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

The CMS collaboration

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

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 ($g_\mathrm{b}\delta_\mathrm{bs}$), 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 $m_{\mathrm{Z}'} = 350$ GeV (2 TeV) and $|\delta_\mathrm{bs}| < 0.25$, the majority of the parameter space with $0.0057 < |g_\ell| < 0.35$ ($0.25 < |g_\ell| < 0.43$) and $0.0079 < |g_\mathrm{b}| < 0.46$ ($0.34 < |g_\mathrm{b}| < 0.57$) is excluded at 95% confidence level. Finally, constraints are set on a Z' model with parameters consistent with low-energy $\mathrm{b} \to \mathrm{s}\ell\ell$ measurements. In this scenario, most of the allowed parameter space is excluded for a Z' boson with $350 < m_{\mathrm{Z}'} < 500$ GeV, while the constraints are less stringent for higher $m_{\mathrm{Z}'}$ 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.

Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Jets, Bottom Quarks

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Contents

1 Introduction

Over the last few years, a number of experimental results [1–13] have suggested that physics beyond the standard model (SM) could manifest itself in $\mathrm{b} \to \mathrm{s}\ell^-\ell^+$ transitions. Experimental results for this process could be explained by the existence of a new neutral vector boson (Z') coupling to lepton (ℓ) pairs [14, 15] 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 figure 1. While the most recent experimental results [16, 17] on the ratio of the branching fractions for $\mathrm{b} \to \mathrm{s}\mu^-\mu^+$ to $\mathrm{b} \to \mathrm{s}\mathrm{e}^-\mathrm{e}^+$ are in agreement with the SM, there remains some tension in other $\mathrm{b} \to \mathrm{s}\ell^-\ell^+$ observables, such as the overall event rates [2, 3, 13] and angular distributions [1, 4, 5, 7–9], although theoretical predictions for these are less well established than those for the ratio of branching fractions. The current situation was recently discussed in ref. [18].

Inclusive searches for beyond-the-SM (BSM) Z' bosons have already been performed at the CERN LHC [19, 20]. 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 $\mathrm{Z}' \to \mu^-\mu^+$ 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. [21],

$$\mathcal{L}_{\mathrm{BSM}} = \mathrm{Z}'_\eta \left\{ g_\ell \sum_{\ell=\mathrm{e},\mu,\tau} \bar{\ell}\gamma^\eta P_\mathrm{L}\ell + g_\nu \sum_{\nu=\nu_\mathrm{e},\nu_\mu,\nu_\tau} \bar{\nu}\gamma^\eta P_\mathrm{L}\nu + g_\mathrm{b}\left[\bar{\mathrm{b}}\gamma^\eta P_\mathrm{L}\mathrm{b} + \delta_{\mathrm{bs}}\left(\bar{\mathrm{s}}\gamma^\eta P_\mathrm{L}\mathrm{b} + \text{ h.c.}\right)\right]\right\}, \tag{1.1}$$

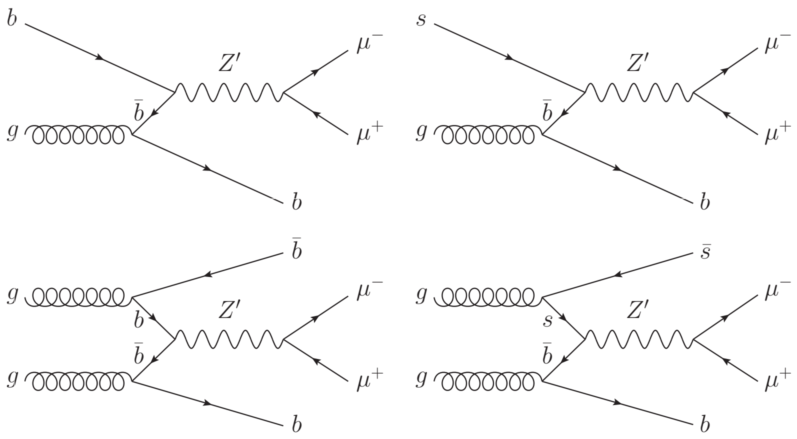

Figure 1. Feynman diagrams of $\mathrm{Z}' \to \mu^-\mu^+$ with a Z' boson produced via $\mathrm{b\overline{b}} \to \mathrm{Z}'$ or $\mathrm{s\overline{b}} \to \mathrm{Z}'$, with at least one b quark in the final state. While a $\mathrm{Z}'\mathrm{bb}$ coupling may be present in any generic model, a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

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 $\mathrm{Z}'\mathrm{bb}$ and $\mathrm{Z}'\mathrm{sb}$ interactions, and the separate δ_bs parameter that solely scales the $\mathrm{Z}'\mathrm{sb}$ interaction. In this analysis, we probe values of δ_bs between 0 and 0.25: the $\mathrm{Z}'\mathrm{sb}$ interaction is fully suppressed at $\delta_\mathrm{bs} = 0$, and δ_bs values above 0.25 may yield scenarios incompatible with the measurement of the mass difference between the mass eigenstates of the neutral $\mathrm{B_s}$ mesons [21].

The B_3–L_2 model is a less generic Z' model introduced in 2017 [22, 23] to accommodate the experimental $\mathrm{b} \to \mathrm{s}\ell^-\ell^+$ 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 muon lepton numbers, respectively. In this model, $g_{\mathrm{Z}'}$ 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 $\arctan(-\delta_\mathrm{bs})$ in the notation of Eq. (1.1). The allowed parameter space for the B_3-L_2 model has been recently reevaluated in ref. [18].

Studies of dilepton invariant mass distributions in final states with b quark jets have previously been performed at the LHC [24–26]. However, these studies either focused on final states with exactly one b quark jet, or used inclusive samples with at least one such jet, or searched for nonresonant signatures in the high dimuon invariant mass tail. Some of the previous studies were based on data sets with only about one fourth of the integrated luminosity used in this analysis. Furthermore, they all suffered from large backgrounds arising from the pair production of t quarks ($\mathrm{t\bar{t}}$), each decaying to one b quark and one W boson, with $\mathrm{W} \to \ell\nu$. 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. We focus on dimuon resonances because the experimental tensions that motivate this search are thought to be consistent with BSM contributions in the muon sector [18].

The analysis can be summarized as follows:

- The search is performed for a narrow $Z' \to \mu^-\mu^+$ 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: $N_\text{b} = 1$ and $N_\text{b} \geq 2$. 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. Events with $N_\text{b} = 0$ are not considered because the background is about 150 times larger in this category due to the contribution from DY events.

- 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 ($\min(m_{\mu\text{b}})$) be >175 GeV, i.e., above the t quark mass. Such a requirement reduces the $t\bar{t}$ background by more than two orders of magnitude while retaining most of the predicted signal with large $m_{Z'}$, thus offering an improved signal discrimination compared to other kinematic requirements used in previous similar studies. 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 unidentified electrons or muons.

- We extract constraints on the total event yield as a function of the fraction of events in each of the $N_\text{b} = 1$ and $N_\text{b} \geq 2$ 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. [27]. 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 [28].

JHEP10(2023)043

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 (up to a pseudorapidity coverage of $|\eta| < 2.5$), a lead tungstate crystal electromagnetic calorimeter ($|\eta| < 3$), and a brass and scintillator hadron calorimeter (HCAL, with $|\eta| < 3$), each composed of a barrel and two endcap sections. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors up to $|\eta| = 5$. Muons are measured in gas-ionization detectors ($|\eta| < 2.4$) 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. [29].

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 μs [30]. 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 [31].

A particle-flow (PF) algorithm [32] 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. [33]). Muons originating from the PV are identified using a set of requirements [34] that are optimized to maximize their selection efficiency at high p_{T}, i.e., roughly above 200 GeV. The muon p_{T} assignment is performed with the 'TuneP' algorithm [35], 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, muons are required to be isolated with respect to nearby charged-particle tracks, i.e., the presence of neutral PF candidates is not considered in assessing the level of isolation. 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 $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.4$. The trigger selection efficiency is measured using the "tag-and-probe" method [36] 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 [37].

Events are further required to contain two oppositely charged muons with $p_{\mathrm{T}} > 53\,\mathrm{GeV}$ and $|\eta| < 2.4$ satisfying the identification and isolation criteria, with an overall muon reconstruction and selection efficiency larger than 90%. The two muons are then used to form a $\mu^-\mu^+$ resonance candidate. Events with additional muons of $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ 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 $p_{\mathrm{T}} > 5\,\mathrm{GeV}$. These vetoes, together with those described below, reduce the SM background arising from tZ+X, tW+X, $\mathrm{t\bar{t}V}$, $\mathrm{t\bar{t}H}$, and diboson production.

In the analysis, electrons are identified using loose requirements [38], 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 $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$ are vetoed, together with events that contain any isolated PF electron candidate originating from the PV with $p_{\mathrm{T}} > 5\,\mathrm{GeV}$.

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 $p_{\mathrm{T}} > 10\,\mathrm{GeV}$.

Jets are reconstructed using the anti-k_{T} algorithm [39, 40] with a distance parameter of 0.4. Jet energies are corrected for instrumental effects and contributions from pileup [41]. We select jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ 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 [42, 43]. 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 $m_{\mu\mathrm{b}}$ among the selected muons and b quark jets, and require $\min(m_{\mu\mathrm{b}}) > 175\,\mathrm{GeV}$, i.e., above the value of the t quark mass. This requirement is used to suppress the $\mathrm{t\bar{t}}$ background, which is reduced by more than two orders of magnitude, while retaining most of the possible signals with large $m_{\mathrm{Z}'}$, as shown in figure 2.

The missing transverse momentum vector ($\vec{p}_{\mathrm{T}}^{\text{miss}}$) is estimated from the negative of the vector p_{T} sum of all PF candidates, where the pileup-per-particle-identification algorithm [41, 44] weights each PF candidate for its probability to originate from the PV in order to reduce the pileup dependence of this observable. The $\vec{p}_{\mathrm{T}}^{\text{miss}}$ 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 $p_{\mathrm{T}}^{\text{miss}}$ is expected except for neutrinos in the case of semileptonic decays of the heavy-flavor quarks, large $p_{\mathrm{T}}^{\text{miss}}$ may nevertheless be observed if the momentum

JHEP10(2023)043

of a muon or b quark jet is mismeasured. Thus, events are vetoed if $p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ 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 possible signals. Other anomalous high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events, due to reconstruction issues, detector malfunctions, or non-collision backgrounds, are rejected by dedicated filters. These filters identify more than 85–90% of these spurious high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events with a mistagging rate less than 0.1% [45]. 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 $39\,\mathrm{fb}^{-1}$, 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 $m_{\mu\mu}$.

3 Event simulation

We use simulated samples of various BSM Z' models to motivate the event selection and 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 $\mathrm{t\bar{t}}$ backgrounds, and the tW+X process, are generated using the POWHEG 2 [46–49] program at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD). Samples for the tZ+X, $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, and $\mathrm{t\bar{t}\gamma^*}$ processes, and for the $\mathrm{t\bar{t}H}$ process are generated at NLO in QCD using MadGraph5_aMC@NLO [50] v2.6.5 and v2.6.1, respectively, with the FxFx [51] 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 $\mathrm{Z'bb}$ and $\mathrm{Z'sb}$ couplings and $\mathrm{Z}' \to \mu\mu$ decays. We generate such interactions using MadGraph5_aMC@NLO v2.9.9 at LO in QCD with $m_{\mathrm{Z}'}$ ranging from 350 to 2500 GeV. For all the generated samples, the total width $\Gamma(\mathrm{Z}')$ 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 $\Gamma(\mathrm{Z}' \to \mathrm{q_i\bar{q}_j})\Gamma(\mathrm{Z}' \to \mu^-\mu^+)/\Gamma(\mathrm{Z}')$ between the target model and the generated sample.

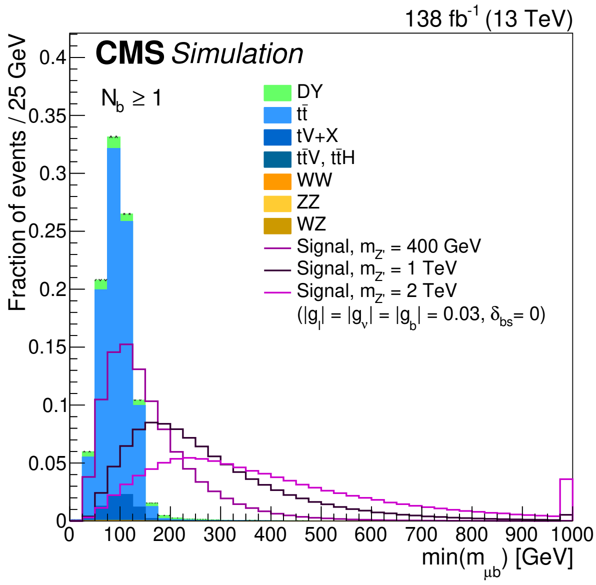

Figure 2. Distribution of $\min(m_{\mu\mathrm{b}})$ as obtained from simulation in events with $N_\mathrm{b} \geq 1$ passing all the other selection requirements. In this search, we require $\min(m_{\mu\mathrm{b}}) > 175\,\mathrm{GeV}$. The stacked histogram displays the expected distribution from the 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. (1.1), for several Z' mass hypotheses. For illustrative purposes, we choose couplings $|g_\ell| = |g_\mathrm{v}| = |g_\mathrm{b}| = 0.03$ and $\delta_\mathrm{bs} = 0$. The efficiency of the requirement on the Z' signal process is about 30%, 70%, and 85% for $m_{\mathrm{Z}'} = 400$, 1000, and 2000 GeV, respectively. The contribution of background processes other than DY and $\mathrm{t\bar{t}}$ 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.

Here, $\Gamma(\mathrm{Z}' \to \mathrm{q_i\bar{q}_j})$ denotes the partial width for $\mathrm{Z}' \to \mathrm{b\bar{b}}$, $\mathrm{Z}' \to \mathrm{s\bar{b}}$ and $\mathrm{Z}' \to \mathrm{b\bar{s}}$, and $\Gamma(\mathrm{Z}' \to \mu^-\mu^+)$ is the partial width for $\mathrm{Z}' \to \mu^-\mu^+$. The reweighting is performed by separating the simulated event sample into contributions from matrix elements with different $\mathrm{q_i\bar{q}_j} \to \mathrm{Z}'$ interactions, as shown in figure 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 [52] using the CP5 [53] tune. The parton distribution functions are taken from NNPDF 3.1 [54]. 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 [55] package.

4 Analysis strategy

The events selected as described in section 2 are categorized according to the multiplicity of b quark jets: $N_\mathrm{b} = 1$ and $N_\mathrm{b} \geq 2$. 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 $m_{\mathrm{Z}'}$ 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 [56, 57] with varying proportions, and a common resolution parameter σ_mass. The choice of the functional form and the dependence of the corresponding parameters on $m_{\mathrm{Z}'}$ are determined from simulation. The fits are performed using a finite grid of simulated signal samples, and the fit parameters are subsequently interpolated across $m_{\mathrm{Z}'}$. As mentioned in section 1, the values of σ_mass range from 6.6 GeV at $m_{\mathrm{Z}'} = 350\,\text{GeV}$ to 30 (106) GeV at $m_{\mathrm{Z}'} = 1\,(2.5)\,\text{TeV}$. Because of the narrow-width approximation intrinsic to the search strategy, the values of σ_mass determined from simulation as a function of $m_{\mathrm{Z}'}$ are independent of the signal coupling values. Fits to the data are performed within an $m_{\mu\mu}$ mass window of $\pm 10\,\sigma_\text{mass}$ around the probed $m_{\mathrm{Z}'}$ value with the restriction $m_{\mu\mu} > 275\,\text{GeV}$. 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. The window slides coherently with the probed value of $m_{\mathrm{Z}'}$, which ranges between 350 and 2500 GeV, in steps reflecting the size of σ_mass. This approach is used, instead of fitting the full $m_{\mu\mu}$ distribution at once, so as not to rely on 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, exponential, or power-law functions. The choice of the functional form for the background model is treated as a discrete nuisance parameter in the fit. An envelope of functional forms is provided to the fit. Then, in the minimization process of the negative logarithm of the likelihood, the discrete profiling method [58] is used to select the best fit background model as a function of the signal strength. 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. [27]. For Bernstein polynomials, the best order in each fit mass window and event category is selected by means of a *Fisher test* [59]. 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 fluctuations due to limited event samples, models that would yield an increasing background as a function of $m_{\mu\mu}$ within the fit mass window are rejected. Only background models that fit the data appropriately are considered: a goodness-of-fit test is performed based on a χ^2 test statistic. This is converted into a p-value through a set of pseudo-experiments, and models with $p < 0.01$ are rejected.

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. First, a varying amount of signal is injected on top of the background generated according to the selected functional form. Then, a background+signal fit is performed allowing the signal

Source	Normalization (%)		Shape
	$N_\mathrm{b} = 1$	$N_\mathrm{b} \geq 2$	
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 $\overline{m}_{\mu\mu}$	—		$\lesssim 0.1\%\, m^2_{\mathrm{Z}'}/\mathrm{TeV}$
μ momentum resolution in $\overline{\sigma}_\mathrm{mass}$	—		$\lesssim 10\%\, \sigma_\mathrm{mass}$

Table 1. Summary of signal uncertainties together with their sizes or size ranges. 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 uncertainties in the signal normalization are expressed as relative uncertainties (%) with respect to the nominal expected yields. The fit parameter $\overline{m}_{\mu\mu}$ defines the position of the maximum of the reconstructed $m_{\mu\mu}$ distribution for a given $m_{\mathrm{Z}'}$ hypothesis. The fit resolution parameter $\overline{\sigma}_\mathrm{mass}$ is distinguished from the values of σ_mass extracted from simulation.

yield to float freely. The bias is quantified as the difference between the measured and injected signal yields relative to the statistical uncertainty in the measured signal yield. 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 [60–62]. 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 $m_{\mathrm{Z}'} = 1\,\mathrm{TeV}$) and resolution ($\lesssim$10% σ_mass). A summary of the sources of signal uncertainty and their sizes is given in table 1. Uncertainties from other sources are found to be negligible.

5 Results

The $m_{\mu\mu}$ distributions in the two event categories are shown in figure 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.

JHEP10(2023)043

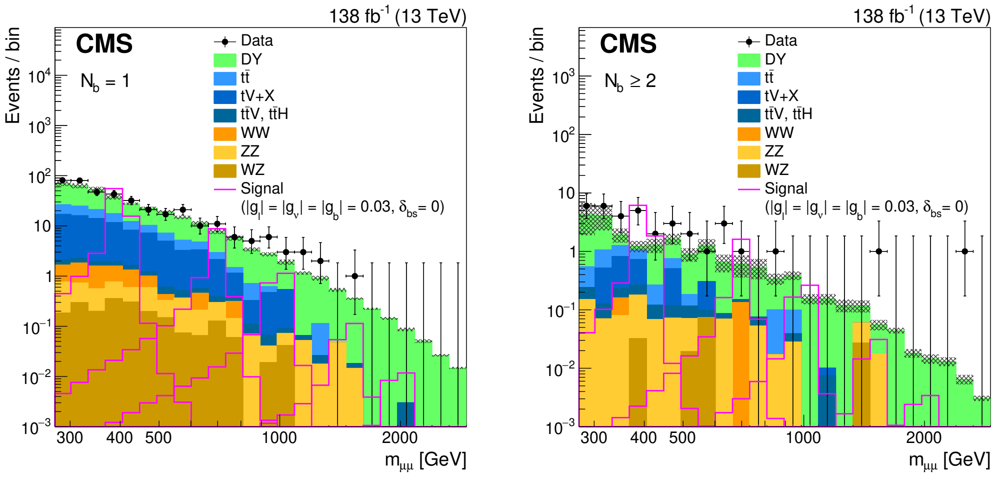

Figure 3. Distributions of $m_{\mu\mu}$ in the $N_{\rm b} = 1$ (left) and $N_{\rm b} \geq 2$ (right) event categories. The stacked histogram displays the expected distribution from the SM background simulation. The overlaid open distributions illustrate the $\rm Z'$ contribution from the LFU model at $|g_\ell| = |g_{\rm v}| = |g_{\rm b}| = 0.03$ and $\delta_{\rm bs} = 0$ for a variety of $\rm Z'$ 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.

The results of a single set of background-only fit to data in the event categories with $N_{\rm b} = 1$ and $N_{\rm b} \geq 2$ are shown in figure 4 for a sample signal mass hypothesis, $m_{\rm Z'} = 500\,\rm GeV$, 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 $N_{\rm b} \geq 1$. The relative fraction of events in the $N_{\rm b} \geq 2$ category, $f_{2\rm b}$, is varied to probe a range of hypotheses of signal production in association with b quarks. These limits are shown in figure 5. They are extracted by performing unbinned fits to the $m_{\mu\mu}$ distribution in data, using windows that slide in steps reflecting the size of $\sigma_{\rm mass}$. 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 $m_{\rm Z'}$ 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 $\rm CL_s$ criterion [63–66].

Figure 6 provides an interpretation for the LFU model described in Eq. (1.1) with the assumed values $|g_{\rm v}| = |g_\ell|$, and either $|\delta_{\rm bs}| = 0$ or 0.25. As $|g_\ell|$ or $|g_{\rm b}|$ increases, the expected value of $\Gamma(\rm Z')$ may approach and exceed the value of $\sigma_{\rm mass}$. Since $\Gamma(\rm Z')$ is assumed to be smaller than $\sigma_{\rm mass}$ in obtaining these results, we restrict our exclusion ranges to the regions where $\Gamma(\rm Z') < \sigma_{\rm mass}/2$. For a $\rm Z'$ boson with a mass of 350 GeV (2 TeV) and $|\delta_{\rm bs}| < 0.25$, the majority of the parameter space with $0.0057 < |g_\ell| < 0.35$ $(0.25 < |g_\ell| < 0.43)$ and $0.0079 < |g_{\rm b}| < 0.46$ $(0.34 < |g_{\rm b}| < 0.57)$ is excluded at 95% CL.

JHEP10(2023)043

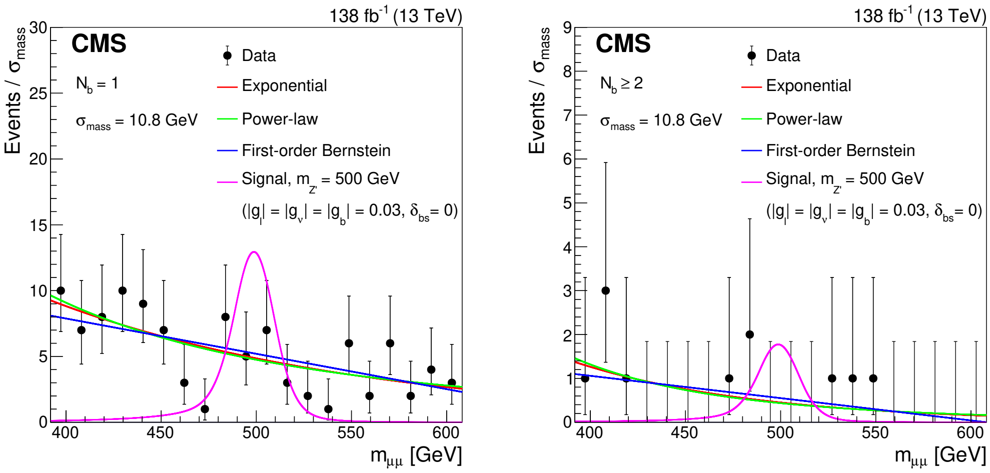

Figure 4. Invariant mass $m_{\mu\mu}$ distributions in the $N_\mathrm{b} = 1$ (left) and $N_\mathrm{b} \geq 2$ (right) categories, shown together with the corresponding selected background functional forms used as input to the *discrete profiling* method [58] when probing the $m_{\mathrm{Z}'} = 500\,\mathrm{GeV}$ hypothesis. The expected signal distribution for the LFU model described in Eq. (1.1), with couplings $|g_\ell| = |g_\mathrm{v}| = |g_\mathrm{b}| = 0.03$ and $\delta_\mathrm{bs} = 0$, is overlaid. The displayed mass range corresponds to the fit window used for this $m_{\mathrm{Z}'}$ hypothesis, which is $\pm 10\,\sigma_\mathrm{mass}$ around the probed $m_{\mathrm{Z}'}$ 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.

The results are also used to set constraints on the B_3–L_2 model from ref. [18]. As in the case of the LFU model, we restrict our exclusion ranges to regions with $\Gamma(\mathrm{Z}') < \sigma_\mathrm{mass}/2$. As shown in figure 7, most of the allowed parameter space is excluded for a Z' boson with $350 < m_{\mathrm{Z}'} < 500\,\mathrm{GeV}$, while the constraints are less stringent for higher $m_{\mathrm{Z}'}$. 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 figure 8 exclusion regions in the $|g_{\mathrm{Z}'}|$–$m_{\mathrm{Z}'}$ plane for a fixed value of $\theta_{23} = 0$.

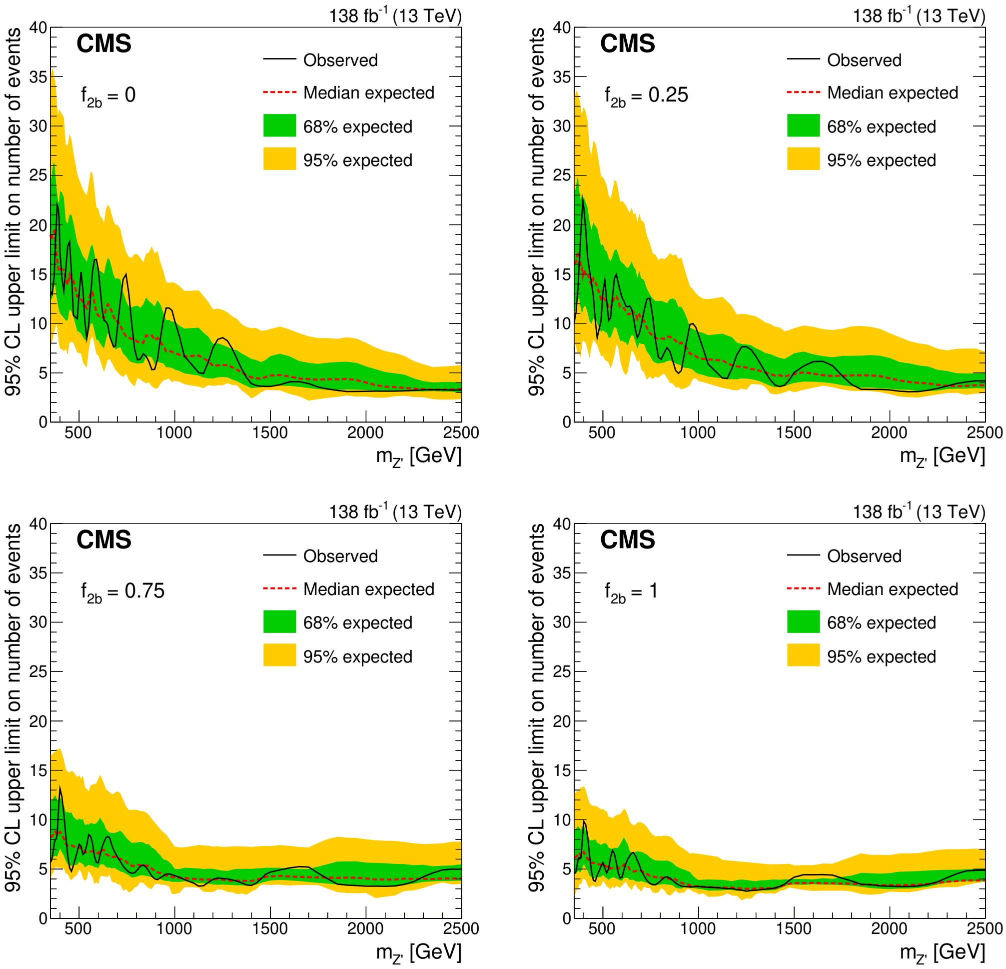

Figure 5. Exclusion limits at 95% CL on the number of selected BSM events with $N_\mathrm{b} \geq 1$ as functions of $m_{\mathrm{Z}'}$ for the different representative values of $f_{2\mathrm{b}} = 0$ (upper left), 0.25 (upper right), 0.75 (lower left), and 1 (lower right). The quantity $f_{2\mathrm{b}}$ 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.

JHEP10(2023)043

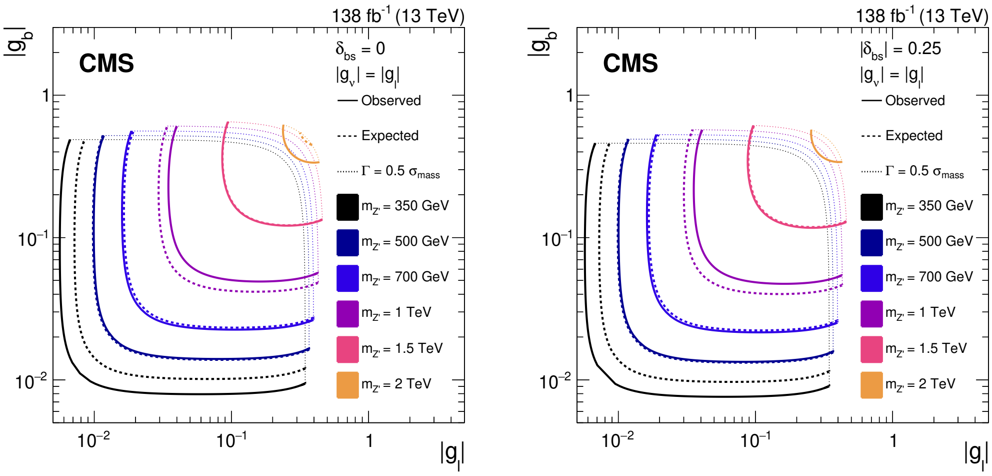

Figure 6. Observed (solid) and median expected (dashed) exclusion limits at 95% CL in the $|g_{\mathrm{b}}|$–$|g_\ell|$ plane for the LFU model. The scenarios considered have $|\delta_{\mathrm{bs}}|$ values of either 0 (left) or 0.25 (right). In all cases, we assume $|g_\nu| = |g_\ell|$. The exclusion limits are given up to coupling values at which the Z′ width is equal to half of the μμ 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. For $|\delta_{\mathrm{bs}}| = 0.25$ and $m_{\mathrm{Z'}} = 2\,\mathrm{TeV}$, no region of the parameter space is expected to be excluded.

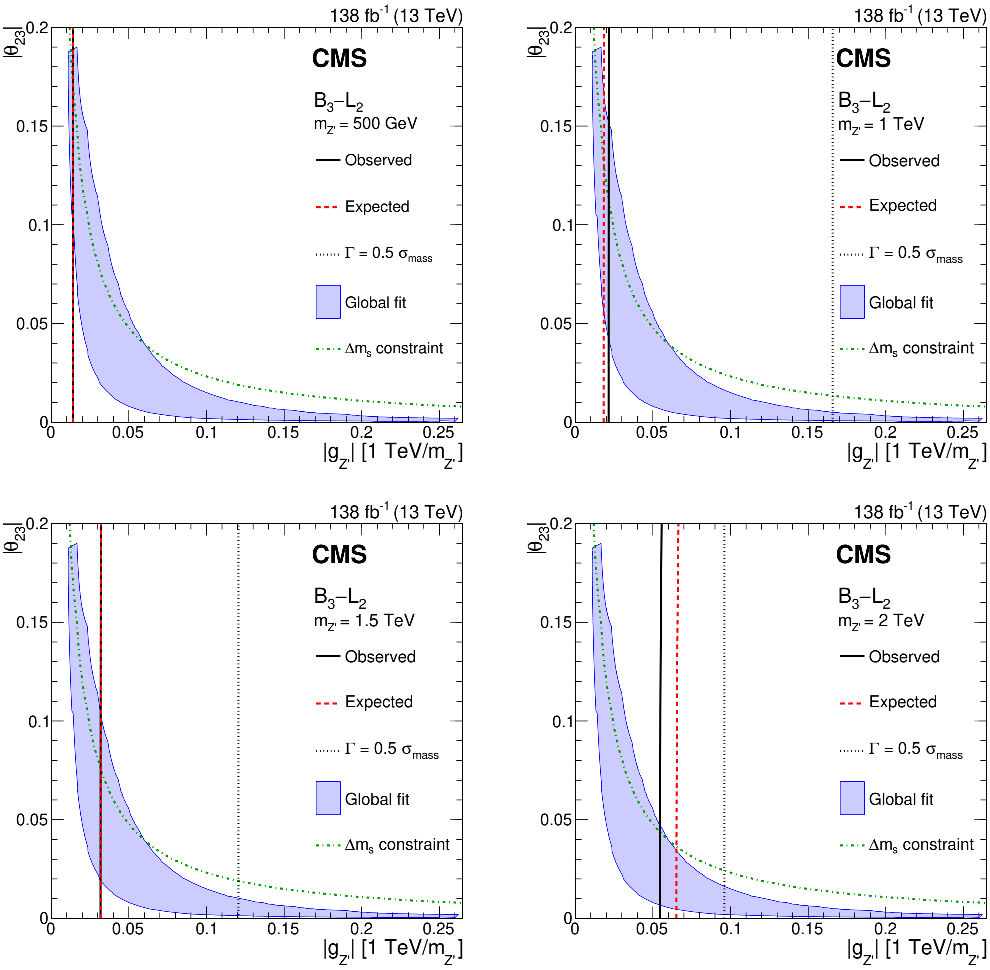

Figure 7. Exclusion limits at 95% CL in the $|\theta_{23}|$–$|g_{\mathrm{Z}'}|$ plane for the $B_3 - L_2$ model [18], for representative values of $m_{\mathrm{Z}'} = 500\,\mathrm{GeV}$ (upper left), $m_{\mathrm{Z}'} = 1\,\mathrm{TeV}$ (upper right), $m_{\mathrm{Z}'} = 1.5\,\mathrm{TeV}$ (lower left), and $m_{\mathrm{Z}'} = 2\,\mathrm{TeV}$ (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 $m_{\mathrm{Z}'} = 500\,\mathrm{GeV}$ lies beyond the displayed $|g_{\mathrm{Z}'}|$ range and is, therefore, not shown. The shaded blue area represents the region preferred from the global fit in ref. [18] 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 $\mathrm{B_s}$ mesons [21].

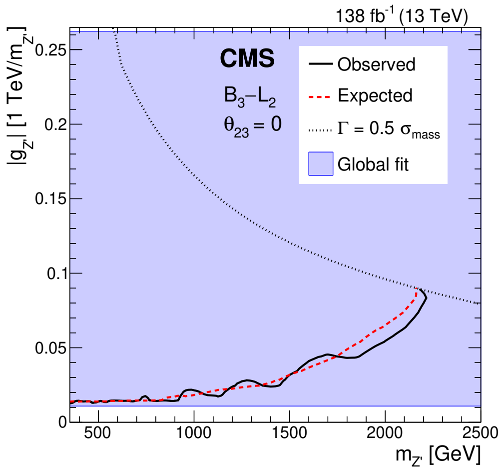

Figure 8. Exclusion limits at 95% CL in the $|g_{Z'}|$–$m_{Z'}$ plane for the B_3-L_2 model [18] for a fixed value of $\theta_{23} = 0$. The solid black (dashed red) curve represents the observed (median expected) exclusion. The dotted curve denotes the coupling values at which the Z′ width equals one half of the μμ 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. [18] 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.

The 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, and these limits are model independent to the extent that the signal arises from the direct production and subsequent decay of a narrow dimuon resonance. 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 $m_{Z'} = 350$ 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 $b \to s\ell^-\ell^+$ transitions beyond the standard model. In this scenario, most of the allowed parameter space is excluded for a Z′ boson with $350 < m_{Z'} < 500$ GeV, while the constraints are less stringent for higher $m_{Z'}$ hypotheses.

JHEP10(2023)043

This is the first dedicated search at the LHC for a high-mass, narrow 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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JHEP10(2023)043

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, I. Makarenko, D. Müller, A.R. Sahasransu, S. Tavernier, M. Tytgat[4], S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, A. Khalilzadeh, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, Y. Hong, J. Knolle, L. Lambrecht, G. Mestdach, C. Rendón, A. Samalan, K. Skovpen, N. Van Den Bossche, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Bruno, C. Caputo, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, K. Mondal, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, S. Thakur

Beihang University, Beijing, China
T. Cheng, Q. Guo, T. Javaid, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
G. Bauer[8,9], Z. Hu, K. Yi[8,10]

Institute of High Energy Physics, Beijing, China
G.M. Chen[11], H.S. Chen[11], M. Chen[11], F. Iemmi, C.H. Jiang, A. Kapoor[12], H. Liao, Z.-A. Liu[13], F. Monti, M.A. Shahzad[11], R. Sharma[14], J.N. Song[13], J. Tao, C. Wang[11], J. Wang, Z. Wang[11], H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Levin, C. Li, Q. Li, Y. Mao, S.J. Qian, X. Sun, D. Wang, H. Yang, C. Zhou

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
N. Lu

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China
X. Gao[15], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, A. Starodumov[16], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[17,18], S. Elgammal[18]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee[19], K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

JHEP10(2023)043

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, K.T.S. Kallonen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva[†]

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, A. De Wit, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, C. Grimault, R. Haeberle, A.-C. Le Bihan, M.A. Sessini, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[23], Z. Tsamalaidze[16]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, A. Novak,

JHEP10(2023)043

F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, S.C. Schuler, A. Sharma, A. Stein, F. Torres Da Silva De Araujo[24], L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[25], T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[26], K. Borras[27], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[26], A. Geiser, A. Giraldi, G. Greau, V. Guglielmi, M. Guthoff, A. Hinzmann, A. Jafari[28], L. Jeppe, N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[29], W. Lohmann[30], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, E. Ranken, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Scham[31,27], S. Schnake[27], P. Schütze, C. Schwanenberger[26], D. Selivanova, M. Shchedrolosiev, R.E. Sosa Ricardo, L.P. Sreelatha Pramod, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[27], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, M. Eich, K. El Morabit, Y. Fischer, A. Fröhlich, C. Garbers, E. Garutti, A. Grohsjean, M. Hajheidari, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[32], R. Hofsaess, M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, S. Wunsch, X. Zuo

JHEP10(2023)043

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Papadopoulos[32], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, A. Panagiotou, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[33], Á. Kadlecsik, P. Major, K. Mandal, G. Pásztor, A.J. Rádl[34], G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[35], C. Hajdu, D. Horvath[36,37], F. Sikler, V. Veszpremi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[38], G. Zilizi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Karancsi[35], J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[34], F. Nemes[34], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[39], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Acharya[40], S. Baradia, S. Barman[41], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[40], P. Palit, G. Saha, B. Sahu[40], S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, P. Jana, P. Kalbhor, J.R. Komaragiri[42], D. Kumar[42], L. Panwar[42], R. Pradhan, P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[43], A.K. Das, C. Kar, D. Maity[44], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[44], K. Naskar[44], A. Nayak[44], P. Sadangi, P. Saha, S.K. Swain, S. Varghese[44], D. Vats[44]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[45], E. Khazaie[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,48], A. Colaleo[a,b], D. Creanza[a,c], B. D‘ Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,c], W. Elmetenawee[a,b,48], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], G. Ramirez-Sanchez[a,c], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,50], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,50], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[51], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a,b], F. Brivio[a], F. Cetorelli[a], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Università G. Marconi[d], Roma, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,52], P. Paolucci[a,32], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,53], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], L. Layer[a,54], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Sgaravatto[a], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,55], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], P. Asenov[a,56], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,56], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

JHEP10(2023)043

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy

P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a,b], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy

P. Barria[a], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], P. Meridiani[a], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], C. Tarricone[a,b], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy

S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a,b], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, J. Hong, C. Huh, B. Kim, D.H. Kim, J. Kim, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, Y.C. Yang

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

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, D. Kim, T.J. Kim, J.A. Merlin, J. Park

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh

JHEP10(2023)043

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, W. Jun, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[57]

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, I. Yusuff[58], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[59], R. Lopez-Fernandez, C.A. Mondragon Herrera, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, M. Ramírez García

JHEP10(2023)043

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, Cristina F. Bedoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo,

JHEP10(2023)043

I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[60], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, F. Fallavollita[61], L. Forthomme, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, B. Huber, V. Innocente, T. James, P. Janot, J. Kieseler, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Moortgat, M. Mulders, S. Orfanelli, F. Pantaleo, M. Peruzzi, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, H. Qu, D. Rabady, G. Reales Gutiérrez, M. Rovere, H. Sakulin, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[62], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[63], K.A. Wozniak[64], P. Zehetner, P. Zejdl, W.D. Zeuner

JHEP10(2023)043

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[65], L. Caminada[65], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[65], L. Noehte[65], T. Rohe

ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[63], M. Backhaus, A. Calandri, C. Cazzaniga, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[63], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, R. Seidita, J. Steggemann[63], D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[66], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[67], C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[42], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, Z.g. Chen, W.-S. Hou, T.h. Hsu, Y.w. Kao, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, X.f. Su, J. Thomas-Wilsker, H.y. Wu, E. Yazgan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[68], E. Eskut, Y. Guler[69], E. Gurpinar Guler[69], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[70], A. Polatoz, B. Tali[71], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[72]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[73], O. Kaya[74], S. Tekten[75]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[68,76], Y. Komurcu, S. Sen[77]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[71], V. Epshteyn, B. Hacisahinoglu, I. Hos[78], B. Isildak[79], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, D. Sunar Cerci[71], C. Zorbilmez

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[80], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[81], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[82], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[83], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, J. Nash[84], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[32], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, U.S.A.
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, J. Hiltbrand, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, M. Toms[85], J. Wilson

JHEP10(2023)043

Catholic University of America, Washington, DC, U.S.A.
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, U.S.A.
R. Chudasama, S.I. Cooper, S.V. Gleyzer, C.U. Perez, P. Rumerio[86], E. Usai, C. West, R. Yi

Boston University, Boston, Massachusetts, U.S.A.
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. Jeon, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, U.S.A.
G. Benelli, X. Coubez[27], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[87], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, S. Sagir[88], F. Simpson, M. Stamenkovic, W.Y. Wong, X. Yan, W. Zhang

University of California, Davis, Davis, California, U.S.A.
S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, W. Wei, Y. Yao, F. Zhang

University of California, Los Angeles, California, U.S.A.
M. Bachtis, R. Cousins, A. Datta, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, U.S.A.
R. Clare, M. Gordon, G. Hanson, W. Si, S. Wimpenny[†]

University of California, San Diego, La Jolla, California, U.S.A.
J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara — Department of Physics, Santa Barbara, California, U.S.A.
A. Barzdukas, L. Brennan, C. Campagnari, G. Collura, A. Dorsett, K. Downham, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, U.S.A.
A. Bornheim, O. Cerri, A. Latorre, J.M. Lawhorn, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, U.S.A.
J. Alison, S. An, M.B. Andrews, P. Bryant, V. Dutta, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, U.S.A.
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, N. Manganelli, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, U.S.A.
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[89], F. Ravera, A. Reinsvold Hall[90], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, U.S.A.
C. Aruta, P. Avery, D. Bourilkov, L. Cadamuro, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang

Florida State University, Tallahassee, Florida, U.S.A.
T. Adams, A. Al Kadhim, A. Askew, N. Bower, R. Habibullah, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, U.S.A.
B. Alsufyani, M.M. Baarmand, S. Butalla, T. Elkafrawy[55], M. Hohlmann, R. Kumar Verma, M. Rahmani

University of Illinois at Chicago (UIC), Chicago, Illinois, U.S.A.
M.R. Adams, C. Bennett, R. Cavanaugh, S. Dittmer, R. Escobar Franco, O. Evdokimov, C.E. Gerber, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit,

C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, U.S.A.
M. Alhusseini, D. Blend, K. Dilsiz[91], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[92], J. Nachtman, O. Neogi, H. Ogul[93], Y. Onel, A. Penzo, C. Snyder, E. Tiras[94]

Johns Hopkins University, Baltimore, Maryland, U.S.A.
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, U.S.A.
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[95], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, U.S.A.
B. Allmond, A. Ivanov, K. Kaadze, A. Kalogeropoulos, D. Kim, Y. Maravin, K. Nam, J. Natoli, D. Roy, G. Sorrentino

Lawrence Livermore National Laboratory, Livermore, California, U.S.A.
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, U.S.A.
E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.
J. Bendavid, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, S. Rothman, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, U.S.A.
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, S. Pandey, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, U.S.A.
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, F. Golf, G. Haza, J. Hossain, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, U.S.A.
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams

Northeastern University, Boston, Massachusetts, U.S.A.
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, B. Wang, D. Wood

Northwestern University, Evanston, Illinois, U.S.A.
S. Bhattacharya, J. Bueghly, Z. Chen, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, U.S.A.
R. Band, R. Bucci, S. Castells, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[16], H. Nelson, M. Osherson, R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, U.S.A.
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, U.S.A.
F.M. Addesa, H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

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

Purdue University, West Lafayette, Indiana, U.S.A.
A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, S. Das, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, W. Xie

Purdue University Northwest, Hammond, Indiana, U.S.A.
J. Dolen, N. Parashar, A. Pathak

JHEP10(2023)043

Rice University, Houston, Texas, U.S.A.
D. Acosta, A. Baty, T. Carnahan, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, U.S.A.
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, P. Parygin[85], E. Popova[85], R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, U.S.A.
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, U.S.A.
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[30], I. Laflotte, A. Lath, R. Montalvo, K. Nash, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, U.S.A.
H. Acharya, D. Ally, A.G. Delannoy, S. Fiorendi, T. Holmes, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, U.S.A.
D. Aebi, M. Ahmad, O. Bouhali[96], M. Dalchenko, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[97], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, U.S.A.
N. Akchurin, J. Damgov, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, U.S.A.
E. Appelt, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, U.S.A.
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara

Wayne State University, Detroit, Michigan, U.S.A.
P.E. Karchin

University of Wisconsin — Madison, Madison, Wisconsin, U.S.A.
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless,

J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[98], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov[98], M. Danilov[98], A. Dermenev, T. Dimova[98], D. Druzhkin[99], M. Dubinin[89], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, Y. Ivanov, V. Kachanov, L. Kardapoltsev[98], V. Karjavine, A. Karneyeu, V. Kim[98], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[100], D. Konstantinov, V. Korenkov, A. Kozyrev[98], N. Krasnikov, A. Lanev, P. Levchenko[101], N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[98], V. Murzin, A. Nikitenko[102,100], S. Obraztsov, V. Oreshkin, V. Palichik, V. Perelygin, M. Perfilov, S. Petrushanko, S. Polikarpov[98], V. Popov, O. Radchenko[98], M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[98], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, A. Vorobyev[†], N. Voytishin, B.S. Yuldashev[103], A. Zarubin, I. Zhizhin, A. Zhokin

[†] *Deceased*
[1] *Also at Yerevan State University, Yerevan, Armenia*
[2] *Also at TU Wien, Vienna, Austria*
[3] *Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*
[4] *Also at Ghent University, Ghent, Belgium*
[5] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[6] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[7] *Also at UFMS, Nova Andradina, Brazil*
[8] *Also at Nanjing Normal University, Nanjing, China*
[9] *Now at Henan Normal University, Xinxiang, China*
[10] *Now at The University of Iowa, Iowa City, Iowa, U.S.A.*
[11] *Also at University of Chinese Academy of Sciences, Beijing, China*
[12] *Also at China Center of Advanced Science and Technology, Beijing, China*
[13] *Also at University of Chinese Academy of Sciences, Beijing, China*
[14] *Also at China Spallation Neutron Source, Guangdong, China*
[15] *Also at Université Libre de Bruxelles, Bruxelles, Belgium*
[16] *Also at an institute or an international laboratory covered by a cooperation agreement with CERN*
[17] *Also at Suez University, Suez, Egypt*
[18] *Now at British University in Egypt, Cairo, Egypt*
[19] *Also at Birla Institute of Technology, Mesra, Mesra, India*
[20] *Also at Purdue University, West Lafayette, Indiana, U.S.A.*
[21] *Also at Université de Haute Alsace, Mulhouse, France*
[22] *Also at Department of Physics, Tsinghua University, Beijing, China*
[23] *Also at Tbilisi State University, Tbilisi, Georgia*
[24] *Also at The University of the State of Amazonas, Manaus, Brazil*

JHEP10(2023)043

[25] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[26] *Also at University of Hamburg, Hamburg, Germany*
[27] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[28] *Also at Isfahan University of Technology, Isfahan, Iran*
[29] *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*
[30] *Also at Brandenburg University of Technology, Cottbus, Germany*
[31] *Also at Forschungszentrum Jülich, Juelich, Germany*
[32] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[33] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[34] *Also at Wigner Research Centre for Physics, Budapest, Hungary*
[35] *Also at Institute of Physics, University of Debrecen, Debrecen, Hungary*
[36] *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[37] *Now at Universitatea Babes-Bolyai — Facultatea de Fizica, Cluj-Napoca, Romania*
[38] *Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
[39] *Also at Punjab Agricultural University, Ludhiana, India*
[40] *Also at University of Hyderabad, Hyderabad, India*
[41] *Also at University of Visva-Bharati, Santiniketan, India*
[42] *Also at Indian Institute of Science (IISc), Bangalore, India*
[43] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[44] *Also at Institute of Physics, Bhubaneswar, India*
[45] *Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran*
[46] *Also at Sharif University of Technology, Tehran, Iran*
[47] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
[48] *Also at Helwan University, Cairo, Egypt*
[49] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
[50] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[51] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*
[52] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[53] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
[54] *Also at Università di Napoli 'Federico II', Napoli, Italy*
[55] *Also at Ain Shams University, Cairo, Egypt*
[56] *Also at Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
[57] *Also at Riga Technical University, Riga, Latvia*
[58] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[59] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[60] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[61] *Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
[62] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[63] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[64] *Also at University of Vienna Faculty of Computer Science, Vienna, Austria*
[65] *Also at Universität Zürich, Zurich, Switzerland*
[66] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[67] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[68] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[69] *Also at Konya Technical University, Konya, Turkey*
[70] *Also at Izmir Bakircay University, Izmir, Turkey*
[71] *Also at Adiyaman University, Adiyaman, Turkey*
[72] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[73] *Also at Marmara University, Istanbul, Turkey*

JHEP10(2023)043

[74] *Also at Milli Savunma University, Istanbul, Turkey*
[75] *Also at Kafkas University, Kars, Turkey*
[76] *Now at stanbul Okan University, Istanbul, Turkey*
[77] *Also at Hacettepe University, Ankara, Turkey*
[78] *Also at Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[79] *Also at Yildiz Technical University, Istanbul, Turkey*
[80] *Also at Vrije Universiteit Brussel, Brussel, Belgium*
[81] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[82] *Also at University of Bristol, Bristol, United Kingdom*
[83] *Also at IPPP Durham University, Durham, United Kingdom*
[84] *Also at Monash University, Faculty of Science, Clayton, Australia*
[85] *Now at an institute or an international laboratory covered by a cooperation agreement with CERN*
[86] *Also at Università di Torino, Torino, Italy*
[87] *Also at Bethel University, St. Paul, Minnesota, U.S.A.*
[88] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[89] *Also at California Institute of Technology, Pasadena, California, U.S.A.*
[90] *Also at United States Naval Academy, Annapolis, Maryland, U.S.A.*
[91] *Also at Bingol University, Bingol, Turkey*
[92] *Also at Georgian Technical University, Tbilisi, Georgia*
[93] *Also at Sinop University, Sinop, Turkey*
[94] *Also at Erciyes University, Kayseri, Turkey*
[95] *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
[96] *Also at Texas A&M University at Qatar, Doha, Qatar*
[97] *Also at Kyungpook National University, Daegu, Korea*
[98] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[99] *Also at Universiteit Antwerpen, Antwerpen, Belgium*
[100] *Also at Yerevan Physics Institute, Yerevan, Armenia*
[101] *Also at Northeastern University, Boston, Massachusetts, U.S.A.*
[102] *Also at Imperial College, London, United Kingdom*
[103] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

JHEP10(2023)043