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Search for a high-mass dimuon resonance produced in association with b quark jets at $\sqrt{s} = 13$ TeV

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Abstract

A search for high-mass dimuon resonance production in association with one or more b quark jets is presented. The study uses proton-proton collision data collected with the CMS detector at the LHC corresponding to an integrated luminosity of 138 fb^{-1} at a center-of-mass energy of 13 TeV. Model-independent limits are derived on the number of signal events with exactly one or more than one b quark jet. Results are also interpreted in a lepton-flavor-universal model with Z' boson couplings to a bb quark pair (g_b), an sb quark pair ($g_b \delta_{bs}$), and any same-flavor charged lepton (g_ℓ) or neutrino pair (g_ν), with $|g_\nu| = |g_\ell|$. For a Z' boson with a mass $m_{Z'} = 350 \text{ GeV}$ (2 TeV) and $|\delta_{bs}| < 0.25$, the majority of the parameter space with $0.0057 < |g_\ell| < 0.35$ ($0.25 < |g_\ell| < 0.43$) and $0.0079 < |g_b| < 0.46$ ($0.34 < |g_b| < 0.57$) is excluded at 95% confidence level. Finally, constraints are set on a Z' model with parameters consistent with low-energy $b \rightarrow s \ell \ell$ measurements. In this scenario, most of the allowed parameter space is excluded for a Z' boson with $350 < m_{Z'} < 500 \text{ GeV}$, while the constraints are less stringent for higher $m_{Z'}$ hypotheses. This is the first dedicated search at the LHC for a high-mass dimuon resonance produced in association with multiple b quark jets, and the constraints obtained on models with this signature are the most stringent to date.

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1 Introduction

Over the last few years, a number of experimental results [1–4] have suggested that physics beyond the standard model (SM) could manifest itself in $b \rightarrow s \ell^- \ell^+$ transitions. Experimental results for this process could be explained by the existence of a new neutral vector boson (Z') coupling to lepton (ℓ) pairs [5, 6] with a mass near the TeV scale. In such a scenario, the new Z' boson would couple to b and s quarks, as represented by the Feynman diagrams in Fig. 1. While the most recent experimental results [7, 8] on the ratio of the branching fractions for $b \rightarrow s \mu^- \mu^+$ to $b \rightarrow s e^- e^+$ are in agreement with the SM, there remains some tension in other $b \rightarrow s \ell^- \ell^+$ observables, as recently discussed in Ref. [9].

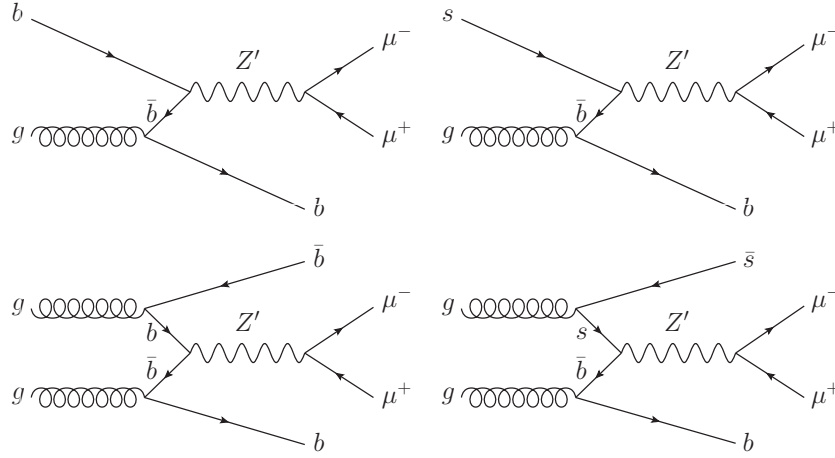


Figure 1: Feynman diagrams of $Z' \rightarrow \mu^- \mu^+$ with a Z' boson produced via $b\bar{b} \rightarrow Z'$ or $s\bar{b} \rightarrow Z'$, with at least one b quark in the final state. While a $Z'b\bar{b}$ coupling may be present in any generic model, a $Z's\bar{b}$ coupling could arise through flavor mixing between the second- and third-generation quarks.

Inclusive searches for beyond-the-SM (BSM) Z' bosons have already been performed at the CERN LHC [10, 11]. However, they are limited by a large Drell–Yan (DY) background and might not be sensitive to scenarios in which the Z' boson couples preferentially to second- or third-generation quarks. Therefore, the goal of this analysis is to search for a $Z' \rightarrow \mu^- \mu^+$ resonance with an explicit requirement on the presence of b quark jets, which strongly disfavors DY events.

The relevant interactions can be described through a lepton-flavor-universal (LFU) model with a Lagrangian simplified from the one in Ref. [12],

$$\mathcal{L}_{\text{BSM}} = Z'_\eta \left\{ g_\ell \sum_{\ell=e,\mu,\tau} \bar{\ell} \gamma^\eta P_L \ell + g_\nu \sum_{\nu=\nu_e,\nu_\mu,\nu_\tau} \bar{\nu} \gamma^\eta P_L \nu + g_b \left[\bar{b} \gamma^\eta P_L b + \delta_{bs} (\bar{s} \gamma^\eta P_L b + \text{h.c.}) \right] \right\}, \quad (1)$$

where P_L denotes the left-handed projection operator. There are four coupling parameters in this model: a common g_ℓ coupling for all charged leptons, a common g_ν coupling for all neutrinos, the g_b coupling that scales both $Z'b\bar{b}$ and $Z's\bar{b}$ interactions, and the separate δ_{bs} parameter that solely scales the $Z's\bar{b}$ interaction.

The $B_3 - L_2$ model is a less generic Z' model introduced in 2017 [13, 14] to accommodate the experimental $b \rightarrow s \ell^- \ell^+$ anomalies. It is based on a new $B_3 - L_2$ $U(1)$ gauge symmetry in which

B_3 and L_2 represent the third-generation baryon and the muon lepton numbers, respectively. In this model, $g_{Z'}$ denotes the coupling of the Z' boson to SM fermions, and the angle θ_{23} controls the mixing angle between the second- and third-generation quarks. This mixing angle is equivalent to $\arctan(-\delta_{bs})$ in the notation of Eq. (1). The allowed parameter space for the B_3-L_2 model has been recently reevaluated in Ref. [9].

Studies of dilepton invariant mass distributions in final states with b quark jets have previously been performed at the LHC [15–17]. However, these studies either focused on final states with exactly one b quark jet, or used inclusive samples with at least one such jet. Furthermore, they suffered from large backgrounds arising from the pair production of t quarks ($t\bar{t}$), each decaying to one b quark and one W boson, with $W \rightarrow \ell\nu$. In this analysis, we reduce this background substantially, as noted below, and we further optimize the event categorization for the presence of one or more b quark jets.

The analysis can be summarized as follows:

- The search is performed for a narrow $Z' \rightarrow \mu^-\mu^+$ resonance with a mass $m_{Z'} > 350$ GeV in the presence of at least one b quark jet. The width of the resonance is assumed to be narrow relative to the dimuon invariant mass ($m_{\mu\mu}$) resolution. The validity of this assumption is ensured by restricting the search to the regions of parameter space where the Z' width does not exceed one half of the $m_{\mu\mu}$ resolution. The resolution itself ranges from 6.6 GeV at $m_{Z'} = 350$ GeV to 30 (106) GeV at $m_{Z'} = 1$ (2.5) TeV.
- The data sample is collected with the CMS detector during the LHC Run 2 data-taking period of 2016–2018 at a center-of-mass energy of 13 TeV, and corresponds to an integrated luminosity of 138 fb^{-1} (2016: 36.3 fb^{-1} ; 2017: 41.5 fb^{-1} ; 2018: 59.8 fb^{-1}).
- Events in this data sample are categorized according to the multiplicity of b quark jets: $N_b = 1$ and $N_b \geq 2$. Tight and relaxed requirements are used together in identifying these jets, as discussed in Section 2, in order to maximize the sensitivity to a possible signal.
- The dominant backgrounds across the probed $m_{\mu\mu}$ range arise from the DY process and $t\bar{t}$ production. The DY background is already reduced by requiring the detection of at least one b quark jet. The $t\bar{t}$ background is suppressed by requiring that the minimum invariant mass of any muon–b quark jet pairing ($\min(m_{\mu b})$) be > 175 GeV, i.e., above the t quark mass. Other background sources, including $tZ+X$, $tW+X$, $t\bar{t}V$ ($V = W, Z, \gamma^*$), and $t\bar{t}H$ processes, as well as diboson (WW, WZ, and ZZ) production, are less important and further reduced by vetoing events with any additional lepton or isolated high transverse momentum (p_T) charged hadron. The veto for events with isolated charged hadrons is used to enhance the rejection of hadronically decaying τ leptons and misidentified electrons or muons.
- We extract constraints on the total event yield as a function of the fraction of events in each of the $N_b = 1$ and $N_b \geq 2$ categories. The constraints are determined using unbinned maximum likelihood fits of the $m_{\mu\mu}$ distributions with analytic functions within mass ranges sliding coherently with the probed value of $m_{Z'}$, as further discussed in Section 4. The functional forms used in the fit and the general statistical procedure are also described in Section 4 and are similar to those in Ref. [18]. The constraints on the total event yield are then reinterpreted in terms of the parameters of specific models with a Z' boson coupled to b quarks.

All of the results for this analysis can also be found on HEPData [19].

2 Experimental setup

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [20]. Events of interest are selected using a two-tiered trigger system. The first level, 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 μ s [21]. The second level, known as the high-level trigger (HLT), 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 [22].

A particle-flow (PF) algorithm [23] aims to reconstruct and identify each individual particle in an event, using an optimized combination of all subdetector information. The particles reconstructed with this algorithm are hereafter referred to as PF candidates, and their isolation is measured from the flux of other charged PF candidates within a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around their direction, where ϕ is the azimuthal angle.

The primary proton-proton (pp) interaction vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone (as described in Section 9.4.1 of Ref. [24]). Muons originating from the PV are identified using a set of requirements [25] that are optimized to maximize their selection efficiency at high p_T . The muon p_T assignment is performed with the ‘TuneP’ algorithm [26], which mainly relies on the tracker information instead of data from the PF algorithm. This avoids the potential bias arising from electromagnetic showers in the muon detectors, caused by extra particles radiated by the high- p_T muon. The difference between the p_T value assigned using only tracker information and that obtained from the PF algorithm is taken into account when applying requirements on other PF-based quantities in the events. As the analysis targets high- p_T muons, which may radiate photons when traversing detector material, the muons are required to be isolated with respect to nearby charged-particle tracks only. The tracker-only isolation of muons, which is defined as the scalar p_T sum of all tracks, excluding that of the muon, within a longitudinal distance of 0.2 cm from the PV and a cone of $\Delta R = 0.3$ relative to the muon track, is required to be less than 5 GeV and less than 5% of the muon p_T as measured in the tracker.

Events are collected with triggers that require the presence of at least one muon at HLT with $p_T > 50$ GeV and $|\eta| < 2.4$. The trigger selection efficiency is measured using the “tag-and-probe” method [27] and independent data sets. The efficiency varies from about 70% in the detector endcaps, i.e., at $|\eta| \gtrsim 2.1$, to about 95% in the detector barrel, yielding an overall efficiency of about 90% with only a slight dependence on the data-taking period [28].

Events are further required to contain two oppositely charged muons with $p_T > 53$ GeV and $|\eta| < 2.4$ satisfying the identification and isolation criteria. The two muons are then used to form a $\mu^- \mu^+$ resonance candidate. Events with additional muons of $p_T > 10$ GeV and $|\eta| < 2.4$ satisfying the same identification and isolation criteria are vetoed. We also veto events that contain isolated PF muon candidates originating from the PV with $p_T > 5$ GeV. These vetoes, together with those described below, reduce the SM background arising from $tZ+X$, $tW+X$, $t\bar{t}V$, $t\bar{t}H$, and diboson production.

In the analysis, electrons are identified using loose requirements [29], for the purpose of vetoing events with electrons originating from the PV. The electron isolation is measured from the flux of PF photons and hadron candidates within a cone of $\Delta R = 0.3$ around its direction, including corrections for contributions from additional pp interactions within the same or nearby bunch crossings (pileup). This PF-based isolation is required to be below a threshold that varies as a function of the electron p_T . Events with any such electron of $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$ are vetoed, together with events that contain any isolated PF electron candidate originating from the PV with $p_T > 5 \text{ GeV}$.

The largest fraction of all visible τ lepton decay products consists of a single charged hadron, often accompanied by multiple neutral pions. For this reason, the veto for events with extra leptons is expanded to include isolated PF charged-hadron candidates originating from the PV with $p_T > 10 \text{ GeV}$.

Jets are reconstructed using the anti- k_T algorithm [30, 31] with a distance parameter of 0.4. Jet energies are corrected for instrumental effects and contributions from pileup. We select jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$, that must also be separated by $\Delta R > 0.4$ from each muon candidate. The identification of b quark jets uses the DEEPJET algorithm [32, 33]. At least one b quark jet must satisfy tight identification criteria ($\sim 58\%$ tagging efficiency for $\sim 0.1\%$ misidentification probability of jets from light quarks and gluons), and all other b quark jets are identified using relaxed requirements ($\sim 76\%$ tagging efficiency for $\sim 1\%$ misidentification probability). In order to reject μb pairs that originate from t quark decays, we calculate all possible values of $m_{\mu b}$ among the selected muons and b quark jets, and require $\min(m_{\mu b}) > 175 \text{ GeV}$, i.e., above the value of the t quark mass. This requirement is used to suppress the $t\bar{t}$ background, which is reduced by more than two orders of magnitude, while retaining most of the predicted signals with large $m_{Z'}$, as shown in Fig. 2.

The missing transverse momentum vector ($\vec{p}_T^{\text{miss}}$) is estimated from the negative of the vector p_T sum of all PF candidates, where the pileup-per-particle-identification algorithm [34, 35] weights each PF candidate for its probability to originate from the PV in order to reduce the pileup dependence of this observable. The $\vec{p}_T^{\text{miss}}$ vector is corrected further for residual inconsistencies that may be introduced from the non-PF high- p_T muon identification criteria and the muon p_T assignment through the ‘TuneP’ algorithm. While no source of significant genuine p_T^{miss} is expected except for neutrinos in the case of semileptonic decays of the heavy-flavor quarks, large p_T^{miss} may nevertheless be observed if the momentum of a muon or b quark jet is mismeasured. Thus, events are vetoed if $p_T^{\text{miss}} > 250 \text{ GeV}$ and $\vec{p}_T^{\text{miss}}$ is aligned ($|\Delta\phi| < 0.3$) or antialigned ($|\Delta\phi| > \pi - 0.3$) with any selected muon or b quark jet. This requirement retains almost the totality of the predicted signals. Other anomalous high- p_T^{miss} events, due to reconstruction issues, detector malfunctions, or noncollision backgrounds, are rejected by dedicated filters. These filters identify more than 85–90% of the spurious high- p_T^{miss} events with a mistagging rate less than 0.1% [36]. In addition, the three-dimensional angle between the two muons is required to be smaller than $\pi - 0.02$ to further suppress cosmic ray muon contributions.

In 2018, a sector of the HCAL ($-3.2 < \eta < -1.3$ and $-1.57 < \phi < -0.87$) was not operational for a data-taking period corresponding to an integrated luminosity of 39 fb^{-1} , resulting in the misreconstruction of hadronic jets in that η - ϕ range. Therefore, events collected during this period are rejected if jets or electrons are found in the affected region, with upper and lower boundaries for jets enlarged by 0.2 in both η and ϕ in order to account for the size of the jet cone. The simulation of events, discussed in Section 3, is also adjusted by applying the same requirement in a subset of events corresponding to the fraction of data affected by this issue. The efficiency loss over the full data set is about 5% regardless of the value of $m_{\mu\mu}$.

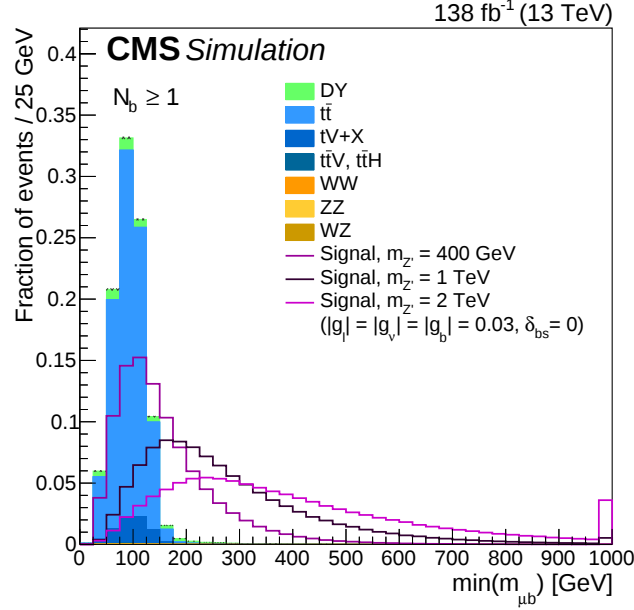


Figure 2: Distribution of $\min(m_{\mu b})$ as obtained from simulation in events with $N_b \geq 1$ passing all the other selection requirements. In this search, we require $\min(m_{\mu b}) > 175$ GeV. The stacked histogram displays the expected distribution from the simulation of the SM backgrounds, while the overlaid open histograms illustrate the size and shape of the Z' contribution from the LFU model described in Eq. (1), for several Z' mass hypotheses. For illustrative purposes, we choose couplings $|g_\ell| = |g_\nu| = |g_b| = 0.03$ and $\delta_{bs} = 0$. The contribution of background processes other than DY and $t\bar{t}$ is so small that it is only barely visible at the bottom of the stacked histogram. The hatched region indicates the statistical uncertainty arising from the limited size of the SM simulated samples (Section 3). Histograms are normalized to unit area.

3 Event simulation

We use simulated samples of various BSM Z' models to motivate the event selection and to provide model-dependent limits. On the other hand, the SM background is estimated directly from data as a continuum background in the $m_{\mu\mu}$ spectrum, parametrized by analytic functions. Thus, the background estimation does not rely on simulation. The SM simulated samples are used only to validate and optimize the event selection as well as to visually compare the observed dimuon mass distribution to the expected SM background from simulation.

The simulated samples for the dominant DY and $t\bar{t}$ backgrounds, and the $tW+X$ process, are generated using the POWHEG 2 [37–40] program at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD). Samples for the $tZ+X$, $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma^*$ processes, and for the $t\bar{t}H$ process are generated at NLO in QCD using MADGRAPH5_aMC@NLO [41] v2.6.5 and v2.6.1, respectively, with the FxFx [42] scheme to match jets from matrix element calculations and parton showers. Samples for diboson production are generated using either MADGRAPH5_aMC@NLO v2.6.5 or POWHEG 2 at NLO in QCD.

As discussed in Section 1, we consider a signal Z' model involving $Z'bb$ and $Z'sb$ couplings and $Z' \rightarrow \mu\mu$ decays. We generate such interactions using MADGRAPH5_aMC@NLO v2.9.9 at LO in QCD with $m_{Z'}$ ranging from 350 to 2500 GeV. For all the generated samples, the total width $\Gamma(Z')$ of the Z' is always smaller than one half of the $m_{\mu\mu}$ resolution to ensure the validity of the narrow width approximation intrinsic to the search strategy. Predictions for any other model

with a likewise narrow width value can be obtained through reweighting by the double ratio of the quantity $\Gamma(Z' \rightarrow q_i \bar{q}_j) \Gamma(Z' \rightarrow \mu^- \mu^+) / \Gamma(Z')$ between the target model and the generated sample. Here, $\Gamma(Z' \rightarrow q_i \bar{q}_j)$ denotes the partial width for $Z' \rightarrow b\bar{b}$, $Z' \rightarrow s\bar{s}$ and $Z' \rightarrow b\bar{s}$, and $\Gamma(Z' \rightarrow \mu^- \mu^+)$ is the partial width for $Z' \rightarrow \mu^- \mu^+$. The reweighting is performed by separating the simulated event sample into contributions from matrix elements with different $q_i \bar{q}_j \rightarrow Z'$ interactions, as shown in Fig. 1, and the use of partial widths ensures generality across different ways to construct target models.

In all samples, the parton shower and hadronization are modeled with PYTHIA 8.230 [43] using the CP5 [44] tune. The parton distribution functions are taken from NNPDF 3.1 [45]. For the SM simulated samples, they are taken at next-to-NLO in QCD. For the signal simulation, they are taken at LO in QCD to match the signal cross section calculations. All the simulated events are generated with a distribution of additional pp interactions per bunch crossing that is adjusted to match the corresponding pileup distribution measured in data. Finally, the detector response is simulated with the GEANT4 [46] package.

4 Analysis strategy

The events selected as described in Section 2 are categorized according to the multiplicity of b quark jets: $N_b = 1$ and $N_b \geq 2$. The search is performed by simultaneously fitting the unbinned $m_{\mu\mu}$ distributions in these two categories with analytic functions, within mass ranges that vary coherently with the value of $m_{Z'}$ to be probed.

We parametrize the signal $m_{\mu\mu}$ distribution as the sum of a Gaussian distribution with a double-sided Crystal Ball function [47, 48] with varying proportions, and a common resolution width parameter σ_{mass} . The choice of the functional form and the dependence of the corresponding parameters on $m_{Z'}$ are determined from simulation. The values of σ_{mass} range from 6.6 GeV at $m_{Z'} = 350$ GeV to 30 (106) GeV at $m_{Z'} = 1$ (2.5) TeV. Fits to the data are performed within an $m_{\mu\mu}$ mass window of $\pm 10 \sigma_{\text{mass}}$ around the probed $m_{Z'}$ value with the restriction $m_{\mu\mu} > 275$ GeV. The fit window is chosen to be relatively wide to ensure that the background is reliably estimated, without any significant bias that may otherwise arise in the presence of a potential signal at its center. This approach is used, instead of fitting the full $m_{\mu\mu}$ distribution at once, in absence of prior knowledge of the SM background shape across the full range of interest.

With a relatively wide mass window, the background $m_{\mu\mu}$ distribution can be modeled analytically using Bernstein polynomials, or exponential or power-law functions. The choice of the background function is treated as a discrete nuisance parameter in the fit [49]. The statistical procedures to determine the goodness of fit for the backgrounds and extract the final fit results are similar to those described in Ref. [18]. For Bernstein polynomials, the best order in each fit mass window and event category is selected by means of a *Fisher test* [50]. Typically, first order Bernstein polynomials are selected, since higher order functions do not significantly improve the description of the data because of the small number of observed events. For the same reason, only Bernstein polynomials of the first order are used to model the backgrounds in windows with less than ten observed events. To avoid artifacts from fluctuating low statistics data, the background is constrained not to increase monotonically as a function of $m_{\mu\mu}$ within the fit mass window. The potential presence of a bias in the measurement of a signal due to the choice of the background functional forms is assessed by means of pseudo-experiments, and no evidence of a statistically significant bias is found.

A systematic uncertainty of 1.6% in the expected signal yields arises from the integrated luminosity measurement [51–53]. In addition, uncertainties in signal event yields from jet energy scale, trigger, muon reconstruction and b tagging efficiencies, and finite simulated sample size are included in the fits. We include a 5% uncertainty in the signal acceptance to account for possible mismodeling of the muon identification efficiency in the simulation. We also assess an uncertainty $\lesssim 5\%$ arising from the estimation of the size of the fit mass window. Finally, we account for possible effects on the signal shape from the uncertainties in the muon momentum scale ($\lesssim 0.1\%$ at $m_{Z'} = 1$ TeV) and resolution ($\lesssim 10\% \sigma_{\text{mass}}$). A summary of the sources of signal uncertainty and their sizes is given in Table 1.

Table 1: Summary of signal uncertainties. The uncertainties are grouped based on whether they affect the normalization or the shape of the signal, and any variations for the two categories of N_b are shown. The fit parameter $\bar{m}_{\mu\mu}$ corresponds to the position of the maximum of the reconstructed $m_{\mu\mu}$ distribution, and $\bar{\sigma}_{\text{mass}}$ is the resolution parameter used in the fit, distinguished from the values of σ_{mass} extracted from simulation.

Source	Normalization		Shape
	$N_b = 1$	$N_b \geq 2$	
Integrated luminosity	1.6%		—
Trigger	1–5%		—
Jet energy scale	1–1.5%	2–5%	—
b tagging	1%	5%	—
μ reconstruction	2.5%		—
μ identification	5%		—
Size of fit window	$\lesssim 5\%$		—
Size of simulated sample	$< 1\%$	$< 5\%$	—
μ momentum scale in $\bar{m}_{\mu\mu}$	—	—	$\lesssim 0.1\% \frac{m_{Z'}^2}{\text{TeV}}$
μ momentum resolution in $\bar{\sigma}_{\text{mass}}$	—	—	$\lesssim 10\% \sigma_{\text{mass}}$

5 Results

The $m_{\mu\mu}$ distributions in the two event categories are shown in Fig. 3 for data, SM background simulation, and several representative signal hypotheses. As already mentioned, the SM background simulation is only used for illustrative purposes since the background is estimated directly from data across the full $m_{\mu\mu}$ range of interest.

The results of a single set of background-only fit to data in the event categories with $N_b = 1$ and $N_b \geq 2$ are shown in Fig. 4 for a sample signal mass hypothesis, $m_{Z'} = 500$ GeV, within the corresponding $m_{\mu\mu}$ fit window. No significant excess is observed over the background-only expectation in any of the mass windows explored.

The results are used to set model-independent limits at 95% confidence level (CL) on the number of signal events with $N_b \geq 1$. The relative fraction of events in the $N_b \geq 2$ category, f_{2b} , is varied to probe a range of hypotheses of signal production in association with b quarks. These limits are shown in Fig. 5. They are extracted by fitting the $m_{\mu\mu}$ distribution in data using windows that slide in steps reflecting the size of σ_{mass} . As different data events are included in each of the fit windows, fluctuations are present in both the expected and observed exclusion limits. The frequency of these fluctuations follows the size of the steps used to probe different $m_{Z'}$ hypotheses, and their amplitude is typically less than the 68% expected band. The statistical procedure to set the limits follows a modified frequentist approach employing the CL_s criterion [54–57].

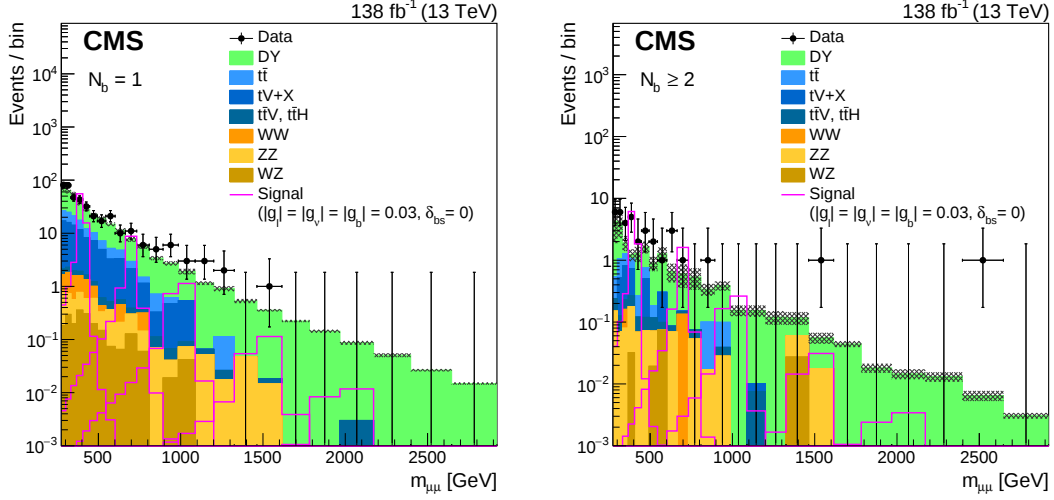


Figure 3: Distributions of $m_{\mu\mu}$ in the $N_b = 1$ (left) and $N_b \geq 2$ (right) event categories. The stacked histogram displays the expected distribution from the SM background simulation. The overlaid open distributions illustrate the Z' contribution from the LFU model at $|g_\ell| = |g_\nu| = |g_b| = 0.03$ and $\delta_{bs} = 0$ for a variety of Z' mass hypotheses. The observed data are shown as black points with statistical error bars. The hatched region indicates the statistical uncertainty arising from the limited size of the SM simulated samples. The size of the bins increases as a function of $m_{\mu\mu}$. In extracting the results of the search, the background is estimated directly from data, so the SM background simulation is only illustrative in these distributions.

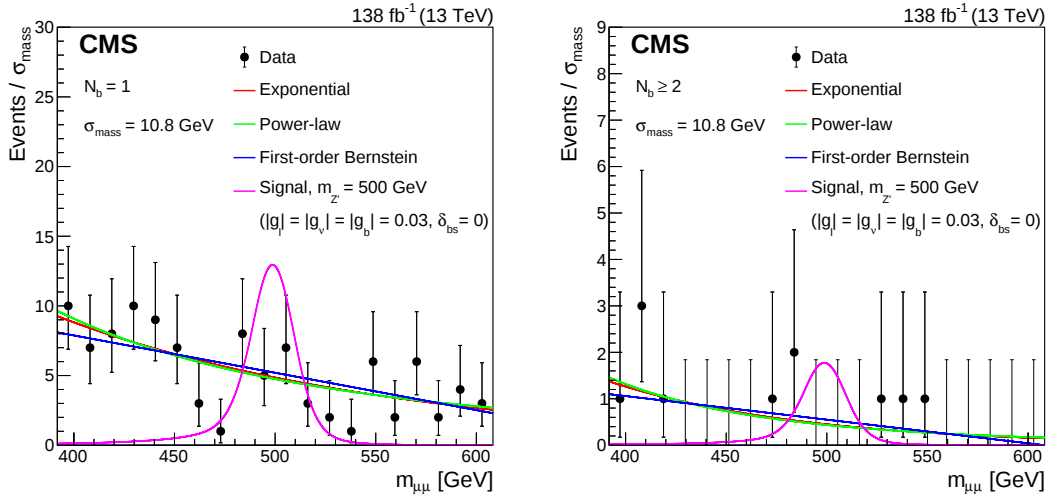


Figure 4: Invariant mass $m_{\mu\mu}$ distributions in the $N_b = 1$ (left) and $N_b \geq 2$ (right) categories, shown together with the corresponding selected background functional forms used as input to the *discrete profiling* method [49] when probing the $m_{Z'} = 500$ GeV hypothesis. The expected signal distribution for the LFU model described in Eq. (1), with couplings $|g_\ell| = |g_\nu| = |g_b| = 0.03$ and $\delta_{bs} = 0$, is overlaid. The displayed mass range corresponds to the fit window used for this $m_{Z'}$ hypothesis, which is $\pm 10\sigma_{\text{mass}}$ around the probed $m_{Z'}$ value. While the likelihood fits are performed on unbinned data, here we present the data in binned histograms with binning chosen to reflect the size of σ_{mass} .

Figure 6 provides an interpretation for the LFU model described in Eq. (1) with the assumed values $|g_\nu| = |g_\ell|$, and either $|\delta_{bs}| = 0$ or 0.25. As $|g_\ell|$ or $|g_b|$ increases, the expected value

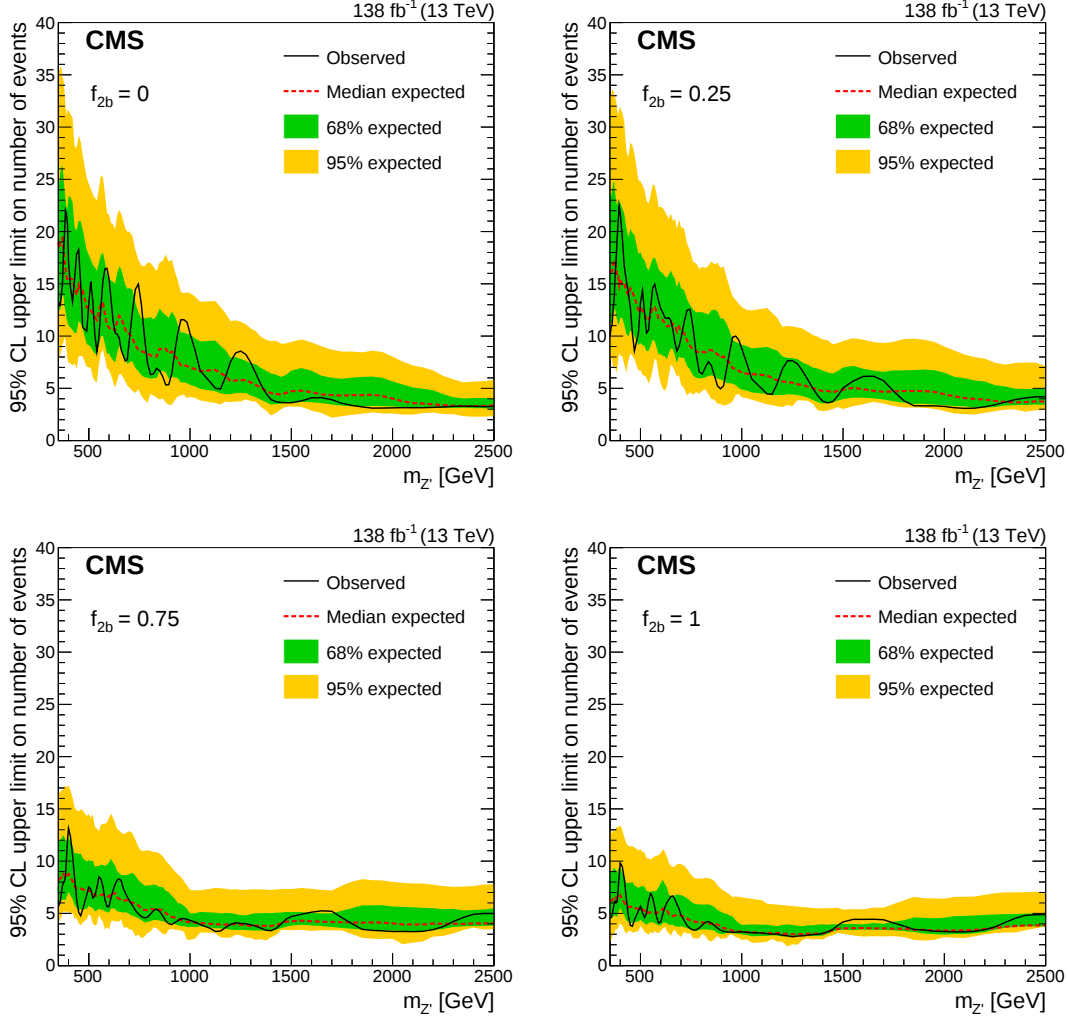


Figure 5: Exclusion limits at 95% CL on the number of selected BSM events with $N_b \geq 1$ as functions of $m_{Z'}$ for the different representative values of $f_{2b} = 0$ (upper left), 0.25 (upper right), 0.75 (lower left), and 1 (lower right). The quantity f_{2b} is the fraction of BSM events passing the analysis selection that have at least two b quark jets. The solid black (dashed red) curve represents the observed (median expected) exclusion. The inner green (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis.

of $\Gamma(Z')$ may approach and exceed the value of σ_{mass} . Since $\Gamma(Z')$ is assumed to be smaller than σ_{mass} in obtaining these results, we restrict our exclusion ranges to the regions where $\Gamma(Z') < \sigma_{\text{mass}}/2$. For a Z' boson with a mass of 350 GeV (2 TeV) and $|\delta_{bs}| < 0.25$, the majority of the parameter space with $0.0057 < |g_\ell| < 0.35$ ($0.25 < |g_\ell| < 0.43$) and $0.0079 < |g_b| < 0.46$ ($0.34 < |g_b| < 0.57$) is excluded at 95% CL.

The results are also used to set constraints on the $B_3 - L_2$ model from Ref. [9]. As in the case of the LFU model, we restrict our exclusion ranges to regions with $\Gamma(Z') < \sigma_{\text{mass}}/2$. As shown in Fig. 7, most of the allowed parameter space is excluded for a Z' boson with $350 < m_{Z'} < 500$ GeV, while the constraints are less stringent for higher $m_{Z'}$. Since exclusion limits are nearly independent of the θ_{23} parameter in the $B_3 - L_2$ model or, equivalently, δ_{bs} in the LFU model, we also show in Fig. 8 exclusion regions in the $|g_{Z'}| - m_{Z'}$ plane for a fixed value of $\theta_{23} = 0$.

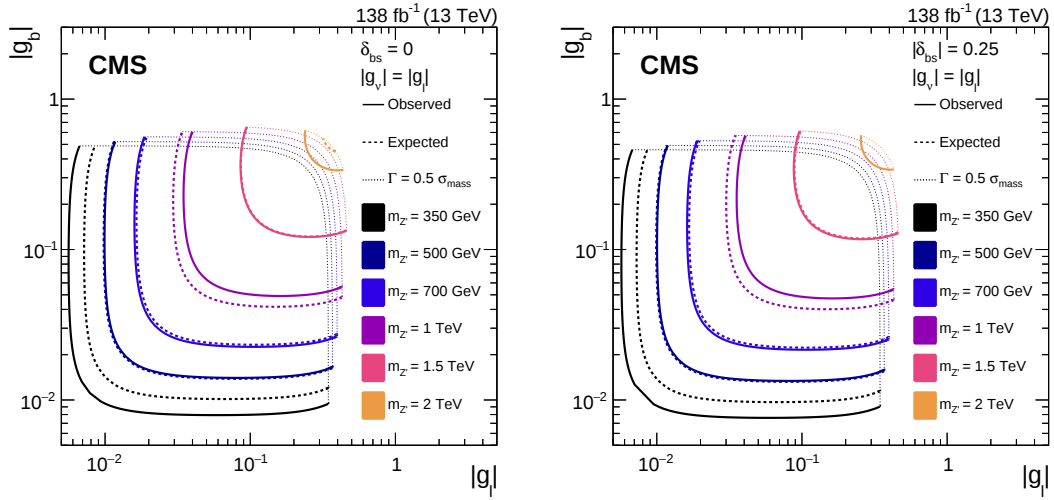


Figure 6: Observed (solid) and median expected (dashed) exclusion limits at 95% CL in the $|g_b|$ - $|g_l|$ plane for the LFU model. The scenarios considered have $|\delta_{bs}|$ values of either 0 (left) or 0.25 (right). In all cases, we assume $|g_\nu| = |g_l|$. The exclusion limits are given up to coupling values at which the Z' width is equal to half of the $\mu\mu$ invariant mass resolution, marked by the dotted curves. Beyond these coupling values, the narrow width approximation intrinsic to the search strategy is not considered valid. The enclosed regions are excluded.

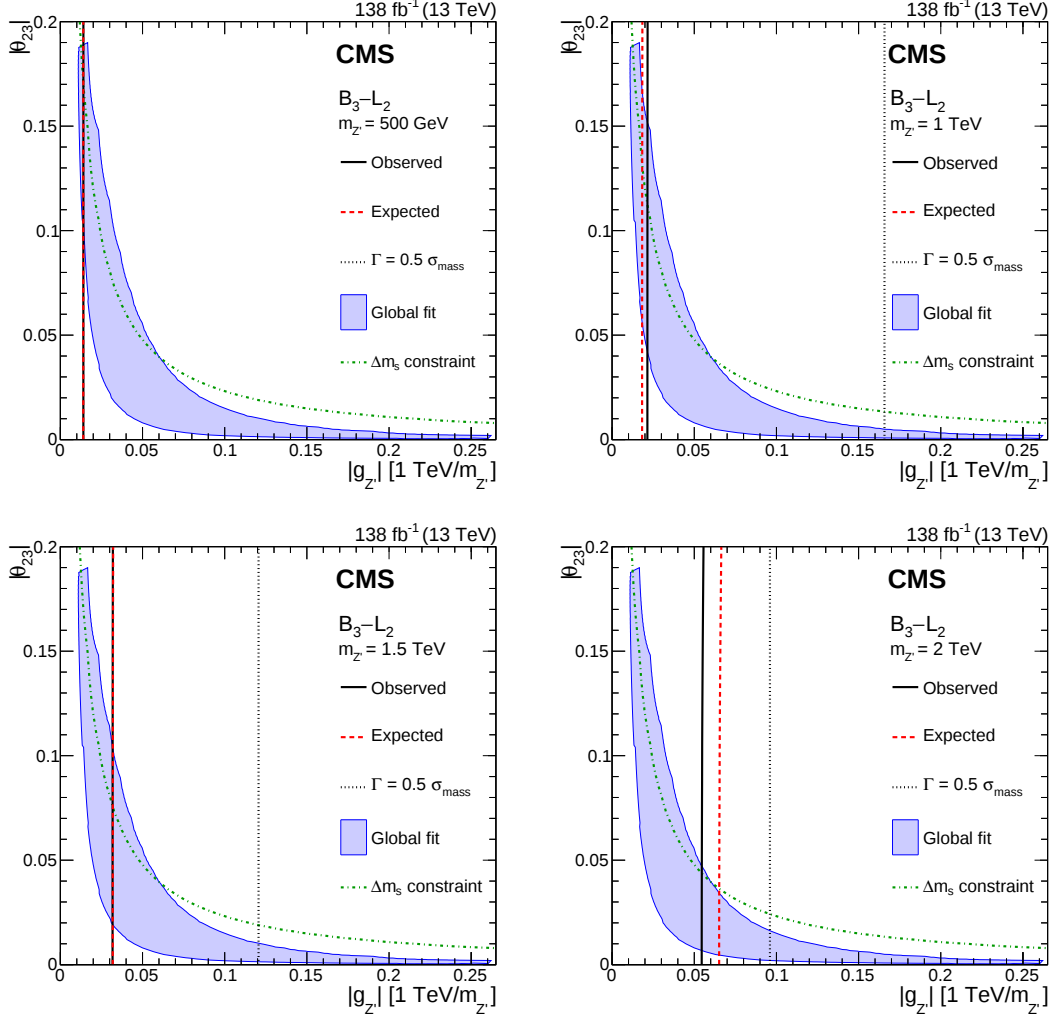


Figure 7: Exclusion limits at 95% CL in the $|\theta_{23}|$ - $|g_{Z'}|$ plane for the B_3-L_2 model [9], for representative values of $m_{Z'} = 500$ GeV (upper left), $m_{Z'} = 1$ TeV (upper right), $m_{Z'} = 1.5$ TeV (lower left), and $m_{Z'} = 2$ TeV (lower right). The solid black (dashed red) curves represent the observed (median expected) exclusions. The dotted curves denote the coupling values at which the Z' width equals one half of the $\mu\mu$ invariant mass resolution. For larger values of the couplings, the narrow width approximation intrinsic to the search strategy is not considered valid. For a given mass, the region enclosed between the solid black (dashed red) and dotted curves is (expected to be) excluded. The dotted curve for $m_{Z'} = 500$ GeV lies beyond the displayed $|g_{Z'}|$ range and is, therefore, not shown. The shaded blue area represents the region preferred from the global fit in Ref. [9] at 95% CL. The region above the green dash-dotted curve is incompatible at 95% CL with the measurement of the mass difference between the mass eigenstates of the neutral B_s mesons [12].

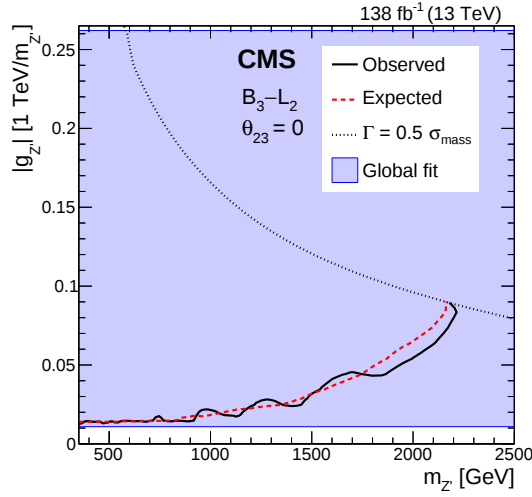


Figure 8: Exclusion limits at 95% CL in the $|g_{Z'}|$ - $m_{Z'}$ plane for the B_3-L_2 model [9] for a fixed value of $\theta_{23} = 0$. The solid black (dashed red) curve represents the observed (median expected) exclusion. The dotted curve denotes the coupling values at which the Z' width equals one half of the $\mu\mu$ invariant mass resolution. For larger values of the couplings, the narrow width approximation intrinsic to the search strategy is not considered valid. The region enclosed between the solid black (dashed red) and the dotted curves is (expected to be) excluded. The shaded blue area represents the $|g_{Z'}|$ range preferred from the global fit in Ref. [9] at 95% CL.

6 Summary

A search for high-mass dimuon resonance production in association with one or more b quark jets has been presented, using data collected with the CMS experiment at the LHC that correspond to an integrated luminosity of 138 fb^{-1} at a center-of-mass energy of 13 TeV.

Model-independent limits are derived on the total number of signal events with $N_b = 1$ and ≥ 2 , where N_b denotes the multiplicity of b quark jets. The relative fraction of events with $N_b \geq 2$ is varied to probe a range of hypotheses of signal production in association with b quarks. The limits are presented as a function of the analyzed dimuon resonance mass values.

Results are also interpreted in terms of a lepton flavor-universal model that involves Z' boson couplings to b quarks (g_b) and muons, where the Z' boson couplings to all neutrinos (g_ν) and to all charged leptons (g_ℓ) are assumed to be equal, the g_b coupling scales both Z' bb and Z' sb interactions, and the separate δ_{bs} coupling solely scales the Z' sb interaction. The exclusions in this model are presented in terms of the coupling strengths g_ℓ and g_b , and the mass of the Z' boson ($m_{Z'}$). For a Z' boson with $m_{Z'} = 350 \text{ GeV}$ (2 TeV) and $|\delta_{bs}| < 0.25$, the majority of the parameter space with $0.0057 < |g_\ell| < 0.35$ ($0.25 < |g_\ell| < 0.43$) and $0.0079 < |g_b| < 0.46$ ($0.34 < |g_b| < 0.57$) is excluded at 95% confidence level.

Constraints are also set on a specific Z' model ($B_3 - L_2$), constructed to accommodate possible contributions to $b \rightarrow s \ell^- \ell^+$ transitions beyond the standard model. In this scenario, most of the allowed parameter space is excluded for a Z' boson with $350 < m_{Z'} < 500 \text{ GeV}$, while the constraints are less stringent for higher $m_{Z'}$ hypotheses.

This is the first dedicated search at the LHC for a high-mass dimuon resonance produced in association with multiple b quark jets, and the constraints obtained on models with this signature are the most stringent to date.

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References

- [1] LHCb Collaboration, "Test of lepton universality with $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays", *JHEP* **08** (2017) 055, doi:10.1007/JHEP08(2017)055, arXiv:1705.05802.
- [2] LHCb Collaboration, "Search for lepton-universality violation in $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays", *Phys. Rev. Lett.* **122** (2019) 191801, doi:10.1103/PhysRevLett.122.191801, arXiv:1903.09252.
- [3] LHCb Collaboration, "Test of lepton universality in beauty-quark decays", *Nature Phys.* **18** (2022) 277, doi:10.1038/s41567-021-01478-8, arXiv:2103.11769.
- [4] LHCb Collaboration, "Tests of lepton universality using $B^0 \rightarrow K_S^0 \ell^+ \ell^-$ and $B^+ \rightarrow K^{*+} \ell^+ \ell^-$ decays", *Phys. Rev. Lett.* **128** (2022) 191802, doi:10.1103/PhysRevLett.128.191802, arXiv:2110.09501.
- [5] A. Leike, "The phenomenology of extra neutral gauge bosons", *Phys. Rept.* **317** (1999) 143, doi:10.1016/S0370-1573(98)00133-1, arXiv:hep-ph/9805494.
- [6] P. Langacker, "The physics of heavy Z' gauge bosons", *Rev. Mod. Phys.* **81** (2009) 1199, doi:10.1103/RevModPhys.81.1199, arXiv:0801.1345.
- [7] LHCb Collaboration, "Test of lepton universality in $b \rightarrow s \ell^+ \ell^-$ decays", 2022. arXiv:2212.09152. Submitted to *Phys. Rev. Lett.*

- [8] LHCb Collaboration, “Measurement of lepton universality parameters in $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays”, 2022. arXiv:2212.09153. Submitted to *Phys. Rev. D*.
- [9] B. Allanach and J. Davighi, “The Rumble in the Meson: a leptoquark versus a Z' to fit $b \rightarrow s \mu^+ \mu^-$ anomalies including 2022 LHCb $R_{K^{(*)}}$ measurements”, *JHEP* **04** (2023) 033, doi:10.1007/JHEP04(2023)033, arXiv:2211.11766.
- [10] ATLAS Collaboration, “Search for high-mass dilepton resonances using 139 fb $^{-1}$ of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Lett. B* **796** (2019) 68, doi:10.1016/j.physletb.2019.07.016, arXiv:1903.06248.
- [11] CMS Collaboration, “Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2021) 208, doi:10.1007/JHEP07(2021)208, arXiv:2103.02708.
- [12] Particle Data Group, “Review of Particle Physics”, *PTEP* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.
- [13] R. Alonso, P. Cox, C. Han, and T. T. Yanagida, “Flavoured $B-L$ local symmetry and anomalous rare B decays”, *Phys. Lett. B* **774** (2017) 643, doi:10.1016/j.physletb.2017.10.027, arXiv:1705.03858.
- [14] C. Bonilla, T. Modak, R. Srivastava, and J. W. F. Valle, “ $U(1)_{B_3-3L_\mu}$ gauge symmetry as a simple description of $b \rightarrow s$ anomalies”, *Phys. Rev. D* **98** (2018) 095002, doi:10.1103/PhysRevD.98.095002, arXiv:1705.00915.
- [15] ATLAS Collaboration, “Search for scalar resonances decaying into $\mu^+ \mu^-$ in events with and without b-tagged jets produced in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **07** (2019) 117, doi:10.1007/JHEP07(2019)117, arXiv:1901.08144.
- [16] CMS Collaboration, “Search for MSSM Higgs bosons decaying to $\mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **798** (2019) 134992, doi:10.1016/j.physletb.2019.134992, arXiv:1907.03152.
- [17] ATLAS Collaboration, “Search for new phenomena in final states with two leptons and one or no b-tagged jets at $\sqrt{s} = 13$ TeV using the ATLAS detector”, *Phys. Rev. Lett.* **127** (2021) 141801, doi:10.1103/PhysRevLett.127.141801, arXiv:2105.13847.
- [18] CMS Collaboration, “Search for long-lived particles decaying into muon pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV collected with a dedicated high-rate data stream”, *JHEP* **04** (2022) 062, doi:10.1007/JHEP04(2022)062, arXiv:2112.13769.
- [19] HEPData record for this analysis, 2023. doi:10.17182/hepdata.141455.
- [20] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [21] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [22] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

-
- [23] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [24] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.
- [25] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [26] CMS Collaboration, “Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P02027, doi:10.1088/1748-0221/15/02/P02027, arXiv:1912.03516.
- [27] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
- [28] CMS Collaboration, “Performance of the CMS muon trigger system in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **16** (2021) P07001, doi:10.1088/1748-0221/16/07/P07001, arXiv:2102.04790.
- [29] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [30] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [31] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [32] E. Bols et al., “Jet flavour classification using DeepJet”, *JINST* **15** (2020) 12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [33] CMS Collaboration, “Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector”, CMS Detector Performance Note CMS-DP-2023-005, 2023.
- [34] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [35] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.
- [36] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [37] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

- [38] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO single-top production matched with shower in POWHEG: s - and t -channel contributions”, *JHEP* **09** (2009) 111, doi:10.1088/1126-6708/2009/09/111, arXiv:0907.4076. [Erratum: doi:10.1007/JHEP02(2010)011].
- [39] T. Melia, P. Nason, R. Röntsch, and G. Zanderighi, “ W^+W^- , WZ and ZZ production in the POWHEG BOX”, *JHEP* **11** (2011) 078, doi:10.1007/JHEP11(2011)078, arXiv:1107.5051.
- [40] P. Nason and G. Zanderighi, “ W^+W^- , WZ and ZZ production in the POWHEG-BOX-V2”, *Eur. Phys. J. C* **74** (2014) 2702, doi:10.1140/epjc/s10052-013-2702-5, arXiv:1311.1365.
- [41] 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, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [42] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [43] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [44] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [45] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [46] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [47] M. J. Oreglia, “A study of the reactions $\psi' \rightarrow \gamma\gamma\psi$ ”. PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236, see Appendix D.
- [48] J. E. Gaiser, “Charmonium spectroscopy from radiative decays of the J/ψ and ψ' ”. PhD thesis, Stanford University, 1982. SLAC Report SLAC-R-255.
- [49] P. D. Dauncey, M. Kenzie, N. Wardle, and G. J. Davies, “Handling uncertainties in background shapes: the discrete profiling method”, *JINST* **10** (2015) P04015, doi:10.1088/1748-0221/10/04/P04015, arXiv:1408.6865.
- [50] R. A. Fisher, “On the interpretation of χ^2 from contingency tables, and the calculation of P ”, *J. R. Stat. Soc.* **85** (1922) 87, doi:10.1098/rsta.1922.0009.
- [51] 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, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [52] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

- [53] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [54] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [55] A. L. Read, “Presentation of search results: The CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [56] 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, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [57] ATLAS and CMS Collaborations, “Procedure for the LHC Higgs boson search combination in summer 2011”, ATL-PHYS-PUB-2011-011, CMS NOTE-2011/005, 2011.

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