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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

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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.

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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.

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 [9–11], which spanned the years 2015–2018. These searches assume flavor universality of the couplings to all quark and lepton generations, 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) [12] and 3.5 TeV (CMS) [13], and for the $Z' \rightarrow b\bar{b}$ decay mode, excluding $m_{Z'}$ up to 2.7 (ATLAS) [14] and 2.4 TeV (CMS) [15]. Models that prefer third-generation quark production modes, such as those in Ref. [16], which proposes a Z' boson decaying to muons that could accommodate flavor anomalies and be detected at the LHC, and those in Refs. [17–19], which propose Z' bosons decaying to tau leptons, are not directly excluded. We probe the muon decay as a benchmark model and are not specifically sensitive to a tau decay scenario. Diagrams for the Z' production and decay are shown in Fig. 1.

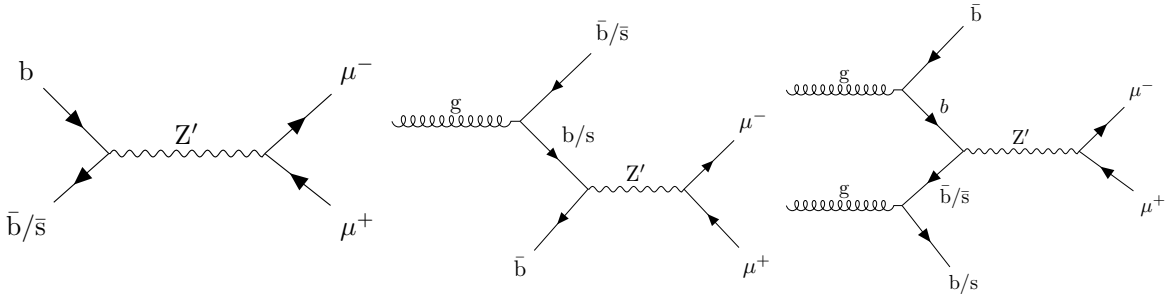


Figure 1: Representative Feynman diagrams of Z' boson production with bottom-bottom or bottom-strange quark fusion with decays into a dimuon final state. Production at tree level (left), single associated initial-state radiation (ISR) jet production (middle), and two associated ISR jet production (right)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

In recent years, potential effects beyond the SM have been examined through precision measurements of B meson decay rates [20–30]. 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 $R(K^*)$ motivates the search for a Z' boson that preferentially couples to third-generation fermions [16, 31]. More recently, 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]. Updated measurements from

the LHCb experiment [29, 30] have removed the tension with the SM that originally motivated the model of low-mass Z' boson used as a signal model. However, charged-current anomalies remain.

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}). 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, produced in association with one or more jets where at least one is b tagged, that decays into a pair of muons.

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 [9, 11, 34]. The sensitivity of the search reported here for flavor-universal lepton couplings is reduced because of the use of dielectron control regions (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.

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.

2 The CMS detector and event reconstruction

The CMS apparatus [37, 38] is a multipurpose, nearly hermetic detector, designed to trigger on [39–41] and identify electrons, muons, photons, and (charged and neutral) hadrons [42–44]. 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. [37, 38].

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 $4 \mu\text{s}$ [39]. 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 [40]. Events are selected using either a trigger requiring a single muon with a minimum p_T threshold of 50 GeV, with additional recovery triggers used to ameliorate high- p_T muon inefficiencies in some data-taking years, or one double-electron trigger with p_T requirements varying by year between 25 and 33 GeV per lepton. 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 [45], 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 [46, 47] 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 [48]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [48]. 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 [49].

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} [50]. 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 [51]. We utilize the medium working point of the DEEPJET algorithm [52, 53] 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) [49, 54]. 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 [51].

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, and also depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [42, 55].

The dielectron mass resolution for $Z \rightarrow ee$ decays is 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. The exact values depend on the bremsstrahlung energy emitted by the electrons and the data-taking year.

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 [43].

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 (HEEP) identification [42], and 0.1% for muons, using the cutoff-based high- p_T identification [43]. 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 [43, 56]. 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% [42]. 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 [42, 43]. This selection is synchronized with the CMS dilepton final-state search [11] 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 [42], as the HEEP identification does not allow for selecting sufficiently low- p_T electrons, and the cutoff-based high- p_T identification for the muons along with the requirements $p_T > 10$ GeV and $|\eta| < 2.4$ [43].

Table 1 summarizes these selection requirements.

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.

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

3 Data and simulated samples

Signal Monte Carlo (MC) samples were prepared with MADGRAPH5_aMC@NLO [57] version 2.4.2 (2.6.0) for 2016 (2017 and 2018) at leading order (LO) with the NNPDF3.1 [58] parton distribution functions (PDFs) in the five flavor scheme. For parton shower and fragmentation, the generator was interfaced with PYTHIA 8.226 (8.230) [59], using the CUETP8M1 tune [60] (CP5 tune [61]) for 2016 (2017 and 2018) samples and MLM matching [62]. The Universal FEYNRULES Output (UFO) for the signal processes was privately FEYNRULES via FeynRules [63] and can be found on the HEPData record for this analysis [64]. 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 narrow compared to the detector resolution.

The MADGRAPH5_aMC@NLO version 2.4.2 (2.6.5) and POWHEG v2.0 generators were used to simulate background processes that are interfaced with PYTHIA. In MADGRAPH5_aMC@NLO backgrounds, jets are MLM matched, and the NNPDF3.0 [65] (NNPDF3.1 [58]) PDFs are used for 2016 (2017 and 2018). The backgrounds include DY+ jets, top quark pair production ($t\bar{t}$), single top, and di-boson (VV) processes (W W, W Z, Z Z). DY + jets is simulated at Next-to-Leading Order, while the rest are simulated at LO.

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 [66] 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 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 dielectron b jet rich CRs require at least one jet are b-tagged, while the light jet regions require that no jets are b-tagged. 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. [16], for backgrounds and signals in $\text{SR}_b^{\mu\mu}$ and $\text{SR}_{b+j/b}^{\mu\mu}$ are shown in Fig. 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.

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 of 122–391 GeV, to cover a Z' boson mass range of 125–350 GeV.

5 Background estimation

In this search, we use an ABCD (matrix) background estimation technique, based on parametric fits to our CRs to smooth statistical fluctuations, employing the light-quark and gluon jet, and electron selections to construct CRs to predict the backgrounds in the muon and b jet enriched SRs.

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-

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.

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

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.

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

dominated. The background yield in the SR is estimated from the yields in the three CRs with the expression: $N_A = \frac{N_B N_C}{N_D}$, 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 (CR_b^{ee}) and two ($\text{CR}_{b+j/b}^{\text{ee}}$) 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: $\text{CR}_j^{\mu\mu}/\text{CR}_j^{\text{ee}}$ and $\text{CR}_{2j}^{\mu\mu}/\text{CR}_{2j}^{\text{ee}}$ 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 $\text{CR}_{b+j/b}^{\text{ee}}$ to create the predictions for backgrounds in $\text{SR}_b^{\mu\mu}$ and $\text{SR}_{b+j/b}^{\mu\mu}$. Thus, the ABCD background prediction equations are given by:

$$\text{SR}_b^{\mu\mu} = \text{CR}_b^{\text{ee}} \frac{\text{CR}_j^{\mu\mu}}{\text{CR}_j^{\text{ee}}}, \quad \text{SR}_{b+j/b}^{\mu\mu} = \text{CR}_{b+j/b}^{\text{ee}} \frac{\text{CR}_{2j}^{\mu\mu}}{\text{CR}_{2j}^{\text{ee}}}. \quad (1)$$

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).

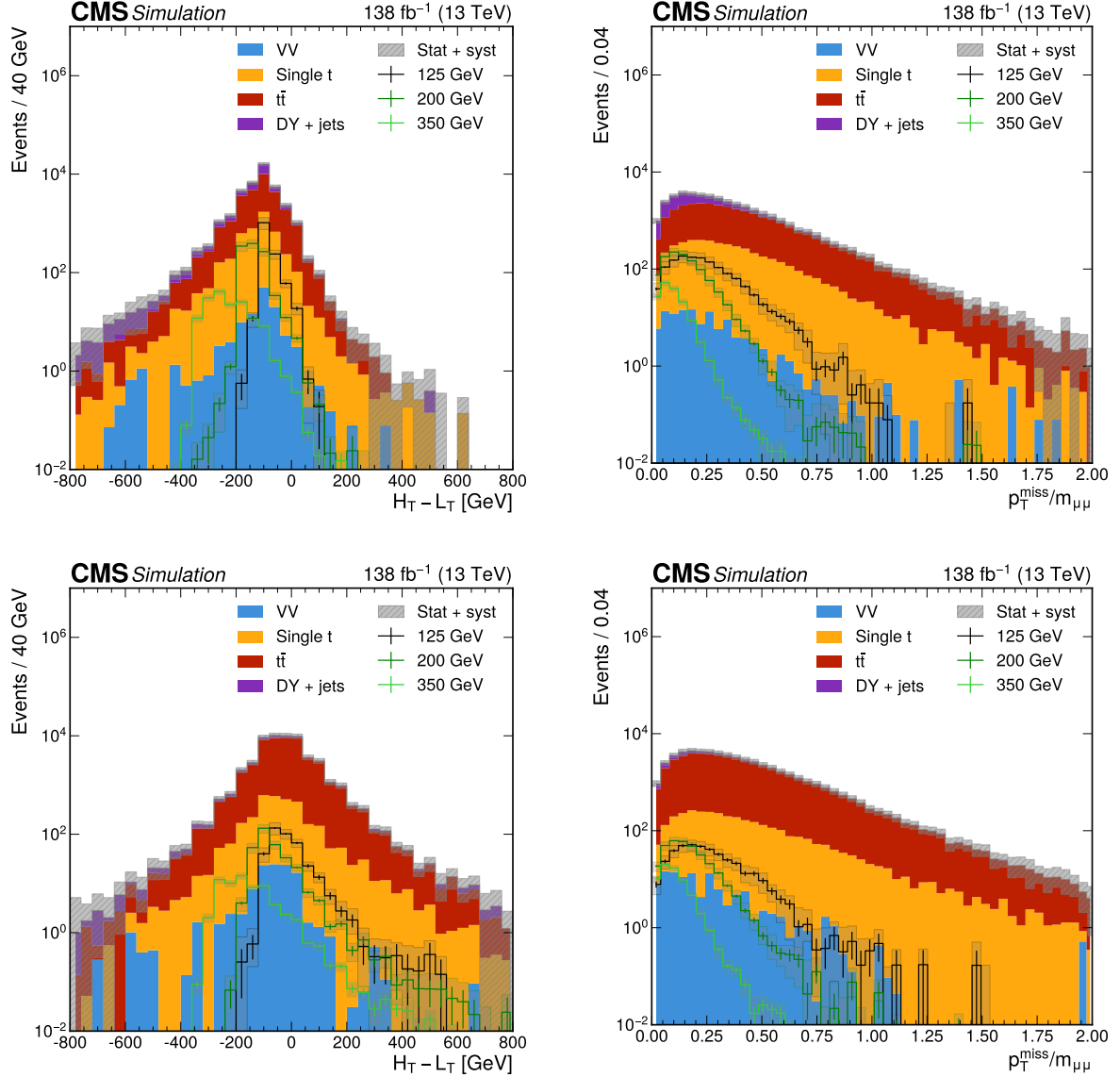


Figure 2: Distributions of the search-specific variables from simulated backgrounds and signals for Z' boson masses of 125, 200, and 350 GeV after object selections including a single-muon requirement and categorization into both jet multiplicities. The left column shows the $H_T - L_T$ distributions, 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.

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. In cross section measurements of DY production with one or two associated b

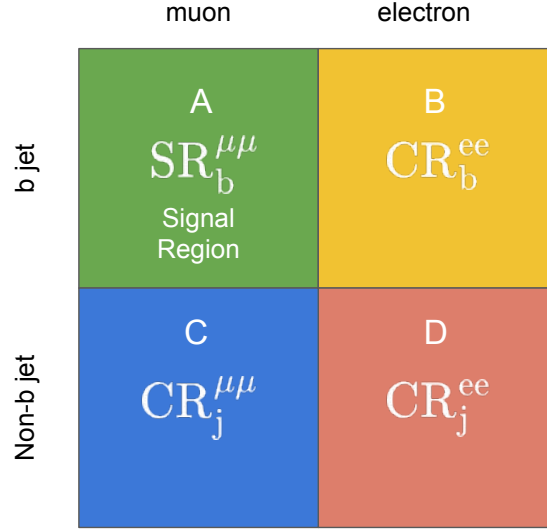


Figure 3: A visualization of the ABCD SRs and CRs. For example, $SR_b^{\mu\mu}$ represents the dimuon b jet enriched SRs ($SR_b^{\mu\mu}$ or $SR_{b+j/b}^{\mu\mu}$) and CR_b^{ee} represents the dielectron b jet enriched CRs (CR_b^{ee} or $CR_{b+j/b}^{ee}$).

jets, discrepancies between simulations and data have been observed [35]. 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 (Figs. 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:

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

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 Fig. 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 Figs. 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 $\text{SR}_b^{\mu\mu}$ ($\text{SR}_{b+j/b}^{\mu\mu}$), respectively.

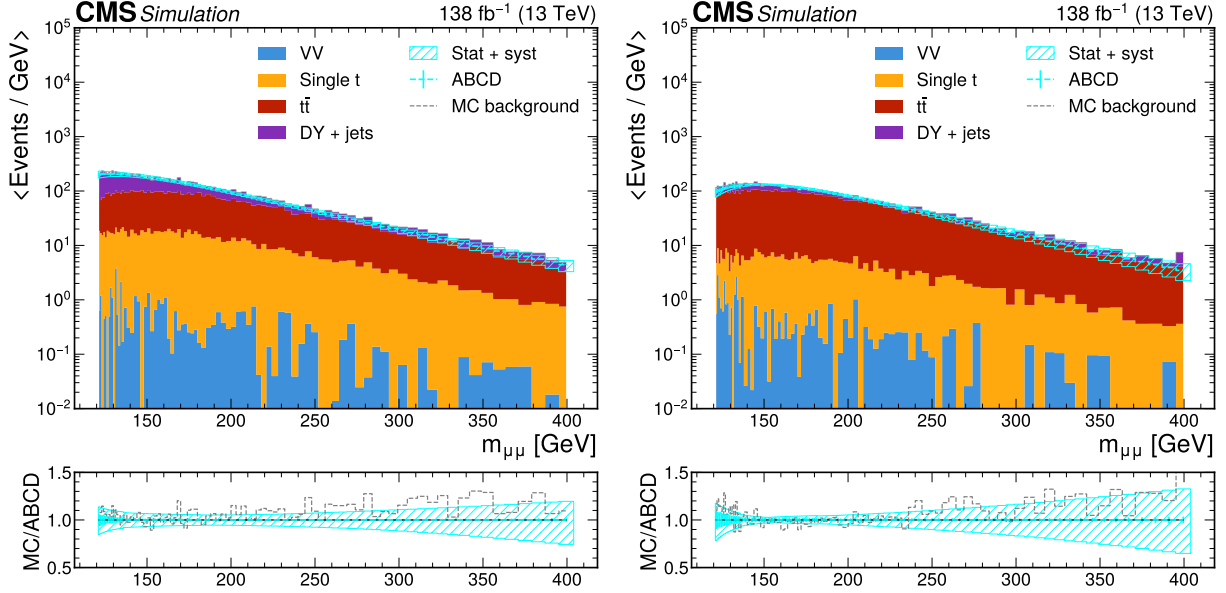


Figure 4: Comparison between the predictions of the $\text{SR}_b^{\mu\mu}$ background from simulation (gray) and the ABCD method (teal) from MC simulation. Events are divided by the bin width. The statistical and systematic uncertainties using the ABCD method are shown around it in a teal hashed area. 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: $\text{SR}_{b+j/b}^{\mu\mu}$.

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.

The integrated luminosities for the 2016, 2017, and 2018 data-taking periods have 1.2–2.5% individual uncertainties [67–69], 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 $\pm 4.6\%$ [70]. 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

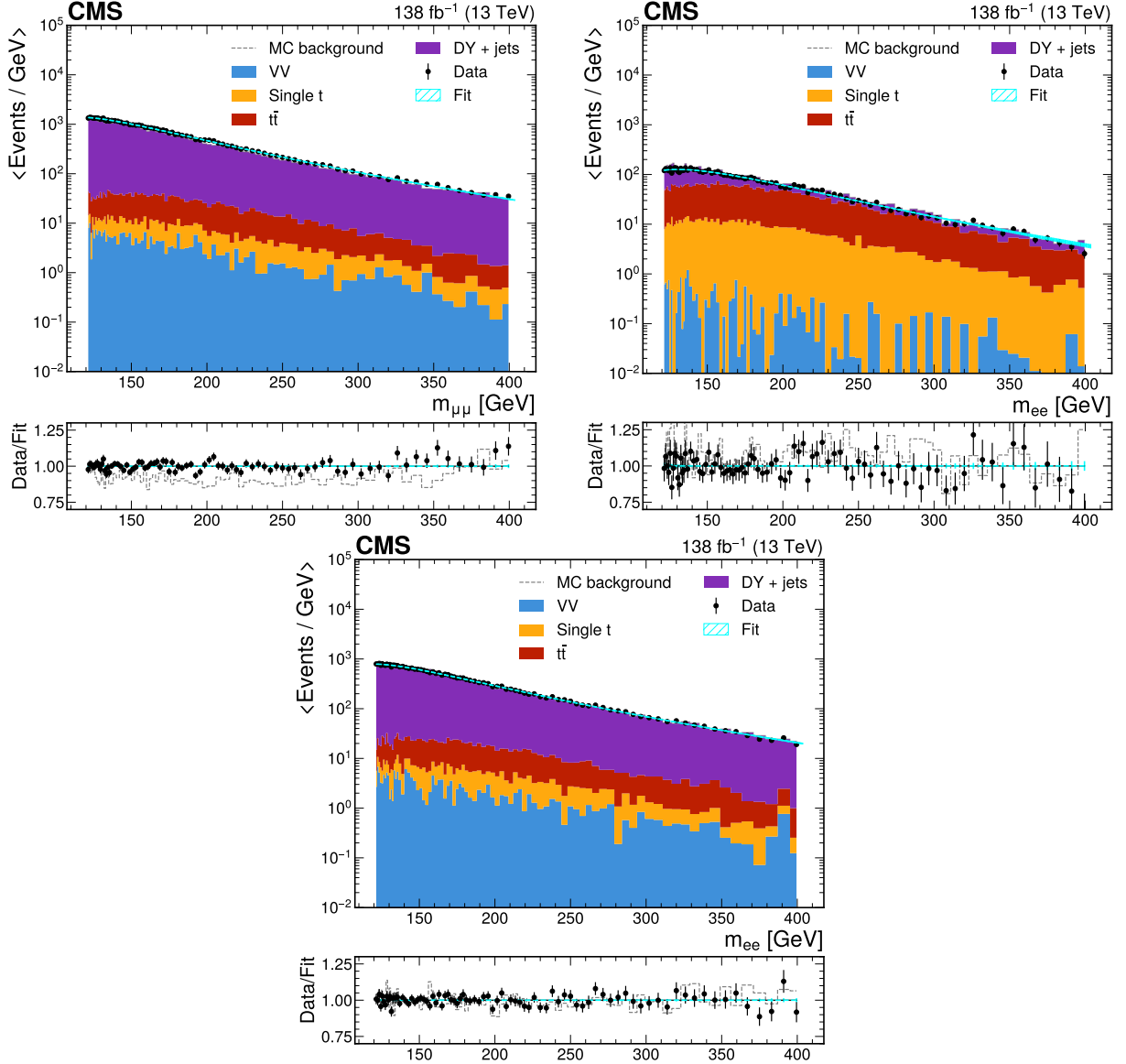


Figure 5: The 1-jet CRs with data fits used for the $SR_b^{\mu\mu}$ background prediction. Upper left: $CR_j^{\mu\mu}$. Upper right: CR_b^{ee} . Lower: CR_j^{ee} . Events are divided by the bin width. We observe a shape difference between data and simulation in $CR_j^{\mu\mu}$. The ratio of the nominal 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.

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%.

During part of Run 2, the HCAL experienced a readout loss covering approximately a $\Delta\phi = 40^\circ$ arc in the region $1.3 < |\eta| < 3.0$. 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.

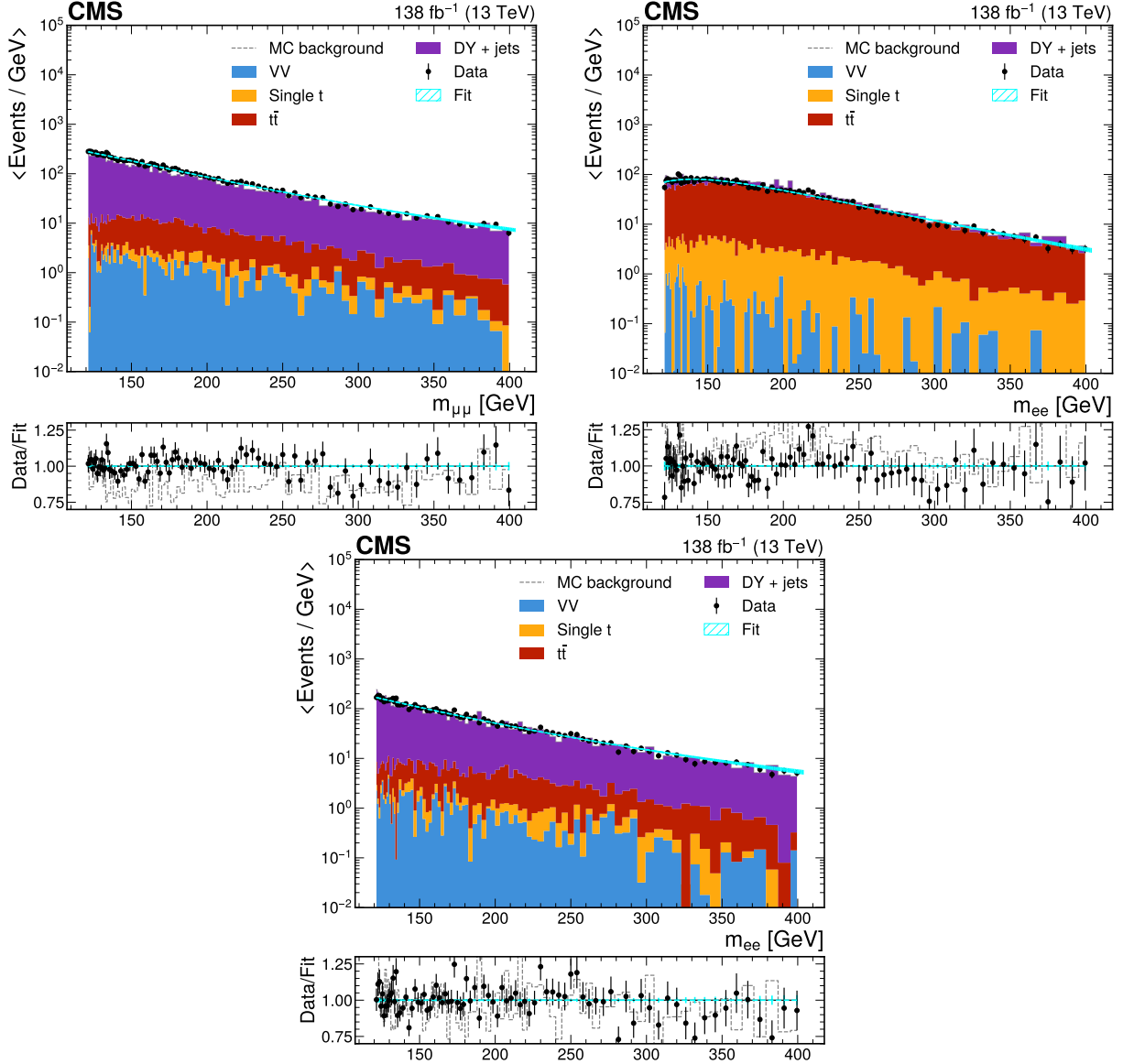


Figure 6: The 2-jet CRs with data fits used for the $\text{SR}_{b+j/b}^{\mu\mu}$ background prediction. Upper left: $\text{CR}_j^{\mu\mu}$. Upper right: CR_b^{ee} . Lower: $\text{CR}_{b+j/b}^{ee}$. Events are divided by the bin width. We observe a shape difference between the MC and data in $\text{CR}_{2j}^{\mu\mu}$. 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.

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 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 $\text{CR}_{b+j/b}^{ee}$ 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 cen-

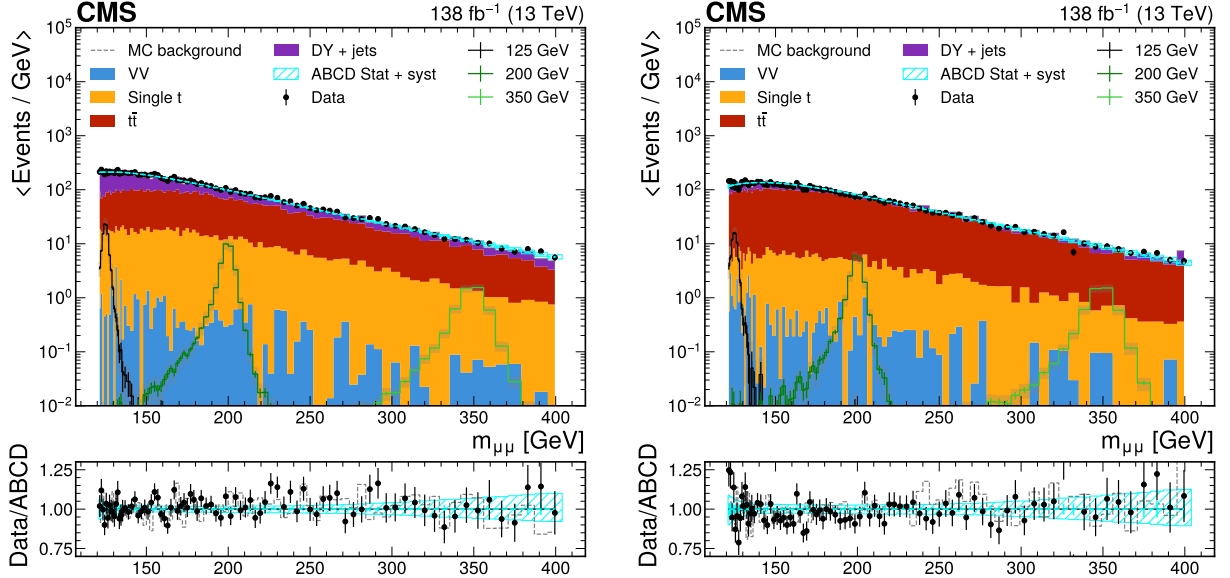


Figure 7: Distributions of $m_{\ell\ell}$ in the $\text{SR}_b^{\mu\mu}$ (left) and $\text{SR}_{b+j/b}^{\mu\mu}$ (right) SRs. Events are divided by the bin width. Simulated signal shapes for Z' boson masses of 125, 200, and 350 GeV are shown. The “Stat + syst” band shows the envelope of the fit variations 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.

tral prediction of the fit is used as a baseline for the per-bin estimated yield. The Poissonian uncertainty in that estimated yield is taken 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 $\text{SR}_b^{\mu\mu}$ ($\text{SR}_{b+j/b}^{\mu\mu}$).

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 [71]. 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, is summarized in Table 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.

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%

7 Results

The SR data agree with the background predictions within the uncertainties. We report limits on the inclusive cross section times branching fraction, as well as limits for individual production processes primarily based on the flavors and multiplicities (b and s) of the initial-state radiation (ISR) for model-independent interpretation. Contributions from 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 Fig. 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) [72] 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 Figs. 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. It has been shown that the dilepton mass shape is the same in our chosen benchmark model for all evaluated signal processes of 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

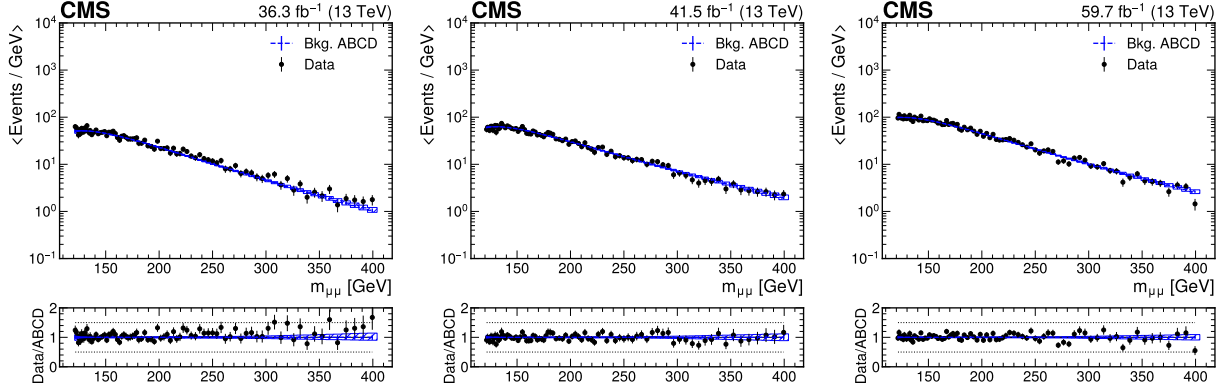


Figure 8: Data (black) vs. the ABCD method background prediction (blue) for 2016 (left), 2017 (middle), and 2018 (right) data-taking years in $\text{SR}_b^{\mu\mu}$. Events are divided by the bin width. Error bars show statistical uncertainties of data. The blue band shows the propagated uncertainty 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.

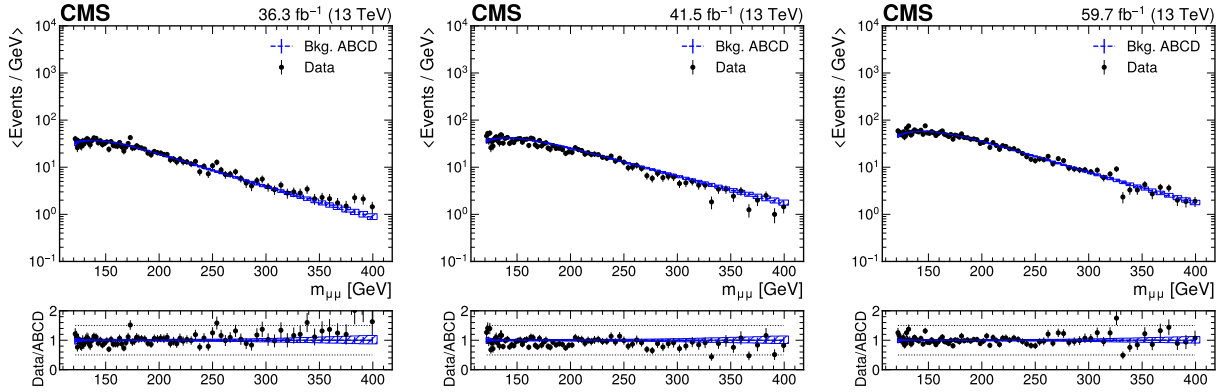


Figure 9: Data (black) vs. the ABCD method background prediction (blue) for 2016 (left), 2017 (middle), and 2018 (right) data-taking years in $\text{SR}_{b+j/b}^{\mu\mu}$. Events are divided by the bin width. Error bars show statistical uncertainties of data. The blue band shows the propagated uncertainty 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.

acceptance for Z' boson masses between 125 and 350 GeV in steps equal to the reconstructed dimuon mass width. The limits are computed using the CMS statistical analysis tool COMBINE [73] which is based on the ROOFIT [74] and ROOSTATS [75] 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 Fig. 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 [76]. 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.

Production process categories we consider are based on matrix element level generator selections after hadronization and jet matching with the MLM prescription [62], as described in Section 3. The primary concern of this categorization is the number of ISR jets and their flavor

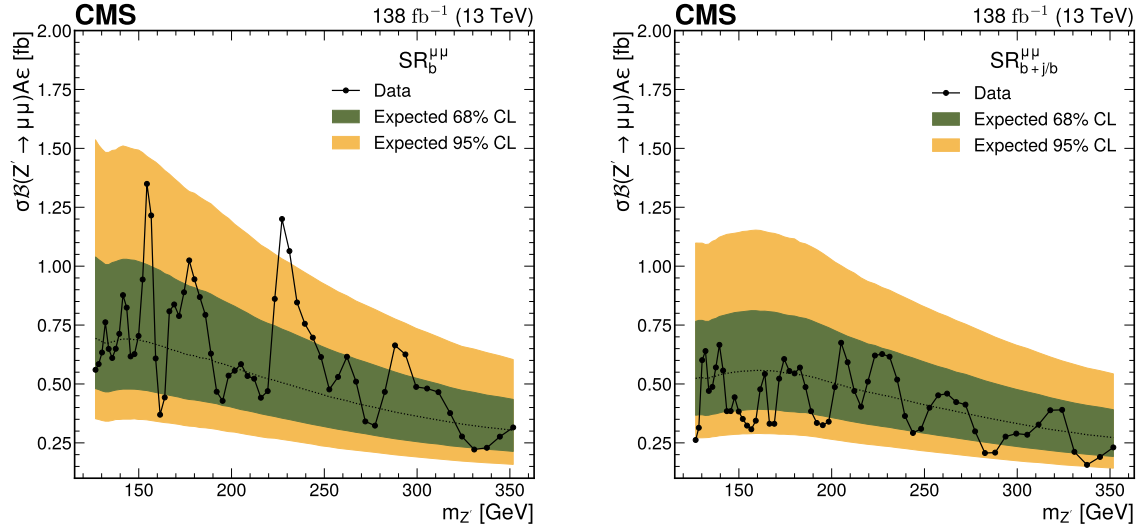


Figure 10: The asymptotic 95% CL limits on the product of cross section(σ), branching fraction into a pair of muons (B) to dimuons, acceptance (A), and efficiency (ϵ). Left is $SR_b^{\mu\mu}$, right is $SR_{b+j/b}^{\mu\mu}$. A combination of both limits depends on the relative acceptance contributions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

(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 Fig. 1:

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

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.

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 (1b) category are listed.

$m_{Z'}$ [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 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 (2b) 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	$9.63 \pm 0.03^{+0.09}_{-0.08}$	$1.86 \pm 0.01^{+0.03}_{-0.03}$

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 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

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.

$m_{Z'}$ [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 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.

$m_{Z'}$ [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	$1.15 \pm 0.04^{+0.01}_{-0.01}$	$3.65 \pm 0.07^{+0.04}_{-0.05}$

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 bjZ' 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

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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	$0.68 \pm 0.21^{+0.02}_{-0.01}$	$4.52 \pm 0.50^{+0.32}_{-0.20}$
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 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	$1.84 \pm 0.17^{+0.06}_{-0.03}$	$5.24 \pm 0.28^{+0.48}_{-0.26}$
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	$4.97 \pm 0.14^{+0.04}_{-0.04}$	$15.55 \pm 0.26^{+0.24}_{-0.23}$

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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.

$m_{Z'}$ [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	$2.84 \pm 0.37^{+0.01}_{-0.01}$	$7.54 \pm 0.60^{+0.10}_{-0.10}$

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