00011 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, “European Union NextGenerationEU/PRTR”, and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, the National Science, Research and Innovation Fund program IND_FF_68_369_2300_097, and the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G680009 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

Data Availability Statement. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the [CMS data preservation, re-use and open access policy](#).

Code Availability Statement. The CMS core software is publicly available on [GitHub](#).

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY4.0](#)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] PARTICLE DATA GROUP collaboration, *Review of particle physics*, [Phys. Rev. D](#) **110** (2024) 030001 [[INSPIRE](#)].
- [2] A. Das, P.S.B. Dev, Y. Hosotani and S. Mandal, *Probing the minimal $U(1)_X$ model at future electron-positron colliders via fermion pair-production channels*, [Phys. Rev. D](#) **105** (2022) 115030 [[arXiv:2104.10902](#)] [[INSPIRE](#)].

- [3] B. Allanach, *LHC di-lepton searches for Z' bosons which explain measurements of $b \rightarrow sl^+l^-$ transitions*, *Phys. Lett. B* **858** (2024) 139055 [[arXiv:2404.14748](#)] [[INSPIRE](#)].
- [4] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [[hep-ph/9905221](#)] [[INSPIRE](#)].
- [5] L. Randall and R. Sundrum, *An alternative to compactification*, *Phys. Rev. Lett.* **83** (1999) 4690 [[hep-th/9906064](#)] [[INSPIRE](#)].
- [6] H. Davoudiasl, J.L. Hewett and T.G. Rizzo, *Experimental probes of localized gravity: On and off the wall*, *Phys. Rev. D* **63** (2001) 075004 [[hep-ph/0006041](#)] [[INSPIRE](#)].
- [7] P.K. Mohapatra, R.N. Mohapatra and P.B. Pal, *Implications of E_6 Grand Unification*, *Phys. Rev. D* **33** (1986) 2010 [[INSPIRE](#)].
- [8] D. London and J.L. Rosner, *Extra gauge bosons in E_6* , *Phys. Rev. D* **34** (1986) 1530 [[INSPIRE](#)].
- [9] BABAR collaboration, *Evidence for an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays*, *Phys. Rev. Lett.* **109** (2012) 101802 [[arXiv:1205.5442](#)] [[INSPIRE](#)].
- [10] BABAR collaboration, *Measurement of an Excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons*, *Phys. Rev. D* **88** (2013) 072012 [[arXiv:1303.0571](#)] [[INSPIRE](#)].
- [11] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$* , *Phys. Rev. Lett.* **115** (2015) 111803 [Erratum *ibid.* **115** (2015) 159901] [[arXiv:1506.08614](#)] [[INSPIRE](#)].
- [12] BELLE collaboration, *Measurement of the branching ratio of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, *Phys. Rev. D* **92** (2015) 072014 [[arXiv:1507.03233](#)] [[INSPIRE](#)].
- [13] BELLE collaboration, *Measurement of the branching ratio of $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method*, *Phys. Rev. D* **94** (2016) 072007 [[arXiv:1607.07923](#)] [[INSPIRE](#)].
- [14] BELLE collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$* , *Phys. Rev. Lett.* **118** (2017) 211801 [[arXiv:1612.00529](#)] [[INSPIRE](#)].
- [15] BELLE collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$ with one-prong hadronic τ decays at Belle*, *Phys. Rev. D* **97** (2018) 012004 [[arXiv:1709.00129](#)] [[INSPIRE](#)].
- [16] LHCb collaboration, *Measurement of the ratio of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ and $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ -lepton decays*, *Phys. Rev. Lett.* **120** (2018) 171802 [[arXiv:1708.08856](#)] [[INSPIRE](#)].
- [17] LHCb collaboration, *Test of Lepton Flavor Universality by the measurement of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev. D* **97** (2018) 072013 [[arXiv:1711.02505](#)] [[INSPIRE](#)].
- [18] LHCb collaboration, *Measurement of lepton universality parameters in $B^+ \rightarrow K^+\ell^+\ell^-$ and $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays*, *Phys. Rev. D* **108** (2023) 032002 [[arXiv:2212.09153](#)] [[INSPIRE](#)].
- [19] LHCb collaboration, *Test of lepton universality in $b \rightarrow sl^+\ell^-$ decays*, *Phys. Rev. Lett.* **131** (2023) 051803 [[arXiv:2212.09152](#)] [[INSPIRE](#)].
- [20] M. Abdullah et al., *Bottom-quark fusion processes at the LHC for probing Z' models and B -meson decay anomalies*, *Phys. Rev. D* **97** (2018) 075035 [[arXiv:1707.07016](#)] [[INSPIRE](#)].
- [21] B.C. Allanach, J.M. Butterworth and T. Corbett, *Collider constraints on Z' models for neutral current B -anomalies*, *JHEP* **08** (2019) 106 [[arXiv:1904.10954](#)] [[INSPIRE](#)].

- [22] ATLAS collaboration, *Search for high-mass dilepton resonances using 139fb^{-1} of pp collision data collected at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *Phys. Lett. B* **796** (2019) 68 [[arXiv:1903.06248](#)] [[INSPIRE](#)].
- [23] ATLAS collaboration, *Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector*, *JHEP* **11** (2020) 005 [Erratum *ibid.* **04** (2021) 142] [[arXiv:2006.12946](#)] [[INSPIRE](#)].
- [24] CMS collaboration, *Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13\text{ TeV}$* , *JHEP* **07** (2021) 208 [[arXiv:2103.02708](#)] [[INSPIRE](#)].
- [25] ATLAS collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36fb^{-1} of pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **01** (2018) 055 [[arXiv:1709.07242](#)] [[INSPIRE](#)].
- [26] CMS collaboration, *Search for heavy neutral resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , *Phys. Rev. D* **111** (2025) 112004 [[arXiv:2412.04357](#)] [[INSPIRE](#)].
- [27] ATLAS collaboration, *Search for new resonances in mass distributions of jet pairs using 139fb^{-1} of pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **03** (2020) 145 [[arXiv:1910.08447](#)] [[INSPIRE](#)].
- [28] CMS collaboration, *Search for narrow resonances in the b-tagged dijet mass spectrum in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , *Phys. Rev. D* **108** (2023) 012009 [[arXiv:2205.01835](#)] [[INSPIRE](#)].
- [29] K.R. Lynch, E.H. Simmons, M. Narain and S. Mrenna, *Finding Z' bosons coupled preferentially to the third family at LEP and the Tevatron*, *Phys. Rev. D* **63** (2001) 035006 [[hep-ph/0007286](#)] [[INSPIRE](#)].
- [30] R.S. Chivukula, E.H. Simmons and J. Terning, *A heavy top quark and the $Zb\bar{b}$ vertex in noncommuting extended technicolor*, *Phys. Lett. B* **331** (1994) 383 [[hep-ph/9404209](#)] [[INSPIRE](#)].
- [31] D.J. Muller and S. Nandi, *Top flavor: A Separate $SU(2)$ for the third family*, *Phys. Lett. B* **383** (1996) 345 [[hep-ph/9602390](#)] [[INSPIRE](#)].
- [32] CMS collaboration, *Search for a high-mass dimuon resonance produced in association with b quark jets at $\sqrt{s} = 13\text{ TeV}$* , *JHEP* **10** (2023) 043 [[arXiv:2307.08708](#)] [[INSPIRE](#)].
- [33] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** (2009) 1199 [[arXiv:0801.1345](#)] [[INSPIRE](#)].
- [34] ATLAS collaboration, *Search for high-mass dilepton resonances in pp collisions at $\sqrt{s} = 8\text{ TeV}$ with the ATLAS detector*, *Phys. Rev. D* **90** (2014) 052005 [[arXiv:1405.4123](#)] [[INSPIRE](#)].
- [35] CMS collaboration, *Measurement of the production cross section for $Z+b$ jets in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , *Phys. Rev. D* **105** (2022) 092014 [[arXiv:2112.09659](#)] [[INSPIRE](#)].
- [36] ATLAS collaboration, *Measurements of the production cross-section for a Z boson in association with b-jets in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **07** (2020) 044 [[arXiv:2003.11960](#)] [[INSPIRE](#)].
- [37] HEPData record for this analysis, (2025) [DOI:10.17182/hepdata.165428](#).
- [38] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [39] CMS collaboration, *Development of the CMS detector for the CERN LHC Run 3*, 2024 *JINST* **19** P05064 [[arXiv:2309.05466](#)] [[INSPIRE](#)].
- [40] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , 2020 *JINST* **15** P10017 [[arXiv:2006.10165](#)] [[INSPIRE](#)].

- [41] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [42] CMS collaboration, *Performance of the CMS high-level trigger during LHC Run 2*, 2024 *JINST* **19** P11021 [[arXiv:2410.17038](#)] [[INSPIRE](#)].
- [43] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, 2021 *JINST* **16** P05014 [[arXiv:2012.06888](#)] [[INSPIRE](#)].
- [44] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P06015 [[arXiv:1804.04528](#)] [[INSPIRE](#)].
- [45] CMS collaboration, *Description and Performance of Track and Primary-Vertex Reconstruction with the CMS Tracker*, 2014 *JINST* **9** P10009 [[arXiv:1405.6569](#)] [[INSPIRE](#)].
- [46] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].
- [47] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [48] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [49] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, 2017 *JINST* **12** P02014 [[arXiv:1607.03663](#)] [[INSPIRE](#)].
- [50] CMS collaboration, *Jet algorithms performance in 13 TeV data*, CMS-PAS-JME-16-003 (2017) [[INSPIRE](#)].
- [51] CMS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector*, 2019 *JINST* **14** P07004 [[arXiv:1903.06078](#)] [[INSPIRE](#)].
- [52] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*, 2018 *JINST* **13** P05011 [[arXiv:1712.07158](#)] [[INSPIRE](#)].
- [53] E. Bols et al., *Jet Flavour Classification Using DeepJet*, 2020 *JINST* **15** P12012 [[arXiv:2008.10519](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector*, (2023) CMS-DP-2023-005.
- [55] CMS collaboration, *Pileup mitigation at CMS in 13 TeV data*, 2020 *JINST* **15** P09018 [[arXiv:2003.00503](#)] [[INSPIRE](#)].
- [56] CMS collaboration, *ECAL 2016 refined calibration and Run2 summary plots*, (2020) CMS-DP-2020-021.
- [57] CMS collaboration, *Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV*, 2015 *JINST* **10** P06005 [[arXiv:1502.02701](#)] [[INSPIRE](#)].
- [58] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [59] NNPDF collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663 [[arXiv:1706.00428](#)] [[INSPIRE](#)].
- [60] M.L. Mangano, M. Moretti, F. Piccinini and M. Treccani, *Matching matrix elements and shower evolution for top-pair production in hadronic collisions*, *JHEP* **01** (2007) 013 [[hep-ph/0611129](#)] [[INSPIRE](#)].

- [61] N.D. Christensen and C. Duhr, *FeynRules — Feynman rules made easy*, *Comput. Phys. Commun.* **180** (2009) 1614 [[arXiv:0806.4194](#)] [[INSPIRE](#)].
- [62] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [[arXiv:1209.6215](#)] [[INSPIRE](#)].
- [63] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [64] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [65] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [[arXiv:1512.00815](#)] [[INSPIRE](#)].
- [66] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [[arXiv:1903.12179](#)] [[INSPIRE](#)].
- [67] GEANT4 collaboration, *GEANT4 — A Simulation Toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [68] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [[arXiv:2104.01927](#)] [[INSPIRE](#)].
- [69] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV*, (2018) [CMS-PAS-LUM-17-004](#).
- [70] CMS Collaboration, *CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV*, (2019) [CMS-PAS-LUM-18-002](#).
- [71] CMS collaboration, *Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV*, *JHEP* **07** (2018) 161 [[arXiv:1802.02613](#)] [[INSPIRE](#)].
- [72] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001 [[arXiv:1510.03865](#)] [[INSPIRE](#)].
- [73] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [Erratum *ibid.* **73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].
- [74] CMS collaboration, *The CMS Statistical Analysis and Combination Tool: Combine*, *Comput. Softw. Big Sci.* **8** (2024) 19 [[arXiv:2404.06614](#)] [[INSPIRE](#)].
- [75] W. Verkerke and D.P. Kirkby, *The RooFit toolkit for data modeling*, *eConf C* **0303241** (2003) MOLT007 [[physics/0306116](#)] [[INSPIRE](#)].
- [76] L. Moneta et al., *The RooStats Project*, *PoS ACAT2010* (2010) 057 [[arXiv:1009.1003](#)] [[INSPIRE](#)].
- [77] E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, *Eur. Phys. J. C* **70** (2010) 525 [[arXiv:1005.1891](#)] [[INSPIRE](#)].

The CMS collaboration

V. Chekhovsky¹, A. Hayrapetyan¹, V. Makarenko¹, A. Tumasyan^{1,a}, W. Adam²,
 J.W. Andrejkovic², L. Benato², T. Bergauer², S. Chatterjee², K. Damanakis²,
 M. Dragicevic², P.S. Hussain², M. Jeitler^{2,b}, N. Krammer², A. Li², D. Liko²,
 I. Mikulec², J. Schieck^{2,b}, R. Schöffbeck^{2,b}, D. Schwarz², M. Sonawane²,
 W. Waltenberger², C.-E. Wulz^{2,b}, T. Janssen³, H. Kwon³, T. Van Laer³,
 P. Van Mechelen³, N. Breugelmans⁴, J. D'Hondt⁴, S. Dansana⁴, A. De Moor⁴,
 M. Delcourt⁴, F. Heyen⁴, Y. Hong⁴, S. Lowette⁴, I. Makarenko⁴, D. Müller⁴,
 S. Tavernier⁴, M. Tytgat^{4,c}, G.P. Van Onsem⁴, S. Van Putte⁴, D. Vannerom⁴, B. Bilin⁵,
 B. Clerbaux⁵, A.K. Das⁵, I. De Bruyn⁵, G. De Lentdecker⁵, H. Evard⁵, L. Favart⁵,
 P. Giannaios⁵, A. Khalilzadeh⁵, F.A. Khan⁵, K. Lee⁵, A. Malara⁵, M.A. Shahzad⁵,
 L. Thomas⁵, M. Vanden Bemden⁵, C. Vander Velde⁵, P. Vanlaer⁵, M. De Coen⁶,
 D. Dobur⁶, G. Gokbulut⁶, J. Knolle⁶, L. Lambrecht⁶, D. Marecx⁶, K. Skovpen⁶,
 N. Van Den Bossche⁶, J. van der Linden⁶, L. Wezenbeek⁶, S. Bein⁷, A. Benecke⁷,
 A. Bethani⁷, G. Bruno⁷, C. Caputo⁷, J. De Favereau De Jeneret⁷, C. Delaere⁷,
 I.S. Donertas⁷, A. Giammanco⁷, A.O. Guzel⁷, Sa. Jain⁷, V. Lemaître⁷, J. Lidrych⁷,
 P. Mastrapasqua⁷, T.T. Tran⁷, S. Turkcapar⁷, G.A. Alves⁸, E. Coelho⁸,
 G. Correia Silva⁸, C. Hensel⁸, T. Menezes De Oliveira⁸, C. Mora Herrera^{8,d},
 P. Rebello Teles⁸, M. Soeiro⁸, E.J. Tonelli Manganote^{8,e}, A. Vilela Pereira^{8,d},
 W.L. Aldá Júnior⁹, M. Barroso Ferreira Filho⁹, H. Brandao Malbouisson⁹, W. Carvalho⁹,
 J. Chinellato^{9,f}, E.M. Da Costa⁹, G.G. Da Silva^{9,g}, D. De Jesus Damiao⁹,
 S. Fonseca De Souza⁹, R. Gomes De Souza⁹, T. Laux Kuhn^{9,g}, M. Macedo⁹, J. Martins⁹,
 K. Mota Amarilo⁹, L. Mundim⁹, H. Nogima⁹, J.P. Pinheiro⁹, A. Santoro⁹, A. Sznajder⁹,
 M. Thiel⁹, C.A. Bernardes^{10,g}, L. Calligaris¹⁰, T.R. Fernandez Perez Tomei¹⁰,
 E.M. Gregores¹⁰, I. Maïetto Silverio¹⁰, P.G. Mercadante¹⁰, S.F. Novaes¹⁰, B. Orzari¹⁰,
 Sandra S. Padula¹⁰, V. Scheurer¹⁰, A. Aleksandrov¹¹, G. Antchev¹¹, R. Hadjiiska¹¹,
 P. Iaydjiev¹¹, M. Misheva¹¹, M. Shopova¹¹, G. Sultanov¹¹, A. Dimitrov¹², L. Litov¹²,
 B. Pavlov¹², P. Petkov¹², A. Petrov¹², E. Shumka¹², S. Keshri¹³, D. Laroze¹³,
 S. Thakur¹³, T. Cheng¹⁴, T. Javaid¹⁴, L. Yuan¹⁴, Z. Hu¹⁵, Z. Liang¹⁵, J. Liu¹⁵,
 G.M. Chen^{16,h}, H.S. Chen^{16,h}, M. Chen^{16,h}, F. Iemmi¹⁶, C.H. Jiang¹⁶, A. Kapoor^{16,i},
 H. Liao¹⁶, Z.-A. Liu^{16,j}, R. Sharma^{16,k}, J.N. Song^{16,j}, J. Tao¹⁶, C. Wang^{16,h}, J. Wang¹⁶,
 Z. Wang^{16,h}, H. Zhang¹⁶, J. Zhao¹⁶, A. Agapitos¹⁷, Y. Ban¹⁷,
 A. Carvalho Antunes De Oliveira¹⁷, S. Deng¹⁷, B. Guo¹⁷, C. Jiang¹⁷, A. Levin¹⁷, C. Li¹⁷,
 Q. Li¹⁷, Y. Mao¹⁷, S. Qian¹⁷, S.J. Qian¹⁷, X. Qin¹⁷, X. Sun¹⁷, D. Wang¹⁷, H. Yang¹⁷,
 Y. Zhao¹⁷, C. Zhou¹⁷, S. Yang¹⁸, Z. You¹⁹, K. Jaffel²⁰, N. Lu²⁰, G. Bauer^{21,l}, B. Li^{21,m},
 H. Wang²¹, K. Yi^{21,n}, J. Zhang²¹, Y. Li²², Z. Lin²³, C. Lu²³, M. Xiao²³, C. Avila²⁴,
 D.A. Barbosa Trujillo²⁴, A. Cabrera²⁴, C. Florez²⁴, J. Fraga²⁴, J.A. Reyes Vega²⁴,
 J. Jaramillo²⁵, C. Rendón²⁵, M. Rodriguez²⁵, A.A. Ruales Barbosa²⁵, J.D. Ruiz Alvarez²⁵,
 D. Giljanovic²⁶, N. Godinovic²⁶, D. Lelas²⁶, A. Sculac²⁶, M. Kovac²⁷, A. Petkovic²⁷,
 T. Sculac²⁷, P. Bargassa²⁸, V. Brigljevic²⁸, B.K. Chitroda²⁸, D. Ferencek²⁸, K. Jakovcic²⁸,
 A. Starodumov^{28,o}, T. Susa²⁸, A. Attikis²⁹, K. Christoforou²⁹, A. Hadjiagapiou²⁹,
 C. Leonidou²⁹, J. Mousa²⁹, C. Nicolaou²⁹, L. Paizanos²⁹, F. Ptochos²⁹, P.A. Razis²⁹,
 H. Rykaczewski²⁹, H. Saka²⁹, A. Steppenov²⁹, M. Finger³⁰, M. Finger Jr.³⁰, A. Kveton³⁰,

E. Ayala ³¹, E. Carrera Jarrin ³², A.A. Abdelalim ^{33,p,q}, S. Elgammal ^{33,r}, A. Ellithi Kamel ^{33,s}, M. Abdullah Al-Mashad ³⁴, M.A. Mahmoud ³⁴, K. Ehataht ³⁵, M. Kadastik ³⁵, T. Lange ³⁵, C. Nielsen ³⁵, J. Pata ³⁵, M. Raidal ³⁵, L. Tani ³⁵, C. Veelken ³⁵, K. Osterberg ³⁶, M. Voutilainen ³⁶, N. Bin Norjoharuddeen ³⁷, E. Brücken ³⁷, F. Garcia ³⁷, P. Inkaew ³⁷, K.T.S. Kallonen ³⁷, T. Lampén ³⁷, K. Lassila-Perini ³⁷, S. Lehti ³⁷, T. Lindén ³⁷, M. Myllymäki ³⁷, M.m. Rantanen ³⁷, J. Tuominiemi ³⁷, H. Kirschenmann ³⁸, P. Luukka ³⁸, H. Petrow ³⁸, M. Besancon ³⁹, F. Couderc ³⁹, M. Dejardin ³⁹, D. Denegri ³⁹, J.L. Faure ³⁹, F. Ferri ³⁹, S. Ganjour ³⁹, P. Gras ³⁹, G. Hamel de Monchenault ³⁹, M. Kumar ³⁹, V. Lohezic ³⁹, J. Malcles ³⁹, F. Orlandi ³⁹, L. Portales ³⁹, A. Rosowsky ³⁹, M.Ö. Sahin ³⁹, A. Savoy-Navarro ^{39,t}, P. Simkina ³⁹, M. Titov ³⁹, M. Tornago ³⁹, F. Beaudette ⁴⁰, G. Boldrini ⁴⁰, P. Busson ⁴⁰, A. Cappati ⁴⁰, C. Charlot ⁴⁰, M. Chiusi ⁴⁰, T.D. Cuisset ⁴⁰, F. Damas ⁴⁰, O. Davignon ⁴⁰, A. De Wit ⁴⁰, I.T. Ehle ⁴⁰, B.A. Fontana Santos Alves ⁴⁰, S. Ghosh ⁴⁰, A. Gilbert ⁴⁰, R. Granier de Cassagnac ⁴⁰, A. Hakimi ⁴⁰, B. Harikrishnan ⁴⁰, L. Kalipoliti ⁴⁰, G. Liu ⁴⁰, M. Nguyen ⁴⁰, S. Obraztsov ⁴⁰, C. Ochando ⁴⁰, R. Salerno ⁴⁰, J.B. Sauvan ⁴⁰, Y. Sirois ⁴⁰, G. Sokmen ⁴⁰, L. Urda Gómez ⁴⁰, E. Vernazza ⁴⁰, A. Zabi ⁴⁰, A. Zghiche ⁴⁰, J.-L. Agram ^{41,u}, J. Andrea ⁴¹, D. Apparu ⁴¹, D. Bloch ⁴¹, J.-M. Brom ⁴¹, E.C. Chabert ⁴¹, C. Collard ⁴¹, S. Falke ⁴¹, U. Goerlach ⁴¹, R. Haeberle ⁴¹, A.-C. Le Bihan ⁴¹, M. Meena ⁴¹, O. Poncet ⁴¹, G. Saha ⁴¹, M.A. Sessini ⁴¹, P. Van Hove ⁴¹, P. Vaucelle ⁴¹, A. Di Florio ⁴², D. Amram ⁴³, S. Beauceron ⁴³, B. Blancon ⁴³, G. Boudoul ⁴³, N. Chanon ⁴³, D. Contardo ⁴³, P. Depasse ⁴³, C. Dozen ^{43,v}, H. El Mamouni ⁴³, J. Fay ⁴³, S. Gascon ⁴³, M. Gouzevitch ⁴³, C. Greenberg ⁴³, G. Grenier ⁴³, B. Ille ⁴³, E. Jourdhuy ⁴³, I.B. Laktineh ⁴³, M. Lethuillier ⁴³, L. Mirabito ⁴³, S. Perries ⁴³, A. Purohit ⁴³, M. Vander Donckt ⁴³, P. Verdier ⁴³, J. Xiao ⁴³, A. Khvedelidze ^{44,w}, I. Lomidze ⁴⁴, Z. Tsamalaidze ^{44,w}, V. Botta ⁴⁵, S. Consuegra Rodríguez ⁴⁵, L. Feld ⁴⁵, K. Klein ⁴⁵, M. Lipinski ⁴⁵, D. Meuser ⁴⁵, A. Pauls ⁴⁵, D. Pérez Adán ⁴⁵, N. Röwert ⁴⁵, M. Teroerde ⁴⁵, S. Diekmann ⁴⁶, A. Dodonova ⁴⁶, N. Eich ⁴⁶, D. Eliseev ⁴⁶, F. Engelke ⁴⁶, J. Erdmann ⁴⁶, M. Erdmann ⁴⁶, B. Fischer ⁴⁶, T. Hebbeker ⁴⁶, K. Hoepfner ⁴⁶, F. Ivone ⁴⁶, A. Jung ⁴⁶, M.y. Lee ⁴⁶, F. Mausolf ⁴⁶, M. Merschmeyer ⁴⁶, A. Meyer ⁴⁶, S. Mukherjee ⁴⁶, D. Noll ⁴⁶, F. Nowotny ⁴⁶, A. Pozdnyakov ⁴⁶, Y. Rath ⁴⁶, W. Redjeb ⁴⁶, F. Rehm ⁴⁶, H. Reithler ⁴⁶, V. Sarkisovi ⁴⁶, A. Schmidt ⁴⁶, C. Seth ⁴⁶, A. Sharma ⁴⁶, J.L. Spah ⁴⁶, F. Torres Da Silva De Araujo ^{46,x}, S. Wiedenbeck ⁴⁶, S. Zaleski ⁴⁶, C. Dziwok ⁴⁷, G. Flügge ⁴⁷, T. Kress ⁴⁷, A. Nowack ⁴⁷, O. Pooth ⁴⁷, A. Stahl ⁴⁷, T. Ziemons ⁴⁷, A. Zotz ⁴⁷, H. Aarup Petersen ⁴⁸, M. Aldaya Martin ⁴⁸, J. Alimena ⁴⁸, S. Amoroso ⁴⁸, Y. An ⁴⁸, J. Bach ⁴⁸, S. Baxter ⁴⁸, M. Bayatmakou ⁴⁸, H. Becerril Gonzalez ⁴⁸, O. Behnke ⁴⁸, A. Belvedere ⁴⁸, F. Blekman ^{48,y}, K. Borras ^{48,z}, A. Campbell ⁴⁸, A. Cardini ⁴⁸, F. Colombina ⁴⁸, M. De Silva ⁴⁸, G. Eckerlin ⁴⁸, D. Eckstein ⁴⁸, L.I. Estevez Banos ⁴⁸, E. Gallo ^{48,y}, A. Geiser ⁴⁸, V. Guglielmi ⁴⁸, M. Guthoff ⁴⁸, A. Hinzmann ⁴⁸, L. Jeppe ⁴⁸, B. Kaech ⁴⁸, M. Kasemann ⁴⁸, C. Kleinwort ⁴⁸, R. Kogler ⁴⁸, M. Komm ⁴⁸, D. Krücker ⁴⁸, W. Lange ⁴⁸, D. Leyva Pernia ⁴⁸, K. Lipka ^{48,aa}, W. Lohmann ^{48,ab}, F. Lorkowski ⁴⁸, R. Mankel ⁴⁸, I.-A. Melzer-Pellmann ⁴⁸, M. Mendizabal Morentin ⁴⁸, A.B. Meyer ⁴⁸, G. Milella ⁴⁸, K. Moral Figueroa ⁴⁸, A. Mussgiller ⁴⁸, L.P. Nair ⁴⁸, J. Niedziela ⁴⁸, A. Nürnberg ⁴⁸, J. Park ⁴⁸, E. Ranken ⁴⁸, A. Raspereza ⁴⁸, D. Rastorguev ⁴⁸, J. Rübenach ⁴⁸, L. Rygaard ⁴⁸, M. Scham ^{48,ac,ad}, S. Schnake ^{48,z}, P. Schütze ⁴⁸, C. Schwanenberger ^{48,y},

D. Selivanova⁴⁸, K. Shako⁴⁸, M. Shchedrolosiev⁴⁸, D. Stafford⁴⁸, F. Vazzoler⁴⁸,
A. Ventura Barroso⁴⁸, R. Walsh⁴⁸, D. Wang⁴⁸, Q. Wang⁴⁸, K. Wichmann⁴⁸, L. Wiens^{48,z},
C. Wissing⁴⁸, Y. Yang⁴⁸, S. Zakharov⁴⁸, A. Zimmermann Castro Santos⁴⁸, A. Albrecht⁴⁹,
S. Albrecht⁴⁹, M. Antonello⁴⁹, S. Bollweg⁴⁹, M. Bonanomi⁴⁹, P. Connor⁴⁹,
K. El Morabit⁴⁹, Y. Fischer⁴⁹, E. Garutti⁴⁹, A. Grohsjean⁴⁹, J. Haller⁴⁹, D. Hundhausen⁴⁹,
H.R. Jabusch⁴⁹, G. Kasieczka⁴⁹, P. Keicher⁴⁹, R. Klanner⁴⁹, W. Korcari⁴⁹, T. Kramer⁴⁹,
C.c. Kuo⁴⁹, V. Kutzner⁴⁹, F. Labe⁴⁹, J. Lange⁴⁹, A. Lobanov⁴⁹, C. Matthies⁴⁹,
L. Moureaux⁴⁹, M. Mrowietz⁴⁹, A. Nigamova⁴⁹, Y. Nissan⁴⁹, A. Paasch⁴⁹,
K.J. Pena Rodriguez⁴⁹, T. Quadfasel⁴⁹, B. Raciti⁴⁹, M. Rieger⁴⁹, D. Savoie⁴⁹,
J. Schindler⁴⁹, P. Schleper⁴⁹, M. Schröder⁴⁹, J. Schwandt⁴⁹, M. Sommerhalder⁴⁹,
H. Stadie⁴⁹, G. Steinbrück⁴⁹, A. Tews⁴⁹, B. Wiederspan⁴⁹, M. Wolf⁴⁹, S. Brommer⁵⁰,
E. Butz⁵⁰, T. Chwalek⁵⁰, A. Dierlamm⁵⁰, G.G. Dincer⁵⁰, U. Elicabuk⁵⁰, N. Faltermann⁵⁰,
M. Giffels⁵⁰, A. Gottmann⁵⁰, F. Hartmann^{50,ae}, R. Hofsaess⁵⁰, M. Horzela⁵⁰,
U. Husemann⁵⁰, J. Kieseler⁵⁰, M. Klute⁵⁰, O. Lavoryk⁵⁰, J.M. Lawhorn⁵⁰, M. Link⁵⁰,
A. Lintuluoto⁵⁰, S. Maier⁵⁰, S. Mitra⁵⁰, M. Mormile⁵⁰, Th. Müller⁵⁰, M. Neukum⁵⁰,
M. Oh⁵⁰, E. Pfeffer⁵⁰, M. Presilla⁵⁰, G. Quast⁵⁰, K. Rabbertz⁵⁰, B. Regnery⁵⁰,
N. Shadskiy⁵⁰, I. Shvetsov⁵⁰, H.J. Simonis⁵⁰, L. Sowa⁵⁰, L. Stockmeier⁵⁰, K. Tauqeer⁵⁰,
M. Toms⁵⁰, B. Topko⁵⁰, N. Trevisani⁵⁰, R.F. Von Cube⁵⁰, M. Wassmer⁵⁰, S. Wieland⁵⁰,
F. Wittig⁵⁰, R. Wolf⁵⁰, X. Zuo⁵⁰, G. Anagnostou⁵¹, G. Daskalakis⁵¹, A. Kyriakis⁵¹,
A. Papadopoulos^{51,ae}, A. Stakia⁵¹, G. Melachroinos⁵², Z. Painesis⁵², I. Paraskevas⁵²,
N. Saoulidou⁵², K. Theofilatos⁵², E. Tziaferi⁵², K. Vellidis⁵², I. Zisopoulos⁵², G. Bakas⁵³,
T. Chatzistavrou⁵³, G. Karapostoli⁵³, K. Kousouris⁵³, I. Papakrivopoulos⁵³, E. Siamarkou⁵³,
G. Tsiopolitis⁵³, A. Zacharopoulou⁵³, I. Bestintzanos⁵⁴, I. Evangelou⁵⁴, C. Foudas⁵⁴,
C. Kamtsikis⁵⁴, P. Katsoulis⁵⁴, P. Kokkas⁵⁴, P.G. Kosmoglou Kioseoglou⁵⁴, N. Manthos⁵⁴,
I. Papadopoulos⁵⁴, J. Strologas⁵⁴, C. Hajdu⁵⁵, D. Horvath^{55,af,ag}, K. Márton⁵⁵,
A.J. Rádl^{55,ah}, F. Sikler⁵⁵, V. Veszpremi⁵⁵, M. Csanád⁵⁶, K. Farkas⁵⁶, A. Fehérkúti^{56,ai},
M.M.A. Gadallah^{56,aj}, Á. Kadlecik⁵⁶, P. Major⁵⁶, G. Pásztor⁵⁶, G.I. Veres⁵⁶,
B. Ujvari⁵⁷, G. Zilizi⁵⁷, G. Bencze⁵⁸, S. Czellar⁵⁸, J. Molnar⁵⁸, Z. Szillasi⁵⁸, T. Csorgo^{59,ai},
F. Nemes^{59,ai}, T. Novak⁵⁹, S. Bansal⁶⁰, S.B. Beri⁶⁰, V. Bhatnagar⁶⁰, G. Chaudhary⁶⁰,
S. Chauhan⁶⁰, N. Dhingra^{60,ak}, A. Kaur⁶⁰, A. Kaur⁶⁰, H. Kaur⁶⁰, M. Kaur⁶⁰,
S. Kumar⁶⁰, T. Sheokand⁶⁰, J.B. Singh⁶⁰, A. Singla⁶⁰, A. Bhardwaj⁶¹, A. Chhetri⁶¹,
B.C. Choudhary⁶¹, A. Kumar⁶¹, A. Kumar⁶¹, M. Naimuddin⁶¹, K. Ranjan⁶¹, M.K. Saini⁶¹,
S. Saumya⁶¹, S. Baradia⁶², S. Barman^{62,al}, S. Bhattacharya⁶², S. Das Gupta⁶², S. Dutta⁶²,
S. Dutta⁶², S. Sarkar⁶², M.M. Ameen⁶³, P.K. Behera⁶³, S.C. Behera⁶³, S. Chatterjee⁶³,
G. Dash⁶³, P. Jana⁶³, P. Kalbhor⁶³, S. Kamble⁶³, J.R. Komaragiri^{63,am}, D. Kumar^{63,am},
T. Mishra⁶³, B. Parida^{63,an}, P.R. Pujahari⁶³, N.R. Saha⁶³, A. Sharma⁶³, A.K. Sikdar⁶³,
R.K. Singh⁶³, P. Verma⁶³, S. Verma⁶³, A. Vijay⁶³, S. Dugad⁶⁴, G.B. Mohanty⁶⁴,
M. Shelake⁶⁴, P. Suryadevara⁶⁴, A. Bala⁶⁵, S. Banerjee⁶⁵, S. Bhowmik⁶⁵, R.M. Chatterjee⁶⁵,
M. Guchait⁶⁵, Sh. Jain⁶⁵, A. Jaiswal⁶⁵, B.M. Joshi⁶⁵, S. Kumar⁶⁵, G. Majumder⁶⁵,
K. Mazumdar⁶⁵, S. Parolia⁶⁵, A. Thachayath⁶⁵, S. Bahinipati^{66,ao}, C. Kar⁶⁶,
D. Maity^{66,ap}, P. Mal⁶⁶, K. Naskar^{66,ap}, A. Nayak^{66,ap}, S. Nayak⁶⁶, K. Pal⁶⁶, P. Sadangi⁶⁶,
S.K. Swain⁶⁶, S. Varghese^{66,ap}, D. Vats^{66,ap}, S. Acharya^{67,aq}, A. Alpana⁶⁷, S. Dube⁶⁷,
B. Gomber^{67,aq}, P. Hazarika⁶⁷, B. Kansal⁶⁷, A. Laha⁶⁷, B. Sahu^{67,aq}, S. Sharma⁶⁷,

K.Y. Vaish ⁶⁷, H. Bakhshiansohi ^{68,ar}, A. Jafari ^{68,as}, M. Zeinali ^{68,at}, S. Bashiri ⁶⁹, S. Chenarani ^{69,au}, S.M. Etesami ⁶⁹, Y. Hosseini ⁶⁹, M. Khakzad ⁶⁹, E. Khazaie ⁶⁹, M. Mohammadi Najafabadi ⁶⁹, S. Tizchang ^{69,av}, M. Felcini ⁷⁰, M. Grunewald ⁷⁰, M. Abbrescia ^{71a,71b}, A. Colaleo ^{71a,71b}, D. Creanza ^{71a,71c}, B. D'Anzi ^{71a,71b}, N. De Filippis ^{71a,71c}, M. De Palma ^{71a,71b}, W. Elmetenawee ^{71a,71b,p}, N. Ferrara ^{71a,71b}, L. Fiore ^{71a}, G. Iaselli ^{71a,71c}, L. Longo ^{71a}, M. Louka ^{71a,71b}, G. Maggi ^{71a,71c}, M. Maggi ^{71a}, I. Margjeka ^{71a}, V. Mastrapasqua ^{71a,71b}, S. My ^{71a,71b}, S. Nuzzo ^{71a,71b}, A. Pellecchia ^{71a,71b}, A. Pompili ^{71a,71b}, G. Pugliese ^{71a,71c}, R. Radogna ^{71a,71b}, D. Ramos ^{71a}, A. Ranieri ^{71a}, L. Silvestris ^{71a}, F.M. Simone ^{71a,71c}, Ü. Sözbilir ^{71a}, A. Stamerra ^{71a,71b}, D. Troiano ^{71a,71b}, R. Venditti ^{71a,71b}, P. Verwilligen ^{71a}, A. Zaza ^{71a,71b}, G. Abbiendi ^{72a}, C. Battilana ^{72a,72b}, D. Bonacorsi ^{72a,72b}, P. Capiluppi ^{72a,72b}, A. Castro ^{72a,72b,†}, F.R. Cavallo ^{72a}, M. Cuffiani ^{72a,72b}, G.M. Dallavalle ^{72a}, T. Diotallevi ^{72a,72b}, F. Fabbri ^{72a}, A. Fanfani ^{72a,72b}, D. Fasanella ^{72a}, P. Giacomelli ^{72a}, L. Giommi ^{72a,72b}, C. Grandi ^{72a}, L. Guiducci ^{72a,72b}, S. Lo Meo ^{72a,aw}, M. Lorusso ^{72a,72b}, L. Lunerti ^{72a}, S. Marcellini ^{72a}, G. Masetti ^{72a}, F.L. Navarria ^{72a,72b}, G. Paggi ^{72a,72b}, A. Perrotta ^{72a}, F. Primavera ^{72a,72b}, A.M. Rossi ^{72a,72b}, S. Rossi Tisbeni ^{72a,72b}, T. Rovelli ^{72a,72b}, G.P. Siroli ^{72a,72b}, S. Costa ^{73a,73b,ax}, A. Di Mattia ^{73a}, A. Lapertosa ^{73a}, R. Potenza ^{73a,73b}, A. Tricomi ^{73a,73b,ax}, P. Assiouras ^{74a}, G. Barbagli ^{74a}, G. Bardelli ^{74a,74b}, B. Camaiani ^{74a,74b}, A. Cassese ^{74a}, R. Ceccarelli ^{74a}, V. Ciulli ^{74a,74b}, C. Civinini ^{74a}, R. D'Alessandro ^{74a,74b}, E. Focardi ^{74a,74b}, T. Kello ^{74a}, G. Latino ^{74a,74b}, P. Lenzi ^{74a,74b}, M. Lizzo ^{74a}, M. Meschini ^{74a}, S. Paoletti ^{74a}, A. Papanastassiou ^{74a,74b}, G. Sguazzoni ^{74a}, L. Viliani ^{74a}, L. Benussi ⁷⁵, S. Bianco ⁷⁵, S. Meola ^{75,ay}, D. Piccolo ⁷⁵, M. Alves Gallo Pereira ^{76a}, F. Ferro ^{76a}, E. Robutti ^{76a}, S. Tosi ^{76a,76b}, A. Benaglia ^{77a}, F. Brivio ^{77a}, F. Cetorelli ^{77a,77b}, F. De Guio ^{77a,77b}, M.E. Dinardo ^{77a,77b}, P. Dini ^{77a}, S. Gennai ^{77a}, R. Gerosa ^{77a,77b}, A. Ghezzi ^{77a,77b}, P. Govoni ^{77a,77b}, L. Guzzi ^{77a}, G. Lavizzari ^{77a,77b}, M.T. Lucchini ^{77a,77b}, M. Malberti ^{77a}, S. Malvezzi ^{77a}, A. Massironi ^{77a}, D. Menasce ^{77a}, L. Moroni ^{77a}, M. Paganoni ^{77a,77b}, S. Palluotto ^{77a,77b}, D. Pedrini ^{77a}, A. Perego ^{77a,77b}, B.S. Pinolini ^{77a}, G. Pizzati ^{77a,77b}, S. Ragazzi ^{77a,77b}, T. Tabarelli de Fatis ^{77a,77b}, S. Buontempo ^{78a}, A. Cagnotta ^{78a,78b}, F. Carnevali ^{78a,78b}, N. Cavallo ^{78a,78c}, F. Fabozzi ^{78a,78c}, A.O.M. Iorio ^{78a,78b}, L. Lista ^{78a,78b,az}, P. Paolucci ^{78a,ae}, B. Rossi ^{78a}, R. Ardino ^{79a}, P. Azzi ^{79a}, N. Bacchetta ^{79a,ba}, M. Benettoni ^{79a}, A. Bergnoli ^{79a}, P. Bortignon ^{79a}, G. Bortolato ^{79a,79b}, A. Bragagnolo ^{79a,79b}, A.C.M. Bulla ^{79a}, R. Carlin ^{79a,79b}, T. Dorigo ^{79a,bb}, F. Gasparini ^{79a,79b}, U. Gasparini ^{79a,79b}, S. Giorgetti ^{79a}, E. Lusiani ^{79a}, M. Margoni ^{79a,79b}, A.T. Meneguzzo ^{79a,79b}, M. Migliorini ^{79a,79b}, J. Pazzini ^{79a,79b}, P. Ronchese ^{79a,79b}, R. Rossin ^{79a,79b}, F. Simonetto ^{79a,79b}, M. Tosi ^{79a,79b}, A. Triossi ^{79a,79b}, S. Ventura ^{79a}, M. Zanetti ^{79a,79b}, P. Zotto ^{79a,79b}, A. Zucchetta ^{79a,79b}, G. Zumerle ^{79a,79b}, A. Braghieri ^{80a}, S. Calzaferri ^{80a}, D. Fiorina ^{80a}, P. Montagna ^{80a,80b}, V. Re ^{80a}, C. Riccardi ^{80a,80b}, P. Salvini ^{80a}, I. Vai ^{80a,80b}, P. Vitulo ^{80a,80b}, S. Ajmal ^{81a,81b}, M.E. Ascioti ^{81a,81b}, G.M. Bilei ^{81a}, C. Carrivale ^{81a,81b}, D. Ciangottini ^{81a,81b}, L. Fanò ^{81a,81b}, V. Mariani ^{81a,81b}, M. Menichelli ^{81a}, F. Moscatelli ^{81a,bc}, A. Rossi ^{81a,81b}, A. Santocchia ^{81a,81b}, D. Spiga ^{81a}, T. Tedeschi ^{81a,81b}, C. Aimè ^{82a}, C.A. Alexe ^{82a,82c}, P. Asenov ^{82a,82b}, P. Azzurri ^{82a}, G. Bagliesi ^{82a}, R. Bhattacharya ^{82a}, L. Bianchini ^{82a,82b}, T. Boccali ^{82a}, E. Bossini ^{82a}, D. Bruschini ^{82a,82c}, R. Castaldi ^{82a}, M.A. Ciocci ^{82a,82b}, M. Cipriani ^{82a,82b},

V. D'Amante ^{82a,82d}, R. Dell'Orso ^{82a}, S. Donato ^{82a}, A. Giassi ^{82a}, F. Ligabue ^{82a,82c},
A.C. Marini ^{82a,82b}, D. Matos Figueiredo ^{82a}, A. Messineo ^{82a,82b}, S. Mishra ^{82a},
V.K. Muraleedharan Nair Bindhu ^{82a,82b,ap}, M. Musich ^{82a,82b}, S. Nandan ^{82a}, F. Palla ^{82a},
A. Rizzi ^{82a,82b}, G. Rolandi ^{82a,82c}, S. Roy Chowdhury ^{82a}, T. Sarkar ^{82a}, A. Scribano ^{82a},
P. Spagnolo ^{82a}, R. Tenchini ^{82a}, G. Tonelli ^{82a,82b}, N. Turini ^{82a,82d}, F. Vaselli ^{82a,82c},
A. Venturi ^{82a}, P.G. Verdini ^{82a}, P. Barria ^{83a}, C. Basile ^{83a,83b}, F. Cavallari ^{83a},
L. Cunqueiro Mendez ^{83a,83b}, D. Del Re ^{83a,83b}, E. Di Marco ^{83a,83b}, M. Diemoz ^{83a},
F. Errico ^{83a,83b}, R. Gargiulo ^{83a,83b}, E. Longo ^{83a,83b}, L. Martikainen ^{83a,83b},
J. Mijuskovic ^{83a,83b}, G. Organtini ^{83a,83b}, F. Pandolfi ^{83a}, R. Paramatti ^{83a,83b},
C. Quaranta ^{83a,83b}, S. Rahatlou ^{83a,83b}, C. Rovelli ^{83a}, F. Santanastasio ^{83a,83b}, L. Soffi ^{83a},
V. Vladimirov ^{83a,83b}, N. Amapane ^{84a,84b}, R. Arcidiacono ^{84a,84c}, S. Argiro ^{84a,84b},
M. Arneodo ^{84a,84c}, N. Bartosik ^{84a}, R. Bellan ^{84a,84b}, C. Biino ^{84a}, C. Borca ^{84a,84b},
N. Cartiglia ^{84a}, M. Costa ^{84a,84b}, R. Covarelli ^{84a,84b}, N. Demaria ^{84a}, L. Finco ^{84a},
M. Grippo ^{84a,84b}, B. Kiani ^{84a,84b}, F. Legger ^{84a}, F. Luongo ^{84a,84b}, C. Mariotti ^{84a},
L. Markovic ^{84a,84b}, S. Maselli ^{84a}, A. Mecca ^{84a,84b}, L. Menzio ^{84a,84b}, P. Meridiani ^{84a},
E. Migliore ^{84a,84b}, M. Monteno ^{84a}, R. Mulargia ^{84a}, M.M. Obertino ^{84a,84b}, G. Ortona ^{84a},
L. Pacher ^{84a,84b}, N. Pastrone ^{84a}, M. Pelliccioni ^{84a}, M. Ruspá ^{84a,84c}, F. Siviero ^{84a,84b},
V. Sola ^{84a,84b}, A. Solano ^{84a,84b}, A. Staiano ^{84a}, C. Tarricone ^{84a,84b}, D. Trocino ^{84a},
G. Umoret ^{84a,84b}, R. White ^{84a,84b}, J. Babbar ^{85a,85b}, S. Belforte ^{85a}, V. Candelise ^{85a,85b},
M. Casarsa ^{85a}, F. Cossutti ^{85a}, K. De Leo ^{85a}, G. Della Ricca ^{85a,85b}, S. Dogra ⁸⁶,
J. Hong ⁸⁶, J. Kim ⁸⁶, D. Lee ⁸⁶, H. Lee ⁸⁶, S.W. Lee ⁸⁶, C.S. Moon ⁸⁶, Y.D. Oh ⁸⁶,
M.S. Ryu ⁸⁶, S. Sekmen ⁸⁶, B. Tae ⁸⁶, Y.C. Yang ⁸⁶, M.S. Kim ⁸⁷, G. Bak ⁸⁸, P. Gwak ⁸⁸,
H. Kim ⁸⁸, D.H. Moon ⁸⁸, E. Asilar ⁸⁹, J. Choi ^{89,8d}, D. Kim ⁸⁹, T.J. Kim ⁸⁹, J.A. Merlin ⁸⁹,
Y. Ryou ⁸⁹, S. Choi ⁹⁰, S. Han ⁹⁰, B. Hong ⁹⁰, K. Lee ⁹⁰, K.S. Lee ⁹⁰, S. Lee ⁹⁰, J. Yoo ⁹⁰,
J. Goh ⁹¹, S. Yang ⁹¹, Y. Kang ⁹², H. S. Kim ⁹², Y. Kim ⁹², S. Lee ⁹², J. Almond ⁹³,
J.H. Bhyun ⁹³, J. Choi ⁹³, J. Choi ⁹³, W. Jun ⁹³, J. Kim ⁹³, Y.W. Kim ⁹³, S. Ko ⁹³, H. Lee ⁹³,
J. Lee ⁹³, J. Lee ⁹³, B.H. Oh ⁹³, S.B. Oh ⁹³, H. Seo ⁹³, U.K. Yang ⁹³, I. Yoon ⁹³,
W. Jang ⁹⁴, D.Y. Kang ⁹⁴, S. Kim ⁹⁴, B. Ko ⁹⁴, J.S.H. Lee ⁹⁴, Y. Lee ⁹⁴, I.C. Park ⁹⁴, Y. Roh ⁹⁴,
I.J. Watson ⁹⁴, S. Ha ⁹⁵, K. Hwang ⁹⁵, B. Kim ⁹⁵, H.D. Yoo ⁹⁵, M. Choi ⁹⁶, M.R. Kim ⁹⁶,
H. Lee ⁹⁶, Y. Lee ⁹⁶, I. Yu ⁹⁶, T. Beyrouthy ⁹⁷, Y. Gharbia ⁹⁷, F. Alazemi ⁹⁸,
K. Dreimanis ⁹⁹, A. Gaile ⁹⁹, C. Munoz Diaz ⁹⁹, D. Osite ⁹⁹, G. Pikurs ⁹⁹, A. Potrebko ⁹⁹,
M. Seidel ⁹⁹, D. Sidiropoulos Kontos ⁹⁹, N.R. Strautnieks ¹⁰⁰, M. Ambrozas ¹⁰¹,
A. Juodagalvis ¹⁰¹, A. Rinkevicius ¹⁰¹, G. Tamulaitis ¹⁰¹, I. Yusuff ^{102,be}, Z. Zolkapli ¹⁰²,
J.F. Benitez ¹⁰³, A. Castaneda Hernandez ¹⁰³, H.A. Encinas Acosta ¹⁰³, L.G. Gallegos Maríñez ¹⁰³,
M. León Coello ¹⁰³, J.A. Murillo Quijada ¹⁰³, A. Sehrawat ¹⁰³, L. Valencia Palomo ¹⁰³,
G. Ayala ¹⁰⁴, H. Castilla-Valdez ¹⁰⁴, H. Crotte Ledesma ¹⁰⁴, E. De La Cruz-Burelo ¹⁰⁴,
I. Heredia-De La Cruz ^{104,bf}, R. Lopez-Fernandez ¹⁰⁴, J. Mejia Guisao ¹⁰⁴,
C.A. Mondragon Herrera ¹⁰⁴, A. Sánchez Hernández ¹⁰⁴, C. Oropeza Barrera ¹⁰⁵,
M. Ramírez García ¹⁰⁵, D.L. Ramirez Guadarrama ¹⁰⁵, I. Bautista ¹⁰⁶, F.E. Neri Huerta ¹⁰⁶,
I. Pedraza ¹⁰⁶, H.A. Salazar Ibarguen ¹⁰⁶, C. Uribe Estrada ¹⁰⁶, I. Bujanja ¹⁰⁷,
N. Raicevic ¹⁰⁷, P.H. Butler ¹⁰⁸, A. Ahmad ¹⁰⁹, M.I. Asghar ¹⁰⁹, A. Awais ¹⁰⁹,
M.I.M. Awan ¹⁰⁹, H.R. Hoorani ¹⁰⁹, W.A. Khan ¹⁰⁹, V. Avati ¹¹⁰, A. Bellora ¹¹⁰,
L. Forthomme ¹¹⁰, L. Grzanka ¹¹⁰, M. Malawski ¹¹⁰, K. Piotrkowski ¹¹⁰, H. Bialkowska ¹¹¹,

M. Bluj¹¹¹, M. Górski¹¹¹, M. Kazana¹¹¹, M. Szleper¹¹¹, P. Zalewski¹¹¹,
 K. Bunkowski¹¹², K. Doroba¹¹², A. Kalinowski¹¹², M. Konecki¹¹², J. Krolikowski¹¹²,
 A. Muhammad¹¹², P. Fokow¹¹³, K. Pozniak¹¹³, W. Zabolotny¹¹³, M. Araujo¹¹⁴,
 D. Bastos¹¹⁴, C. Beirão Da Cruz E Silva¹¹⁴, A. Boletti¹¹⁴, M. Bozzo¹¹⁴, T. Camporesi¹¹⁴,
 G. Da Molin¹¹⁴, P. Faccioli¹¹⁴, M. Gallinaro¹¹⁴, J. Hollar¹¹⁴, N. Leonardo¹¹⁴,
 G.B. Marozzo¹¹⁴, A. Petrilli¹¹⁴, M. Pisano¹¹⁴, J. Seixas¹¹⁴, J. Varela¹¹⁴, J.W. Wulff¹¹⁴,
 P. Adzic¹¹⁵, P. Milenovic¹¹⁵, D. Devetak¹¹⁶, M. Dordevic¹¹⁶, J. Milosevic¹¹⁶,
 L. Nadder¹¹⁶, V. Reko¹¹⁶, M. Stojanovic¹¹⁶, J. Alcaraz Maestre¹¹⁷,
 Cristina F. Bedoya¹¹⁷, J.A. Brochero Cifuentes¹¹⁷, Oliver M. Carretero¹¹⁷, M. Cepeda¹¹⁷,
 M. Cerrada¹¹⁷, N. Colino¹¹⁷, B. De La Cruz¹¹⁷, A. Delgado Peris¹¹⁷,
 A. Escalante Del Valle¹¹⁷, D. Fernández Del Val¹¹⁷, J.P. Fernández Ramos¹¹⁷, J. Flix¹¹⁷,
 M.C. Fouz¹¹⁷, O. Gonzalez Lopez¹¹⁷, S. Goy Lopez¹¹⁷, J.M. Hernandez¹¹⁷, M.I. Josa¹¹⁷,
 J. Llorente Merino¹¹⁷, C. Martin Perez¹¹⁷, E. Martin Viscasillas¹¹⁷, D. Moran¹¹⁷,
 C. M. Morcillo Perez¹¹⁷, Á. Navarro Tobar¹¹⁷, C. Perez Dengra¹¹⁷,
 A. Pérez-Calero Yzquierdo¹¹⁷, J. Puerta Pelayo¹¹⁷, I. Redondo¹¹⁷, J. Sastre¹¹⁷,
 J. Vazquez Escobar¹¹⁷, J.F. de Trocóniz¹¹⁸, B. Alvarez Gonzalez¹¹⁹, J. Cuevas¹¹⁹,
 J. Fernandez Menendez¹¹⁹, S. Folgueras¹¹⁹, I. Gonzalez Caballero¹¹⁹, P. Leguina¹¹⁹,
 E. Palencia Cortezon¹¹⁹, J. Prado Pico¹¹⁹, V. Rodríguez Bouza¹¹⁹, A. Soto Rodríguez¹¹⁹,
 A. Trapote¹¹⁹, C. Vico Villalba¹¹⁹, P. Vischia¹¹⁹, S. Blanco Fernández¹²⁰, I.J. Cabrillo¹²⁰,
 A. Calderon¹²⁰, J. Duarte Campderros¹²⁰, M. Fernandez¹²⁰, G. Gomez¹²⁰,
 C. Lasaosa García¹²⁰, R. Lopez Ruiz¹²⁰, C. Martinez Rivero¹²⁰,
 P. Martinez Ruiz del Arbol¹²⁰, F. Matorras¹²⁰, P. Matorras Cuevas¹²⁰,
 E. Navarrete Ramos¹²⁰, J. Piedra Gomez¹²⁰, L. Scodellaro¹²⁰, I. Vila¹²⁰,
 J.M. Vizán García¹²⁰, B. Kailasapathy^{121,bg}, D.D.C. Wickramarathna¹²¹,
 W.G.D. Dharmaratna^{122,bh}, K. Liyanage¹²², N. Perera¹²², D. Abbaneo¹²³,
 C. Amendola¹²³, E. Auffray¹²³, G. Auzinger¹²³, J. Baechler¹²³, D. Barney¹²³,
 A. Bermúdez Martínez¹²³, M. Bianco¹²³, A.A. Bin Anuar¹²³, A. Bocci¹²³, L. Borgonovi¹²³,
 C. Botta¹²³, E. Brondolin¹²³, C.E. Brown¹²³, C. Caillol¹²³, G. Cerminara¹²³,
 N. Chernyavskaya¹²³, D. d’Enterria¹²³, A. Dabrowski¹²³, A. David¹²³, A. De Roeck¹²³,
 M.M. Defranchis¹²³, M. Deile¹²³, M. Dobson¹²³, G. Franzoni¹²³, W. Funk¹²³, S. Giani¹²³,
 D. Gigi¹²³, K. Gill¹²³, F. Glege¹²³, M. Glowacki¹²³, J. Hegeman¹²³, J.K. Heikkilä¹²³,
 B. Huber¹²³, V. Innocente¹²³, T. James¹²³, P. Janot¹²³, O. Kaluzinska¹²³,
 O. Karachaban^{123,ab}, G. Karathanasis¹²³, S. Laurila¹²³, P. Lecoq¹²³, E. Leutgeb¹²³,
 C. Lourenço¹²³, M. Magherini¹²³, L. Malgeri¹²³, M. Mannelli¹²³, M. Matthewman¹²³,
 A. Mehta¹²³, F. Meijers¹²³, S. Mersi¹²³, E. Meschi¹²³, V. Milosevic¹²³, F. Monti¹²³,
 F. Moortgat¹²³, M. Mulders¹²³, I. Neutelings¹²³, S. Orfanelli¹²³, F. Pantaleo¹²³,
 G. Petrucciani¹²³, A. Pfeiffer¹²³, M. Pierini¹²³, H. Qu¹²³, D. Rabady¹²³,
 B. Ribeiro Lopes¹²³, F. Riti¹²³, M. Rovere¹²³, H. Sakulin¹²³, R. Salvatico¹²³,
 S. Sanchez Cruz¹²³, S. Scarfi¹²³, M. Selvaggi¹²³, A. Sharma¹²³, K. Shchelina¹²³,
 P. Silva¹²³, P. Sphicas^{123,bi}, A.G. Stahl Leiton¹²³, A. Steen¹²³, S. Summers¹²³,
 D. Treille¹²³, P. Tropea¹²³, D. Walter¹²³, J. Wanczyk^{123,bj}, J. Wang¹²³, S. Wuchterl¹²³,
 P. Zehetner¹²³, P. Zejdl¹²³, W.D. Zeuner¹²³, T. Bevilacqua^{124,bk}, L. Caminada^{124,bk},
 A. Ebrahimi¹²⁴, W. Erdmann¹²⁴, R. Horisberger¹²⁴, Q. Ingram¹²⁴, H.C. Kaestli¹²⁴,

D. Kotlinski ¹²⁴, C. Lange ¹²⁴, M. Missiroli ^{124,bk}, L. Noehte ^{124,bk}, T. Rohe ¹²⁴,
 A. Samalan ¹²⁴, T.K. Aarrestad ¹²⁵, M. Backhaus ¹²⁵, G. Bonomelli ¹²⁵, A. Calandri ¹²⁵,
 C. Cazzaniga ¹²⁵, K. Datta ¹²⁵, P. De Bryas Dexmiers D'archiac ^{125,bj}, A. De Cosa ¹²⁵,
 G. Dissertori ¹²⁵, M. Dittmar ¹²⁵, M. Donegà ¹²⁵, F. Eble ¹²⁵, M. Galli ¹²⁵, K. Gedia ¹²⁵,
 F. Glessgen ¹²⁵, C. Grab ¹²⁵, N. Härringer ¹²⁵, T.G. Harte ¹²⁵, D. Hits ¹²⁵,
 W. Lustermann ¹²⁵, A.-M. Lyon ¹²⁵, R.A. Manzoni ¹²⁵, M. Marchegiani ¹²⁵, L. Marchese ¹²⁵,
 A. Mascellani ^{125,bj}, F. Nessi-Tedaldi ¹²⁵, F. Pauss ¹²⁵, V. Perovic ¹²⁵, S. Pigazzini ¹²⁵,
 B. Ristic ¹²⁵, R. Seidita ¹²⁵, J. Steggemann ^{125,bj}, A. Tarabini ¹²⁵, D. Valsecchi ¹²⁵,
 R. Wallny ¹²⁵, C. Amsler ^{126,bl}, P. Bärtschi ¹²⁶, M.F. Canelli ¹²⁶, K. Cormier ¹²⁶,
 M. Huwiler ¹²⁶, W. Jin ¹²⁶, A. Jofrehei ¹²⁶, B. Kilminster ¹²⁶, S. Leontsinis ¹²⁶,
 S.P. Liechti ¹²⁶, A. Macchiolo ¹²⁶, P. Meiring ¹²⁶, F. Meng ¹²⁶, J. Motta ¹²⁶, A. Reimers ¹²⁶,
 P. Robmann ¹²⁶, M. Senger ¹²⁶, E. Shokr ¹²⁶, F. Stäger ¹²⁶, R. Tramontano ¹²⁶, C. Adloff ^{127,bm},
 D. Bhowmik ¹²⁷, C.M. Kuo ¹²⁷, W. Lin ¹²⁷, P.K. Rout ¹²⁷, P.C. Tiwari ^{127,am}, L. Ceard ¹²⁸,
 K.F. Chen ¹²⁸, Z.g. Chen ¹²⁸, A. De Iorio ¹²⁸, W.-S. Hou ¹²⁸, T.h. Hsu ¹²⁸, Y.w. Kao ¹²⁸,
 S. Karmakar ¹²⁸, G. Kole ¹²⁸, Y.y. Li ¹²⁸, R.-S. Lu ¹²⁸, E. Paganis ¹²⁸, X.f. Su ¹²⁸,
 J. Thomas-Wilsker ¹²⁸, L.s. Tsai ¹²⁸, D. Tsionou ¹²⁸, H.y. Wu ¹²⁸, E. Yazgan ¹²⁸,
 C. Asawatangtrakuldee ¹²⁹, N. Srimanobhas ¹²⁹, V. Wachirapusanand ¹²⁹, Y. Maghrbi ¹³⁰,
 D. Agyel ¹³¹, F. Boran ¹³¹, F. Dolek ¹³¹, I. Dumanoglu ^{131,bn}, E. Eskut ¹³¹, Y. Guler ^{131,bo},
 E. Gurpinar Guler ^{131,bo}, C. Isik ¹³¹, O. Kara ¹³¹, A. Kayis Topaksu ¹³¹, Y. Komurcu ¹³¹,
 G. Onengut ¹³¹, K. Ozdemir ^{131,bp}, A. Polatoz ¹³¹, B. Tali ^{131,bq}, U.G. Tok ¹³¹, E. Uslan ¹³¹,
 I.S. Zorbakir ¹³¹, M. Yalvac ^{132,br}, B. Akgun ¹³³, I.O. Atakisi ¹³³, E. Gülmez ¹³³,
 M. Kaya ^{133,bs}, O. Kaya ^{133,bt}, S. Tekten ^{133,bu}, A. Cakir ¹³⁴, K. Cankocak ^{134,bn,bv},
 S. Sen ^{134,bw}, O. Aydilek ^{135,bx}, B. Haciasahinoglu ¹³⁵, I. Hos ^{135,by}, B. Kaynak ¹³⁵,
 S. Ozkorucuklu ¹³⁵, O. Potok ¹³⁵, H. Sert ¹³⁵, C. Simsek ¹³⁵, C. Zorbilmez ¹³⁵, S. Cerci ¹³⁶,
 B. Isildak ^{136,bz}, D. Sunar Cerci ¹³⁶, T. Yetkin ¹³⁶, A. Boyaryntsev ¹³⁷, B. Grynyov ¹³⁷,
 L. Levchuk ¹³⁸, D. Anthony ¹³⁹, J.J. Brooke ¹³⁹, A. Bundock ¹³⁹, F. Bury ¹³⁹,
 E. Clement ¹³⁹, D. Cussans ¹³⁹, H. Flacher ¹³⁹, J. Goldstein ¹³⁹, H.F. Heath ¹³⁹,
 M.-L. Holmberg ¹³⁹, L. Kreczko ¹³⁹, S. Paramesvaran ¹³⁹, L. Robertshaw ¹³⁹, V.J. Smith ¹³⁹,
 K. Walkingshaw Pass ¹³⁹, A.H. Ball ¹⁴⁰, K.W. Bell ¹⁴⁰, A. Belyaev ^{140,ca}, C. Brew ¹⁴⁰,
 R.M. Brown ¹⁴⁰, D.J.A. Cockerill ¹⁴⁰, C. Cooke ¹⁴⁰, A. Elliot ¹⁴⁰, K.V. Ellis ¹⁴⁰, K. Harder ¹⁴⁰,
 S. Harper ¹⁴⁰, J. Linacre ¹⁴⁰, K. Manolopoulos ¹⁴⁰, D.M. Newbold ¹⁴⁰, E. Olaiya ¹⁴⁰,
 D. Petyt ¹⁴⁰, T. Reis ¹⁴⁰, A.R. Sahasransu ¹⁴⁰, G. Salvi ¹⁴⁰, T. Schuh ¹⁴⁰,
 C.H. Shepherd-Themistocleous ¹⁴⁰, I.R. Tomalin ¹⁴⁰, K.C. Whalen ¹⁴⁰, T. Williams ¹⁴⁰,
 I. Andreou ¹⁴¹, R. Bainbridge ¹⁴¹, P. Bloch ¹⁴¹, O. Buchmuller ¹⁴¹, C.A. Carrillo Montoya ¹⁴¹,
 G.S. Chahal ^{141,cb}, D. Colling ¹⁴¹, J.S. Dancu ¹⁴¹, I. Das ¹⁴¹, P. Dauncey ¹⁴¹, G. Davies ¹⁴¹,
 M. Della Negra ¹⁴¹, S. Fayer ¹⁴¹, G. Fedi ¹⁴¹, G. Hall ¹⁴¹, A. Howard ¹⁴¹, G. Iles ¹⁴¹,
 C.R. Knight ¹⁴¹, P. Krueper ¹⁴¹, J. Langford ¹⁴¹, K.H. Law ¹⁴¹, J. León Holgado ¹⁴¹,
 L. Lyons ¹⁴¹, A.-M. Magnan ¹⁴¹, B. Maier ¹⁴¹, S. Mallios ¹⁴¹, M. Mieskolainen ¹⁴¹,
 J. Nash ^{141,cc}, M. Pesaresi ¹⁴¹, P.B. Pradeep ¹⁴¹, B.C. Radburn-Smith ¹⁴¹, A. Richards ¹⁴¹,
 A. Rose ¹⁴¹, K. Savva ¹⁴¹, C. Seez ¹⁴¹, R. Shukla ¹⁴¹, A. Tapper ¹⁴¹, K. Uchida ¹⁴¹,
 G.P. Uttley ¹⁴¹, T. Virdee ^{141,ae}, M. Vojinovic ¹⁴¹, N. Wardle ¹⁴¹, D. Winterbottom ¹⁴¹,
 J.E. Cole ¹⁴², A. Khan ¹⁴², P. Kyberd ¹⁴², I.D. Reid ¹⁴², S. Abdullin ¹⁴³, A. Brinkerhoff ¹⁴³,
 E. Collins ¹⁴³, M.R. Darwish ¹⁴³, J. Dittmann ¹⁴³, K. Hatakeyama ¹⁴³, V. Hegde ¹⁴³,

J. Hiltbrand¹⁴³, B. McMaster¹⁴³, J. Samudio¹⁴³, S. Sawant¹⁴³, C. Sutantawibul¹⁴³,
 J. Wilson¹⁴³, R. Bartek¹⁴⁴, A. Dominguez¹⁴⁴, A.E. Simsek¹⁴⁴, S.S. Yu¹⁴⁴, B. Bam¹⁴⁵,
 A. Buchot Perraguin¹⁴⁵, R. Chudasama¹⁴⁵, S.I. Cooper¹⁴⁵, C. Crovella¹⁴⁵, S.V. Gleyzer¹⁴⁵,
 E. Pearson¹⁴⁵, C.U. Perez¹⁴⁵, P. Rumerio^{145,cd}, E. Usai¹⁴⁵, R. Yi¹⁴⁵, A. Akpinar¹⁴⁶,
 C. Cosby¹⁴⁶, G. De Castro¹⁴⁶, Z. Demiragli¹⁴⁶, C. Erice¹⁴⁶, C. Fangmeier¹⁴⁶,
 C. Fernandez Madrazo¹⁴⁶, E. Fontanesi¹⁴⁶, D. Gastler¹⁴⁶, F. Golf¹⁴⁶, S. Jeon¹⁴⁶,
 J. O'cain¹⁴⁶, I. Reed¹⁴⁶, J. Rohlf¹⁴⁶, K. Salyer¹⁴⁶, D. Sperka¹⁴⁶, D. Spitzbart¹⁴⁶,
 I. Suarez¹⁴⁶, A. Tsatsos¹⁴⁶, A.G. Zecchinelli¹⁴⁶, G. Barone¹⁴⁷, G. Benelli¹⁴⁷, D. Cutts¹⁴⁷,
 L. Gouskos¹⁴⁷, M. Hadley¹⁴⁷, U. Heintz¹⁴⁷, K.W. Ho¹⁴⁷, J.M. Hogan^{147,ce}, T. Kwon¹⁴⁷,
 G. Landsberg¹⁴⁷, K.T. Lau¹⁴⁷, J. Luo¹⁴⁷, S. Mondal¹⁴⁷, T. Russell¹⁴⁷, S. Sagir^{147,cf},
 X. Shen¹⁴⁷, M. Stamenkovic¹⁴⁷, N. Venkatasubramanian¹⁴⁷, S. Abbott¹⁴⁸, B. Barton¹⁴⁸,
 C. Brainerd¹⁴⁸, R. Breedon¹⁴⁸, H. Cai¹⁴⁸, M. Calderon De La Barca Sanchez¹⁴⁸,
 M. Chertok¹⁴⁸, M. Citron¹⁴⁸, J. Conway¹⁴⁸, P.T. Cox¹⁴⁸, R. Erbacher¹⁴⁸, F. Jensen¹⁴⁸,
 O. Kukral¹⁴⁸, G. Mocellin¹⁴⁸, M. Mulhearn¹⁴⁸, S. Ostrom¹⁴⁸, W. Wei¹⁴⁸, S. Yoo¹⁴⁸,
 F. Zhang¹⁴⁸, K. Adamidis¹⁴⁹, M. Bachtis¹⁴⁹, D. Campos¹⁴⁹, R. Cousins¹⁴⁹, A. Datta¹⁴⁹,
 G. Flores Avila¹⁴⁹, J. Hauser¹⁴⁹, M. Ignatenko¹⁴⁹, M.A. Iqbal¹⁴⁹, T. Lam¹⁴⁹, Y.f. Lo¹⁴⁹,
 E. Manca¹⁴⁹, A. Nunez Del Prado¹⁴⁹, D. Saltzberg¹⁴⁹, V. Valuev¹⁴⁹, R. Clare¹⁵⁰,
 J.W. Gary¹⁵⁰, G. Hanson¹⁵⁰, A. Aportela¹⁵¹, A. Arora¹⁵¹, J.G. Branson¹⁵¹,
 S. Cittolin¹⁵¹, S. Cooperstein¹⁵¹, D. Diaz¹⁵¹, J. Duarte¹⁵¹, L. Giannini¹⁵¹, Y. Gu¹⁵¹,
 J. Guiang¹⁵¹, R. Kansal¹⁵¹, V. Krutelyov¹⁵¹, R. Lee¹⁵¹, J. Letts¹⁵¹,
 M. Masciovecchio¹⁵¹, F. Mokhtar¹⁵¹, S. Mukherjee¹⁵¹, M. Pieri¹⁵¹, D. Primosch¹⁵¹,
 M. Quinnan¹⁵¹, V. Sharma¹⁵¹, M. Tadel¹⁵¹, E. Vourliotis¹⁵¹, F. Würthwein¹⁵¹,
 Y. Xiang¹⁵¹, A. Yagil¹⁵¹, A. Barzdukas¹⁵², L. Brennan¹⁵², C. Campagnari¹⁵²,
 K. Downham¹⁵², C. Grieco¹⁵², M.M. Hussain¹⁵², J. Incandela¹⁵², J. Kim¹⁵², A.J. Li¹⁵²,
 P. Masterson¹⁵², H. Mei¹⁵², J. Richman¹⁵², S.N. Santpur¹⁵², U. Sarica¹⁵², R. Schmitz¹⁵²,
 F. Setti¹⁵², J. Sheplock¹⁵², D. Stuart¹⁵², T.Á. Vámi¹⁵², X. Yan¹⁵², D. Zhang¹⁵²,
 S. Bhattacharya¹⁵³, A. Bornheim¹⁵³, O. Cerri¹⁵³, J. Mao¹⁵³, H.B. Newman¹⁵³,
 G. Reales Gutiérrez¹⁵³, M. Spiropulu¹⁵³, J.R. Vlimant¹⁵³, C. Wang¹⁵³, S. Xie¹⁵³,
 R.Y. Zhu¹⁵³, J. Alison¹⁵⁴, S. An¹⁵⁴, P. Bryant¹⁵⁴, M. Cremonesi¹⁵⁴, V. Dutta¹⁵⁴,
 T. Ferguson¹⁵⁴, T.A. Gómez Espinosa¹⁵⁴, A. Harilal¹⁵⁴, A. Kallil Tharayil¹⁵⁴, M. Kanemura¹⁵⁴,
 C. Liu¹⁵⁴, T. Mudholkar¹⁵⁴, S. Murthy¹⁵⁴, P. Palit¹⁵⁴, K. Park¹⁵⁴, M. Paulini¹⁵⁴,
 A. Roberts¹⁵⁴, A. Sanchez¹⁵⁴, W. Terrill¹⁵⁴, J.P. Cumalat¹⁵⁵, W.T. Ford¹⁵⁵, A. Hart¹⁵⁵,
 A. Hassani¹⁵⁵, N. Manganelli¹⁵⁵, J. Pearkes¹⁵⁵, C. Savard¹⁵⁵, N. Schonbeck¹⁵⁵,
 K. Stenson¹⁵⁵, K.A. Ulmer¹⁵⁵, S.R. Wagner¹⁵⁵, N. Zipper¹⁵⁵, D. Zuolo¹⁵⁵,
 J. Alexander¹⁵⁶, X. Chen¹⁵⁶, D.J. Cranshaw¹⁵⁶, J. Dickinson¹⁵⁶, J. Fan¹⁵⁶, X. Fan¹⁵⁶,
 S. Hogan¹⁵⁶, P. Kotamnives¹⁵⁶, J. Monroy¹⁵⁶, M. Oshiro¹⁵⁶, J.R. Patterson¹⁵⁶,
 M. Reid¹⁵⁶, A. Ryd¹⁵⁶, J. Thom¹⁵⁶, P. Wittich¹⁵⁶, R. Zou¹⁵⁶, M. Albrow¹⁵⁷,
 M. Alyari¹⁵⁷, O. Amram¹⁵⁷, G. Apollinari¹⁵⁷, A. Apresyan¹⁵⁷, L.A.T. Bauerdick¹⁵⁷,
 D. Berry¹⁵⁷, J. Berryhill¹⁵⁷, P.C. Bhat¹⁵⁷, K. Burkett¹⁵⁷, J.N. Butler¹⁵⁷, A. Canepa¹⁵⁷,
 G.B. Cerati¹⁵⁷, H.W.K. Cheung¹⁵⁷, F. Chlebana¹⁵⁷, G. Cummings¹⁵⁷, I. Dutta¹⁵⁷,
 V.D. Elvira¹⁵⁷, J. Freeman¹⁵⁷, A. Gandrakota¹⁵⁷, Z. Gece¹⁵⁷, L. Gray¹⁵⁷, D. Green¹⁵⁷,
 A. Grummer¹⁵⁷, S. Grünendahl¹⁵⁷, D. Guerrero¹⁵⁷, O. Gutsche¹⁵⁷, R.M. Harris¹⁵⁷,
 T.C. Herwig¹⁵⁷, J. Hirschauer¹⁵⁷, B. Jayatilaka¹⁵⁷, S. Jindariani¹⁵⁷, M. Johnson¹⁵⁷,

U. Joshi¹⁵⁷, T. Klijsma¹⁵⁷, B. Klima¹⁵⁷, K.H.M. Kwok¹⁵⁷, S. Lammel¹⁵⁷, C. Lee¹⁵⁷, D. Lincoln¹⁵⁷, R. Lipton¹⁵⁷, T. Liu¹⁵⁷, K. Maeshima¹⁵⁷, D. Mason¹⁵⁷, P. McBride¹⁵⁷, P. Merkel¹⁵⁷, S. Mrenna¹⁵⁷, S. Nahn¹⁵⁷, J. Ngadiuba¹⁵⁷, D. Noonan¹⁵⁷, S. Norberg¹⁵⁷, V. Papadimitriou¹⁵⁷, N. Pastika¹⁵⁷, K. Pedro¹⁵⁷, C. Pena^{157,cg}, F. Ravera¹⁵⁷, A. Reinsvold Hall^{157,ch}, L. Ristori¹⁵⁷, M. Safdari¹⁵⁷, E. Sexton-Kennedy¹⁵⁷, N. Smith¹⁵⁷, A. Soha¹⁵⁷, L. Spiegel¹⁵⁷, S. Stoynev¹⁵⁷, J. Strait¹⁵⁷, L. Taylor¹⁵⁷, S. Tkaczyk¹⁵⁷, N.V. Tran¹⁵⁷, L. Uplegger¹⁵⁷, E.W. Vaandering¹⁵⁷, I. Zoi¹⁵⁷, C. Aruta¹⁵⁸, P. Avery¹⁵⁸, D. Bourilkov¹⁵⁸, P. Chang¹⁵⁸, V. Cherepanov¹⁵⁸, R.D. Field¹⁵⁸, C. Huh¹⁵⁸, E. Koenig¹⁵⁸, M. Kolosova¹⁵⁸, J. Konigsberg¹⁵⁸, A. Korytov¹⁵⁸, K. Matchev¹⁵⁸, N. Menendez¹⁵⁸, G. Mitselmakher¹⁵⁸, K. Mohrman¹⁵⁸, A. Muthirakalayil Madhu¹⁵⁸, N. Rawal¹⁵⁸, S. Rosenzweig¹⁵⁸, Y. Takahashi¹⁵⁸, J. Wang¹⁵⁸, T. Adams¹⁵⁹, A. Al Kadhimi¹⁵⁹, A. Askew¹⁵⁹, S. Bower¹⁵⁹, R. Hashmi¹⁵⁹, R.S. Kim¹⁵⁹, S. Kim¹⁵⁹, T. Kolberg¹⁵⁹, G. Martinez¹⁵⁹, H. Prosper¹⁵⁹, P.R. Prova¹⁵⁹, M. Wulansatiti¹⁵⁹, R. Yohay¹⁵⁹, J. Zhang¹⁵⁹, B. Alsufyani¹⁶⁰, S. Butalla¹⁶⁰, S. Das¹⁶⁰, T. Elkafrawy^{160,ci}, M. Hohlmann¹⁶⁰, E. Yanes¹⁶⁰, M.R. Adams¹⁶¹, A. Baty¹⁶¹, C. Bennett¹⁶¹, R. Cavanaugh¹⁶¹, R. Escobar Franco¹⁶¹, O. Evdokimov¹⁶¹, C.E. Gerber¹⁶¹, M. Hawksworth¹⁶¹, A. Hingrajiya¹⁶¹, D.J. Hofman¹⁶¹, J.h. Lee¹⁶¹, D. S. Lemos¹⁶¹, C. Mills¹⁶¹, S. Nanda¹⁶¹, G. Oh¹⁶¹, B. Ozek¹⁶¹, D. Pilipovic¹⁶¹, R. Pradhan¹⁶¹, E. Prifti¹⁶¹, T. Roy¹⁶¹, S. Rudrabhatla¹⁶¹, N. Singh¹⁶¹, M.B. Tonjes¹⁶¹, N. Varelas¹⁶¹, M.A. Wadud¹⁶¹, Z. Ye¹⁶¹, J. Yoo¹⁶¹, M. Alhusseini¹⁶², D. Blend¹⁶², K. Dilsiz^{162,cj}, L. Emediato¹⁶², G. Karaman¹⁶², O.K. Köseyan¹⁶², J.-P. Merlo¹⁶², A. Mestvirishvili^{162,ck}, O. Neogi¹⁶², H. Ogul^{162,cl}, Y. Onel¹⁶², A. Penzo¹⁶², C. Snyder¹⁶², E. Tiras^{162,cm}, B. Blumenfeld¹⁶³, L. Corcodilos¹⁶³, J. Davis¹⁶³, A.V. Gritsan¹⁶³, L. Kang¹⁶³, S. Kyriacou¹⁶³, P. Maksimovic¹⁶³, M. Roguljic¹⁶³, J. Roskes¹⁶³, S. Sekhar¹⁶³, M. Swartz¹⁶³, A. Abreu¹⁶⁴, L.F. Alcerro Alcerro¹⁶⁴, J. Anguiano¹⁶⁴, S. Arteaga Escatel¹⁶⁴, P. Baringer¹⁶⁴, A. Bean¹⁶⁴, Z. Flowers¹⁶⁴, D. Grove¹⁶⁴, J. King¹⁶⁴, G. Krintiras¹⁶⁴, M. Lazarovits¹⁶⁴, C. Le Mahieu¹⁶⁴, J. Marquez¹⁶⁴, M. Murray¹⁶⁴, M. Nickel¹⁶⁴, M. Pitt¹⁶⁴, S. Popescu^{164,cn}, C. Rogan¹⁶⁴, C. Royon¹⁶⁴, S. Sanders¹⁶⁴, C. Smith¹⁶⁴, G. Wilson¹⁶⁴, B. Allmond¹⁶⁵, R. Gujju Gurunadha¹⁶⁵, A. Ivanov¹⁶⁵, K. Kaadze¹⁶⁵, Y. Maravin¹⁶⁵, J. Natoli¹⁶⁵, D. Roy¹⁶⁵, G. Sorrentino¹⁶⁵, A. Baden¹⁶⁶, A. Belloni¹⁶⁶, J. Bistany-riebman¹⁶⁶, Y.M. Chen¹⁶⁶, S.C. Eno¹⁶⁶, N.J. Hadley¹⁶⁶, S. Jabeen¹⁶⁶, R.G. Kellogg¹⁶⁶, T. Koeth¹⁶⁶, B. Kronheim¹⁶⁶, Y. Lai¹⁶⁶, S. Lascio¹⁶⁶, A.C. Mignerey¹⁶⁶, S. Nabili¹⁶⁶, C. Palmer¹⁶⁶, C. Papageorgakis¹⁶⁶, M.M. Paranjpe¹⁶⁶, E. Popova^{166,co}, A. Shevelev¹⁶⁶, L. Wang¹⁶⁶, L. Zhang¹⁶⁶, C. Baldenegro Barrera¹⁶⁷, J. Bendavid¹⁶⁷, S. Bright-Thonney¹⁶⁷, I.A. Cali¹⁶⁷, P.c. Chou¹⁶⁷, M. D'Alfonso¹⁶⁷, J. Eysermans¹⁶⁷, C. Freer¹⁶⁷, G. Gomez-Ceballos¹⁶⁷, M. Goncharov¹⁶⁷, G. Grosso¹⁶⁷, P. Harris¹⁶⁷, D. Hoang¹⁶⁷, D. Kovalskyi¹⁶⁷, J. Krupa¹⁶⁷, L. Lavezzo¹⁶⁷, Y.-J. Lee¹⁶⁷, K. Long¹⁶⁷, C. McGinn¹⁶⁷, A. Novak¹⁶⁷, M.I. Park¹⁶⁷, C. Paus¹⁶⁷, C. Reissel¹⁶⁷, C. Roland¹⁶⁷, G. Roland¹⁶⁷, S. Rothman¹⁶⁷, G.S.F. Stephans¹⁶⁷, Z. Wang¹⁶⁷, B. Wyslouch¹⁶⁷, T. J. Yang¹⁶⁷, B. Crossman¹⁶⁸, C. Kapsiak¹⁶⁸, M. Krohn¹⁶⁸, D. Mahon¹⁶⁸, J. Mans¹⁶⁸, B. Marzocchi¹⁶⁸, M. Revering¹⁶⁸, R. Rusack¹⁶⁸, R. Saradhy¹⁶⁸, N. Strobbe¹⁶⁸, K. Bloom¹⁶⁹, D.R. Claes¹⁶⁹, G. Haza¹⁶⁹, J. Hossain¹⁶⁹, C. Joo¹⁶⁹, I. Kravchenko¹⁶⁹, A. Rohilla¹⁶⁹, J.E. Siado¹⁶⁹, W. Tabb¹⁶⁹, A. Vagnerini¹⁶⁹, A. Wightman¹⁶⁹, F. Yan¹⁶⁹, D. Yu¹⁶⁹, H. Bandyopadhyay¹⁷⁰, L. Hay¹⁷⁰,

H.w. Hsia¹⁷⁰, I. Iashvili¹⁷⁰, A. Kalogeropoulos¹⁷⁰, A. Kharchilava¹⁷⁰, M. Morris¹⁷⁰,
D. Nguyen¹⁷⁰, S. Rappoccio¹⁷⁰, H. Rejeb Sfar¹⁷⁰, A. Williams¹⁷⁰, P. Young¹⁷⁰,
G. Alverson¹⁷¹, E. Barberis¹⁷¹, J. Bonilla¹⁷¹, B. Bylsma¹⁷¹, M. Campana¹⁷¹, J. Dervan¹⁷¹,
Y. Haddad¹⁷¹, Y. Han¹⁷¹, I. Israr¹⁷¹, A. Krishna¹⁷¹, P. Levchenko¹⁷¹, J. Li¹⁷¹,
M. Lu¹⁷¹, R. McCarthy¹⁷¹, D.M. Morse¹⁷¹, V. Nguyen¹⁷¹, T. Orimoto¹⁷¹, A. Parker¹⁷¹,
L. Skinnari¹⁷¹, E. Tsai¹⁷¹, D. Wood¹⁷¹, S. Dittmer¹⁷², K.A. Hahn¹⁷², D. Li¹⁷²,
Y. Liu¹⁷², M. McGinnis¹⁷², Y. Miao¹⁷², D.G. Monk¹⁷², M.H. Schmitt¹⁷², A. Taliencio¹⁷²,
M. Velasco¹⁷², G. Agarwal¹⁷³, R. Band¹⁷³, R. Bucci¹⁷³, S. Castells¹⁷³, A. Das¹⁷³,
R. Goldouzian¹⁷³, M. Hildreth¹⁷³, K. Hurtado Anampa¹⁷³, T. Ivanov¹⁷³, C. Jessop¹⁷³,
K. Lannon¹⁷³, J. Lawrence¹⁷³, N. Loukas¹⁷³, L. Lutton¹⁷³, J. Mariano¹⁷³, N. Marinelli¹⁷³,
I. Mcalister¹⁷³, T. McCauley¹⁷³, C. Mcgrady¹⁷³, C. Moore¹⁷³, Y. Musienko^{173,o},
H. Nelson¹⁷³, M. Osherson¹⁷³, A. Piccinelli¹⁷³, R. Ruchti¹⁷³, A. Townsend¹⁷³, Y. Wan¹⁷³,
M. Wayne¹⁷³, H. Yockey¹⁷³, M. Zarucki¹⁷³, L. Zygala¹⁷³, A. Basnet¹⁷⁴, M. Carrigan¹⁷⁴,
L.S. Durkin¹⁷⁴, C. Hill¹⁷⁴, M. Joyce¹⁷⁴, M. Nunez Ornelas¹⁷⁴, K. Wei¹⁷⁴, D.A. Wenzl¹⁷⁴,
B.L. Winer¹⁷⁴, B. R. Yates¹⁷⁴, H. Bouchamaoui¹⁷⁵, K. Coldham¹⁷⁵, P. Das¹⁷⁵,
G. Dezoort¹⁷⁵, P. Elmer¹⁷⁵, P. Fackeldey¹⁷⁵, A. Frankenthal¹⁷⁵, B. Greenberg¹⁷⁵,
N. Haubrich¹⁷⁵, K. Kennedy¹⁷⁵, G. Kopp¹⁷⁵, S. Kwan¹⁷⁵, D. Lange¹⁷⁵, A. Loeliger¹⁷⁵,
D. Marlow¹⁷⁵, I. Ojalvo¹⁷⁵, J. Olsen¹⁷⁵, F. Simpson¹⁷⁵, D. Stickland¹⁷⁵, C. Tully¹⁷⁵,
L.H. Vage¹⁷⁵, S. Malik¹⁷⁶, R. Sharma¹⁷⁶, A.S. Bakshi¹⁷⁷, S. Chandra¹⁷⁷, R. Chawla¹⁷⁷,
A. Gu¹⁷⁷, L. Gutay¹⁷⁷, M. Jones¹⁷⁷, A.W. Jung¹⁷⁷, A.M. Koshy¹⁷⁷, M. Liu¹⁷⁷,
G. Negro¹⁷⁷, N. Neumeister¹⁷⁷, G. Paspalaki¹⁷⁷, S. Piperov¹⁷⁷, J.F. Schulte¹⁷⁷,
A. K. Virdi¹⁷⁷, F. Wang¹⁷⁷, A. Wildridge¹⁷⁷, W. Xie¹⁷⁷, Y. Yao¹⁷⁷, J. Dolen¹⁷⁸,
N. Parashar¹⁷⁸, A. Pathak¹⁷⁸, D. Acosta¹⁷⁹, A. Agrawal¹⁷⁹, T. Carnahan¹⁷⁹,
K.M. Ecklund¹⁷⁹, P.J. Fernández Manteca¹⁷⁹, S. Freed¹⁷⁹, P. Gardner¹⁷⁹, F.J.M. Geurts¹⁷⁹,
I. Krommydas¹⁷⁹, W. Li¹⁷⁹, J. Lin¹⁷⁹, O. Miguel Colin¹⁷⁹, B.P. Padley¹⁷⁹,
R. Redjimi¹⁷⁹, J. Rotter¹⁷⁹, E. Yigitbasi¹⁷⁹, Y. Zhang¹⁷⁹, A. Bodek¹⁸⁰,
P. de Barbaro¹⁸⁰, R. Demina¹⁸⁰, J.L. Dulemba¹⁸⁰, A. Garcia-Bellido¹⁸⁰, O. Hindrichs¹⁸⁰,
A. Khukhunaishvili¹⁸⁰, N. Parmar¹⁸⁰, P. Parygin^{180,co}, R. Taus¹⁸⁰, B. Chiarito¹⁸¹,
J.P. Chou¹⁸¹, S.V. Clark¹⁸¹, D. Gadkari¹⁸¹, Y. Gershtein¹⁸¹, E. Halkiadakis¹⁸¹,
M. Heindl¹⁸¹, C. Houghton¹⁸¹, D. Jaroslawski¹⁸¹, S. Konstantinou¹⁸¹, I. Laflotte¹⁸¹,
A. Lath¹⁸¹, R. Montalvo¹⁸¹, K. Nash¹⁸¹, J. Reichert¹⁸¹, P. Saha¹⁸¹, S. Salur¹⁸¹,
S. Schnetzer¹⁸¹, S. Somalwar¹⁸¹, R. Stone¹⁸¹, S.A. Thayil¹⁸¹, S. Thomas¹⁸¹, J. Vora¹⁸¹,
D. Ally¹⁸², A.G. Delannoy¹⁸², S. Fiorendi¹⁸², S. Higginbotham¹⁸², T. Holmes¹⁸²,
A.R. Kanuganti¹⁸², N. Karunarathna¹⁸², L. Lee¹⁸², E. Nibigira¹⁸², S. Spanier¹⁸²,
D. Aebi¹⁸³, M. Ahmad¹⁸³, T. Akhter¹⁸³, K. Androsov^{183,bj}, O. Bouhali^{183,cp},
M. Dalchenko¹⁸³, R. Eusebi¹⁸³, J. Gilmore¹⁸³, T. Huang¹⁸³, T. Kamon^{183,cq}, H. Kim¹⁸³,
S. Luo¹⁸³, R. Mueller¹⁸³, D. Overton¹⁸³, A. Safonov¹⁸³, N. Akchurin¹⁸⁴, J. Damgov¹⁸⁴,
Y. Feng¹⁸⁴, N. Gogate¹⁸⁴, Y. Kazhykarim¹⁸⁴, K. Lamichane¹⁸⁴, S.W. Lee¹⁸⁴,
C. Madrid¹⁸⁴, A. Mankel¹⁸⁴, T. Peltola¹⁸⁴, I. Volobouev¹⁸⁴, E. Appelt¹⁸⁵, Y. Chen¹⁸⁵,
S. Greene¹⁸⁵, A. Gurrola¹⁸⁵, W. Johns¹⁸⁵, R. Kunnawalkam Elayavalli¹⁸⁵, A. Melo¹⁸⁵,
D. Rathjens¹⁸⁵, F. Romeo¹⁸⁵, P. Sheldon¹⁸⁵, S. Tuo¹⁸⁵, J. Velkovska¹⁸⁵,
J. Viinikainen¹⁸⁵, B. Cardwell¹⁸⁶, H. Chung¹⁸⁶, B. Cox¹⁸⁶, J. Hakala¹⁸⁶, R. Hirosky¹⁸⁶,
A. Ledovskoy¹⁸⁶, C. Mantilla¹⁸⁶, C. Neu¹⁸⁶, C. Ramón Álvarez¹⁸⁶, S. Bhattacharya¹⁸⁷,

P.E. Karchin¹⁸⁷, A. Aravind¹⁸⁸, S. Banerjee¹⁸⁸, K. Black¹⁸⁸, T. Bose¹⁸⁸, E. Chavez¹⁸⁸, S. Dasu¹⁸⁸, P. Everaerts¹⁸⁸, C. Galloni¹⁸⁸, H. He¹⁸⁸, M. Herndon¹⁸⁸, A. Herve¹⁸⁸, C.K. Koraka¹⁸⁸, A. Lanaro¹⁸⁸, R. Loveless¹⁸⁸, J. Madhusudanan Sreekala¹⁸⁸, A. Mallampalli¹⁸⁸, A. Mohammadi¹⁸⁸, S. Mondal¹⁸⁸, G. Parida¹⁸⁸, L. Pétrelle¹⁸⁸, D. Pinna¹⁸⁸, A. Savin¹⁸⁸, V. Shang¹⁸⁸, V. Sharma¹⁸⁸, W.H. Smith¹⁸⁸, D. Teague¹⁸⁸, H.F. Tsoi¹⁸⁸, W. Vetens¹⁸⁸, A. Warden¹⁸⁸, S. Afanasiev¹⁸⁹, V. Alexakhin¹⁸⁹, D. Budkouski¹⁸⁹, I. Golutvin^{189,†}, I. Gorbunov¹⁸⁹, V. Karjavine¹⁸⁹, O. Kodolova^{189,cr,co}, V. Korenkov¹⁸⁹, A. Lanev¹⁸⁹, A. Malakhov¹⁸⁹, V. Matveev^{189,o}, A. Nikitenko^{189,cs,ct}, V. Palichik¹⁸⁹, V. Perelygin¹⁸⁹, M. Savina¹⁸⁹, V. Shalaev¹⁸⁹, S. Shmatov¹⁸⁹, S. Shulha¹⁸⁹, V. Smirnov¹⁸⁹, O. Teryaev¹⁸⁹, N. Voytishin¹⁸⁹, B.S. Yuldashev^{189,cu,†}, A. Zarubin¹⁸⁹, I. Zhizhin¹⁸⁹, V. Andreev¹⁹⁰, Yu. Andreev¹⁹⁰, T. Aushev¹⁹⁰, M. Azarkin¹⁹⁰, A. Babaev¹⁹⁰, V. Blinov^{190,o}, E. Boos¹⁹⁰, V. Borshch¹⁹⁰, V. Bunichev¹⁹⁰, R. Chistov^{190,o}, M. Danilov^{190,o}, A. Dermenev¹⁹⁰, T. Dimova^{190,o}, D. Druzhkin¹⁹⁰, M. Dubinin^{190,cg}, L. Dudko¹⁹⁰, A. Ershov¹⁹⁰, G. Gavrilo¹⁹⁰, V. Gavrilo¹⁹⁰, S. Gninenko¹⁹⁰, V. Golovtsov¹⁹⁰, N. Golubev¹⁹⁰, A. Gribushin¹⁹⁰, K. Ivanov¹⁹⁰, Y. Ivanov¹⁹⁰, V. Kachanov¹⁹⁰, A. Karneyev¹⁹⁰, V. Kim^{190,o}, M. Kirakosyan¹⁹⁰, D. Kirpichnikov¹⁹⁰, M. Kirsanov¹⁹⁰, V. Klyukhin¹⁹⁰, A. Kozyrev^{190,o}, N. Krasnikov¹⁹⁰, N. Lychkovskaya¹⁹⁰, V. Murzin¹⁹⁰, V. Oreshkin¹⁹⁰, M. Perfilov¹⁹⁰, S. Polikarpov^{190,o}, V. Popov¹⁹⁰, O. Radchenko^{190,o}, V. Savrin¹⁹⁰, Y. Skovpen^{190,o}, S. Slabospitskii¹⁹⁰, D. Sosnov¹⁹⁰, V. Sulimov¹⁹⁰, A. Terkulov¹⁹⁰, I. Tliso¹⁹⁰, A. Toropin¹⁹⁰, L. Uvarov¹⁹⁰, A. Uzunian¹⁹⁰, A. Vorobyev^{190,†}, G. Vorotnikov¹⁹⁰, A. Zhokin¹⁹⁰

¹ Yerevan Physics Institute, Yerevan, Armenia

² Institut für Hochenergiephysik, Vienna, Austria

³ Universiteit Antwerpen, Antwerpen, Belgium

⁴ Vrije Universiteit Brussel, Brussel, Belgium

⁵ Université Libre de Bruxelles, Bruxelles, Belgium

⁶ Ghent University, Ghent, Belgium

⁷ Université Catholique de Louvain, Louvain-la-Neuve, Belgium

⁸ Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

⁹ Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

¹⁰ Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

¹¹ Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

¹² University of Sofia, Sofia, Bulgaria

¹³ Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

¹⁴ Beihang University, Beijing, China

¹⁵ Department of Physics, Tsinghua University, Beijing, China

¹⁶ Institute of High Energy Physics, Beijing, China

¹⁷ State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

¹⁸ State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China

¹⁹ Sun Yat-Sen University, Guangzhou, China

²⁰ University of Science and Technology of China, Hefei, China

²¹ Nanjing Normal University, Nanjing, China

²² Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) – Fudan University, Shanghai, China

²³ Zhejiang University, Hangzhou, Zhejiang, China

²⁴ Universidad de Los Andes, Bogota, Colombia

²⁵ Universidad de Antioquia, Medellin, Colombia

- ²⁶ *University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
- ²⁷ *University of Split, Faculty of Science, Split, Croatia*
- ²⁸ *Institute Rudjer Boskovic, Zagreb, Croatia*
- ²⁹ *University of Cyprus, Nicosia, Cyprus*
- ³⁰ *Charles University, Prague, Czech Republic*
- ³¹ *Escuela Politecnica Nacional, Quito, Ecuador*
- ³² *Universidad San Francisco de Quito, Quito, Ecuador*
- ³³ *Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
- ³⁴ *Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
- ³⁵ *National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ³⁶ *Department of Physics, University of Helsinki, Helsinki, Finland*
- ³⁷ *Helsinki Institute of Physics, Helsinki, Finland*
- ³⁸ *Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
- ³⁹ *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ⁴⁰ *Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
- ⁴¹ *Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
- ⁴² *Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
- ⁴³ *Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
- ⁴⁴ *Georgian Technical University, Tbilisi, Georgia*
- ⁴⁵ *RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ⁴⁶ *RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ⁴⁷ *RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ⁴⁸ *Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ⁴⁹ *University of Hamburg, Hamburg, Germany*
- ⁵⁰ *Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
- ⁵¹ *Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁵² *National and Kapodistrian University of Athens, Athens, Greece*
- ⁵³ *National Technical University of Athens, Athens, Greece*
- ⁵⁴ *University of Ioánnina, Ioánnina, Greece*
- ⁵⁵ *HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
- ⁵⁶ *MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ⁵⁷ *Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
- ⁵⁸ *HUN-REN ATOMKI – Institute of Nuclear Research, Debrecen, Hungary*
- ⁵⁹ *Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
- ⁶⁰ *Panjab University, Chandigarh, India*
- ⁶¹ *University of Delhi, Delhi, India*
- ⁶² *Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁶³ *Indian Institute of Technology Madras, Madras, India*
- ⁶⁴ *Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶⁵ *Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶⁶ *National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
- ⁶⁷ *Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁶⁸ *Isfahan University of Technology, Isfahan, Iran*
- ⁶⁹ *Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁷⁰ *University College Dublin, Dublin, Ireland*
- ^{71a} *INFN Sezione di Bari, Bari, Italy*
- ^{71b} *Università di Bari, Bari, Italy*

- ^{71c} *Politecnico di Bari, Bari, Italy*
- ^{72a} *INFN Sezione di Bologna, Bologna, Italy*
- ^{72b} *Università di Bologna, Bologna, Italy*
- ^{73a} *INFN Sezione di Catania, Catania, Italy*
- ^{73b} *Università di Catania, Catania, Italy*
- ^{74a} *INFN Sezione di Firenze, Firenze, Italy*
- ^{74b} *Università di Firenze, Firenze, Italy*
- ⁷⁵ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{76a} *INFN Sezione di Genova, Genova, Italy*
- ^{76b} *Università di Genova, Genova, Italy*
- ^{77a} *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{77b} *Università di Milano-Bicocca, Milano, Italy*
- ^{78a} *INFN Sezione di Napoli, Napoli, Italy*
- ^{78b} *Università di Napoli ‘Federico II’, Napoli, Italy*
- ^{78c} *Università della Basilicata, Potenza, Italy*
- ^{78d} *Scuola Superiore Meridionale (SSM), Napoli, Italy*
- ^{79a} *INFN Sezione di Padova, Padova, Italy*
- ^{79b} *Università di Padova, Padova, Italy*
- ^{79c} *Università degli Studi di Cagliari, Cagliari, Italy*
- ^{80a} *INFN Sezione di Pavia, Pavia, Italy*
- ^{80b} *Università di Pavia, Pavia, Italy*
- ^{81a} *INFN Sezione di Perugia, Perugia, Italy*
- ^{81b} *Università di Perugia, Perugia, Italy*
- ^{82a} *INFN Sezione di Pisa, Pisa, Italy*
- ^{82b} *Università di Pisa, Pisa, Italy*
- ^{82c} *Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{82d} *Università di Siena, Siena, Italy*
- ^{83a} *INFN Sezione di Roma, Roma, Italy*
- ^{83b} *Sapienza Università di Roma, Roma, Italy*
- ^{84a} *INFN Sezione di Torino, Torino, Italy*
- ^{84b} *Università di Torino, Torino, Italy*
- ^{84c} *Università del Piemonte Orientale, Novara, Italy*
- ^{85a} *INFN Sezione di Trieste, Trieste, Italy*
- ^{85b} *Università di Trieste, Trieste, Italy*
- ⁸⁶ *Kyungpook National University, Daegu, Korea*
- ⁸⁷ *Department of Mathematics and Physics – GWNu, Gangneung, Korea*
- ⁸⁸ *Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁹ *Hanyang University, Seoul, Korea*
- ⁹⁰ *Korea University, Seoul, Korea*
- ⁹¹ *Kyung Hee University, Department of Physics, Seoul, Korea*
- ⁹² *Sejong University, Seoul, Korea*
- ⁹³ *Seoul National University, Seoul, Korea*
- ⁹⁴ *University of Seoul, Seoul, Korea*
- ⁹⁵ *Yonsei University, Department of Physics, Seoul, Korea*
- ⁹⁶ *Sungkyunkwan University, Suwon, Korea*
- ⁹⁷ *College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
- ⁹⁸ *Kuwait University – College of Science – Department of Physics, Safat, Kuwait*
- ⁹⁹ *Riga Technical University, Riga, Latvia*
- ¹⁰⁰ *University of Latvia (LU), Riga, Latvia*
- ¹⁰¹ *Vilnius University, Vilnius, Lithuania*
- ¹⁰² *National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- ¹⁰³ *Universidad de Sonora (UNISON), Hermosillo, Mexico*
- ¹⁰⁴ *Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*

- 105 *Universidad Iberoamericana, Mexico City, Mexico*
- 106 *Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- 107 *University of Montenegro, Podgorica, Montenegro*
- 108 *University of Canterbury, Christchurch, New Zealand*
- 109 *National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- 110 *AGH University of Krakow, Krakow, Poland*
- 111 *National Centre for Nuclear Research, Swierk, Poland*
- 112 *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- 113 *Warsaw University of Technology, Warsaw, Poland*
- 114 *Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- 115 *Faculty of Physics, University of Belgrade, Belgrade, Serbia*
- 116 *VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
- 117 *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- 118 *Universidad Autónoma de Madrid, Madrid, Spain*
- 119 *Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- 120 *Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- 121 *University of Colombo, Colombo, Sri Lanka*
- 122 *University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- 123 *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- 124 *PSI Center for Neutron and Muon Sciences, Villigen, Switzerland*
- 125 *ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- 126 *Universität Zürich, Zurich, Switzerland*
- 127 *National Central University, Chung-Li, Taiwan*
- 128 *National Taiwan University (NTU), Taipei, Taiwan*
- 129 *High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
- 130 *Tunis El Manar University, Tunis, Tunisia*
- 131 *Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- 132 *Middle East Technical University, Physics Department, Ankara, Turkey*
- 133 *Bogazici University, Istanbul, Turkey*
- 134 *Istanbul Technical University, Istanbul, Turkey*
- 135 *Istanbul University, Istanbul, Turkey*
- 136 *Yildiz Technical University, Istanbul, Turkey*
- 137 *Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
- 138 *National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
- 139 *University of Bristol, Bristol, U.K.*
- 140 *Rutherford Appleton Laboratory, Didcot, U.K.*
- 141 *Imperial College, London, U.K.*
- 142 *Brunel University, Uxbridge, U.K.*
- 143 *Baylor University, Waco, Texas, U.S.A.*
- 144 *Catholic University of America, Washington, DC, U.S.A.*
- 145 *The University of Alabama, Tuscaloosa, Alabama, U.S.A.*
- 146 *Boston University, Boston, Massachusetts, U.S.A.*
- 147 *Brown University, Providence, Rhode Island, U.S.A.*
- 148 *University of California, Davis, Davis, California, U.S.A.*
- 149 *University of California, Los Angeles, California, U.S.A.*
- 150 *University of California, Riverside, Riverside, California, U.S.A.*
- 151 *University of California, San Diego, La Jolla, California, U.S.A.*
- 152 *University of California, Santa Barbara – Department of Physics, Santa Barbara, California, U.S.A.*
- 153 *California Institute of Technology, Pasadena, California, U.S.A.*
- 154 *Carnegie Mellon University, Pittsburgh, Pennsylvania, U.S.A.*
- 155 *University of Colorado Boulder, Boulder, Colorado, U.S.A.*

- ¹⁵⁶ *Cornell University, Ithaca, New York, U.S.A.*
- ¹⁵⁷ *Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
- ¹⁵⁸ *University of Florida, Gainesville, Florida, U.S.A.*
- ¹⁵⁹ *Florida State University, Tallahassee, Florida, U.S.A.*
- ¹⁶⁰ *Florida Institute of Technology, Melbourne, Florida, U.S.A.*
- ¹⁶¹ *University of Illinois Chicago, Chicago, Illinois, U.S.A.*
- ¹⁶² *The University of Iowa, Iowa City, Iowa, U.S.A.*
- ¹⁶³ *Johns Hopkins University, Baltimore, Maryland, U.S.A.*
- ¹⁶⁴ *The University of Kansas, Lawrence, Kansas, U.S.A.*
- ¹⁶⁵ *Kansas State University, Manhattan, Kansas, U.S.A.*
- ¹⁶⁶ *University of Maryland, College Park, Maryland, U.S.A.*
- ¹⁶⁷ *Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.*
- ¹⁶⁸ *University of Minnesota, Minneapolis, Minnesota, U.S.A.*
- ¹⁶⁹ *University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.*
- ¹⁷⁰ *State University of New York at Buffalo, Buffalo, New York, U.S.A.*
- ¹⁷¹ *Northeastern University, Boston, Massachusetts, U.S.A.*
- ¹⁷² *Northwestern University, Evanston, Illinois, U.S.A.*
- ¹⁷³ *University of Notre Dame, Notre Dame, Indiana, U.S.A.*
- ¹⁷⁴ *The Ohio State University, Columbus, Ohio, U.S.A.*
- ¹⁷⁵ *Princeton University, Princeton, New Jersey, U.S.A.*
- ¹⁷⁶ *University of Puerto Rico, Mayaguez, Puerto Rico, U.S.A.*
- ¹⁷⁷ *Purdue University, West Lafayette, Indiana, U.S.A.*
- ¹⁷⁸ *Purdue University Northwest, Hammond, Indiana, U.S.A.*
- ¹⁷⁹ *Rice University, Houston, Texas, U.S.A.*
- ¹⁸⁰ *University of Rochester, Rochester, New York, U.S.A.*
- ¹⁸¹ *Rutgers, The State University of New Jersey, Piscataway, New Jersey, U.S.A.*
- ¹⁸² *University of Tennessee, Knoxville, Tennessee, U.S.A.*
- ¹⁸³ *Texas A&M University, College Station, Texas, U.S.A.*
- ¹⁸⁴ *Texas Tech University, Lubbock, Texas, U.S.A.*
- ¹⁸⁵ *Vanderbilt University, Nashville, Tennessee, U.S.A.*
- ¹⁸⁶ *University of Virginia, Charlottesville, Virginia, U.S.A.*
- ¹⁸⁷ *Wayne State University, Detroit, Michigan, U.S.A.*
- ¹⁸⁸ *University of Wisconsin – Madison, Madison, Wisconsin, U.S.A.*
- ¹⁸⁹ *An institute or international laboratory covered by a cooperation agreement with CERN*
- ¹⁹⁰ *An institute formerly covered by a cooperation agreement with CERN*

^a *Also at Yerevan State University, Yerevan, Armenia*

^b *Also at TU Wien, Vienna, Austria*

^c *Also at Ghent University, Ghent, Belgium*

^d *Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

^e *Also at FACAMP – Faculdades de Campinas, Sao Paulo, Brazil*

^f *Also at Universidade Estadual de Campinas, Campinas, Brazil*

^g *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*

^h *Also at University of Chinese Academy of Sciences, Beijing, China*

ⁱ *Also at China Center of Advanced Science and Technology, Beijing, China*

^j *Also at University of Chinese Academy of Sciences, Beijing, China*

^k *Also at China Spallation Neutron Source, Guangdong, China*

^l *Now at Henan Normal University, Xinxiang, China*

^m *Also at University of Shanghai for Science and Technology, Shanghai, China*

ⁿ *Now at The University of Iowa, Iowa City, Iowa, U.S.A.*

^o *Also at Another institute formerly covered by a cooperation agreement with CERN*

^p *Also at Helwan University, Cairo, Egypt*

^q *Now at Zewail City of Science and Technology, Zewail, Egypt*

- ^r Now at *British University in Egypt, Cairo, Egypt*
- ^s Now at *Cairo University, Cairo, Egypt*
- ^t Also at *Purdue University, West Lafayette, Indiana, U.S.A.*
- ^u Also at *Université de Haute Alsace, Mulhouse, France*
- ^v Also at *Istinye University, Istanbul, Turkey*
- ^w Also at *Another institute or international laboratory covered by a cooperation agreement with CERN*
- ^x Also at *The University of the State of Amazonas, Manaus, Brazil*
- ^y Also at *University of Hamburg, Hamburg, Germany*
- ^z Also at *RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ^{aa} Also at *Bergische University Wuppertal (BUW), Wuppertal, Germany*
- ^{ab} Also at *Brandenburg University of Technology, Cottbus, Germany*
- ^{ac} Also at *Forschungszentrum Jülich, Jülich, Germany*
- ^{ad} Now at *RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ^{ae} Also at *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ^{af} Also at *HUN-REN ATOMKI – Institute of Nuclear Research, Debrecen, Hungary*
- ^{ag} Now at *Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania*
- ^{ah} Also at *MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ^{ai} Also at *HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
- ^{aj} Also at *Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
- ^{ak} Also at *Punjab Agricultural University, Ludhiana, India*
- ^{al} Also at *University of Visva-Bharati, Santiniketan, India*
- ^{am} Also at *Indian Institute of Science (IISc), Bangalore, India*
- ^{an} Also at *Amity University Uttar Pradesh, Noida, India*
- ^{ao} Also at *IIT Bhubaneswar, Bhubaneswar, India*
- ^{ap} Also at *Institute of Physics, Bhubaneswar, India*
- ^{aq} Also at *University of Hyderabad, Hyderabad, India*
- ^{ar} Also at *Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ^{as} Also at *Isfahan University of Technology, Isfahan, Iran*
- ^{at} Also at *Sharif University of Technology, Tehran, Iran*
- ^{au} Also at *Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
- ^{av} Also at *Department of Physics, Faculty of Science, Arak University, ARAK, Iran*
- ^{aw} Also at *Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
- ^{ax} Also at *Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
- ^{ay} Also at *Università degli Studi Guglielmo Marconi, Roma, Italy*
- ^{az} Also at *Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy*
- ^{ba} Also at *Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
- ^{bb} Also at *Lulea University of Technology, Lulea, Sweden*
- ^{bc} Also at *Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy*
- ^{bd} Also at *Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
- ^{be} Also at *Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
- ^{bf} Also at *Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
- ^{bg} Also at *Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
- ^{bh} Also at *Saegis Campus, Nugegoda, Sri Lanka*
- ^{bi} Also at *National and Kapodistrian University of Athens, Athens, Greece*
- ^{bj} Also at *Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
- ^{bk} Also at *Universität Zürich, Zurich, Switzerland*
- ^{bl} Also at *Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
- ^{bm} Also at *Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
- ^{bn} Also at *Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
- ^{bo} Also at *Konya Technical University, Konya, Turkey*

- ^{bp} Also at *Izmir Bakircay University, Izmir, Turkey*
- ^{bq} Also at *Adiyaman University, Adiyaman, Turkey*
- ^{br} Also at *Bozok Universitetsi Rektörlüğü, Yozgat, Turkey*
- ^{bs} Also at *Marmara University, Istanbul, Turkey*
- ^{bt} Also at *Milli Savunma University, Istanbul, Turkey*
- ^{bu} Also at *Kafkas University, Kars, Turkey*
- ^{bv} Now at *Istanbul Okan University, Istanbul, Turkey*
- ^{bw} Also at *Hacettepe University, Ankara, Turkey*
- ^{bx} Also at *Erzincan Binali Yildirim University, Erzincan, Turkey*
- ^{by} Also at *Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
- ^{bz} Also at *Yildiz Technical University, Istanbul, Turkey*
- ^{ca} Also at *School of Physics and Astronomy, University of Southampton, Southampton, U.K.*
- ^{cb} Also at *IPPP Durham University, Durham, U.K.*
- ^{cc} Also at *Monash University, Faculty of Science, Clayton, Australia*
- ^{cd} Also at *Università di Torino, Torino, Italy*
- ^{ce} Also at *Bethel University, St. Paul, Minnesota, U.S.A.*
- ^{cf} Also at *Karamanoğlu Mehmetbey University, Karaman, Turkey*
- ^{cg} Also at *California Institute of Technology, Pasadena, California, U.S.A.*
- ^{ch} Also at *United States Naval Academy, Annapolis, Maryland, U.S.A.*
- ^{ci} Also at *Ain Shams University, Cairo, Egypt*
- ^{cj} Also at *Bingol University, Bingol, Turkey*
- ^{ck} Also at *Georgian Technical University, Tbilisi, Georgia*
- ^{cl} Also at *Sinop University, Sinop, Turkey*
- ^{cm} Also at *Erciyes University, Kayseri, Turkey*
- ^{cn} Also at *Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
- ^{co} Now at *Another institute formerly covered by a cooperation agreement with CERN*
- ^{cp} Also at *Texas A&M University at Qatar, Doha, Qatar*
- ^{cq} Also at *Kyungpook National University, Daegu, Korea*
- ^{cr} Also at *Yerevan Physics Institute, Yerevan, Armenia*
- ^{cs} Also at *Imperial College, London, U.K.*
- ^{ct} Now at *Yerevan Physics Institute, Yerevan, Armenia*
- ^{cu} Also at *Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*
- [†] Deceased