



Search for resonances in events with photon and jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for resonances in events with the γ +jet final state has been performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC. The total data analyzed correspond to an integrated luminosity of 138 fb^{-1} . Models of excited quarks and quantum black holes are considered. The invariant mass spectrum of the γ +jet system is examined for the presence of resonances over the standard model continuum background. The data exhibit no statistically significant deviations from the expected standard model background. Exclusion limits at 95% confidence level on the resonance mass and other parameters are set. Excited light-flavor quarks (excited bottom quarks) are excluded up to a mass of 6.0 (3.8) TeV. Quantum black hole production is excluded for masses up to 7.5 (5.2) TeV in the Arkani-Hamed–Dimopoulos–Dvali (Randall–Sundrum) model. These lower mass bounds are the most stringent to date among those obtained in the γ +jet final state.

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1 Introduction

Various theoretical proposals of beyond the standard model (BSM) physics predict the production of new resonances at hadron collider experiments. In the last decade, experiments at the CERN LHC have searched extensively for signatures of such phenomena to help understand some of the unresolved questions concerning features of the standard model (SM) of particle physics, for example the existence of only three fermion families and the hierarchy problem [1]. A variety of models have been proposed to address these questions, some of which predict new resonances producing a γ +jet final state. Models of compositeness [2–4] address the existence of three fermion families, and other models address the origin of the hierarchy problem by predicting the existence of extra dimensions [5, 6].

The composite models postulate that the quarks and leptons are composed of more fundamental particles, known as “preons” [7]. These preons experience a new force that becomes very strong at the compositeness scale (Λ), when forming the quark and lepton composite states. This paper considers the excited states of composite quarks produced via gauge-mediated interactions with the dominant process $qg \rightarrow q^*$, and decaying to SM particles. It is assumed that the compositeness scale Λ is equal to the mass of the excited quark M_{q^*} .

The interactions between excited quarks, SM quarks, and the gauge bosons can be described by an effective Lagrangian [8]

$$\mathcal{L}_{\text{eff}} = \frac{1}{2\Lambda} \bar{q}^* \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} F_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q + \text{h.c.}, \quad (1)$$

where \bar{q}^* is the right-handed excited quark field; $F_{\mu\nu}^a$, $W_{\mu\nu}$, and $B_{\mu\nu}$ are the field strength tensors associated with the SU(3), SU(2), and U(1) gauge fields, respectively; λ_a , τ , and Y are the corresponding Lie algebra generators; g_s , g , and g' are the gauge couplings; σ is the Pauli spin matrix; and f_s , f , and f' are coupling strengths between the excited quark and SM quarks. An assumption is also made that f_s , f , and f' have identical values and henceforth these coupling strengths will be collectively referred to as f .

In this paper we consider excited light-flavor quarks and bottom quarks (q^* and b^* , respectively) radiating a photon and thus resulting in the γ +jet final state. The corresponding Feynman diagram for the production and decay of the q^* , b^* signals through gauge mediation is shown in Fig. 1 (left). Additionally, an interpretation for b^* production from contact interactions (CI) [4] is also considered for the search of excited bottom quarks. Similar searches for excited quarks have been performed previously by the CMS [9–13] and ATLAS [14–17] Collaborations at the LHC and at other high-energy particle colliders [18–20] and have reported no evidence of a signal. Lately, the ATLAS and CMS experiments have set exclusion limits of 5.3 [15] and 5.5 TeV [13] on the mass of q^* in the γ +jet channel with data corresponding to 36 and 37 fb⁻¹ of integrated luminosity, respectively, collected at $\sqrt{s} = 13$ TeV.

In addition, we also consider the models of Arkani-Hamed, Dimopoulos, and Dvali (ADD) [5], and Randall–Sundrum (RS1) [6], which have extra spatial dimensions. The basic assumption of these models is that the fundamental gravitational scale (M_D) can be as low as 1 TeV, while the size of the extra dimensions can be as large as 1 millimeter, assuming the extra dimensions are only accessible to gravity and not to the SM fields. The ADD model assumes $(4 + n)$ dimensions with $n = 6$ flat compact extra dimensions, and RS1 considers $n = 1$ extra dimension with a warped metric. As a consequence, the models predict the production of microscopic black holes [21], which can be either semi-classical black holes or quantum black holes (QBHs) [22, 23]. In this model, the threshold mass M_{th} for production of a QBH at the LHC is assumed to be M_D , and the maximum mass limit is set to the smaller of either $3M_D$

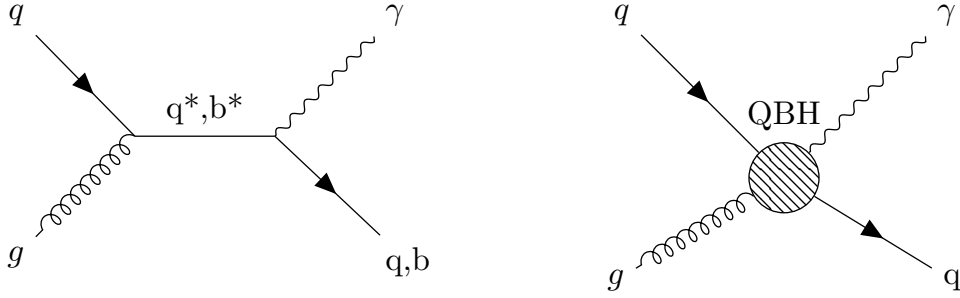


Figure 1: Illustrative Feynman diagrams for $qg \rightarrow \gamma + \text{jet}$ resonance signal models of q^* , b^* (left), and QBH production (right).

or $\sqrt{s} = 13$ TeV. A QBH with a mass in this range will decay preferentially to a few-particle state, rather than undergo thermal decay. The QBH production occurs with a continuous QBH mass spectrum, falling rapidly from M_{th} toward the maximum mass limit; however, because of radiation and experimental effects on the low-mass side of the mass spectrum, the signal shape resembles a resonance-like structure, as shown in Fig. 2. Previous searches for QBHs performed at $\sqrt{s} = 13$ TeV by the CMS and ATLAS experiments are reported in Refs. [10, 12, 15, 24–27]. This paper also reports the first search by the CMS experiment for QBHs in the $\gamma + \text{jet}$ final state (as shown in the Feynman diagram of Fig. 1 (right)). The ATLAS Collaboration has excluded QBH production in the $\gamma + \text{jet}$ channel with mass up to 7.1 (4.4) TeV in the ADD (RS1) model using 13 TeV data corresponding to 37 fb^{-1} of integrated luminosity [15].

The main background to this analysis are $\gamma + \text{jet}$ production, quantum chromodynamics (QCD) multijet production, and $W/Z + \gamma$ processes of the SM. The $\gamma + \text{jet}$ background is an irreducible background, and is the largest contributing. Despite its large cross section, the QCD multijet background is only the second largest, contributing when one of the jets fragments decays into an high energy π^0 decaying into two overlapping photons that are reconstructed as a single photon in the detector. Electroweak processes contribute to the background via the production of $W/Z + \gamma$, with the heavy boson decaying to a pair of jets, in the scenario where just one jet passes the selections or where one jet is reconstructed and the second jet is either merged with the first or escapes detection.

This search for excited quarks and QBHs is performed using proton-proton (pp) collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1} . The analysis strategy consists of searching for a resonance-like excess in the $\gamma + \text{jet}$ invariant mass, above the expected SM background.

This paper is organized as follows: Section 2 provides a brief description of the CMS detector. The triggers used for data selection are discussed in Section 3. In Section 4, the data sets and simulation samples used in this analysis are described. The event reconstruction and selection criteria are detailed in Section 5. The background estimation and systematic uncertainties are discussed in Sections 6 and 7, respectively. The results and their interpretation are presented in Section 8, followed by a summary given in Section 9. Tabulated results are provided in the HEPData record for this analysis [28].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. The muon detection system consists of a gas-ionization detector installed outside the solenoid and embedded in the steel flux-return yoke.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The energy resolution of the remaining barrel photons is about 1.3% up to $|\eta| = 1$, changing to about 2.5% at $|\eta| = 1.4$. In the endcaps, the energy resolution is about 2.5% for unconverted or late-converting photons, and between 3 and 4% for the other ones [29]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [30]. 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. [31].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μ s [32]. 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 [33].

3 Trigger selection

Events used in this analysis must pass a HLT single-photon trigger, which requires the photon transverse momentum p_T greater than 175 GeV in 2016, and greater than 200 GeV in 2017–2018. The higher p_T threshold in 2017–2018 is set to optimize available bandwidth and storage of events for offline analysis. The trigger also requires that the fraction of energy associated with the photon deposited in the HCAL is less than 15% of that deposited in the ECAL ($H/E < 0.15$). The efficiency of single-photon triggers is calculated using the single-photon data set with a low- p_T requirement and is found to be 99%. To calculate the possible bias on single-photon trigger due to any systematic detector effects, the efficiency is also calculated using jet- and muon-triggered independent data sets. The trigger efficiency with the independent data sets is found to be about 97–98% and the trigger inefficiency is taken as an estimate of systematic uncertainty.

4 Simulated data samples

The signal and background samples are obtained from event generators using Monte Carlo (MC) simulations. The signal samples for q^* and b^* are generated at leading order (LO) with the PYTHIA 8.205 (8.230) event generator [34] for 2016 (2017/2018) using coupling values $f = 1.0, 0.5, \text{ and } 0.1$ and different resonance masses. The generated events are processed through the full CMS detector simulation based on GEANT4 [35]. Additional pp interactions in the same and nearby proton bunch crossings, referred to as pileup, are also simulated and a weight is applied to simulated events to reproduce the same pileup distribution as measured in data. The simulation uses the CUETP8M1 and CP5 underlying event tunes [36, 37] for 2016 and 2017–

2018 data sets, respectively, and renormalization (μ_R) and factorization scale (μ_F) corresponding to $\mu_R = \mu_F = \mu = p_T$ for the hard-scattered partons. The samples with the CUETP8M1 tune use the NNPDF3.0 LO [38] parton distribution functions (PDFs), while simulated samples generated with the CP5 tune use the NNPDF3.1 next-to-next-LO [39] PDFs. For b^* signals, only events with M_{b^*} within $\pm 20\%$ of the input M_{b^*} are considered in order to avoid sizable off-shell nonresonant contributions, which are otherwise present for high- M_{b^*} scenarios with coupling parameters $f = 0.5$ and 1.0 but do not contribute to the search sensitivity. The signals for intermediate mass values are extracted with an interpolation technique at intervals of 0.1 TeV.

The QBH signal events in the ADD ($n = 6$) and the RS1 ($n = 1$) models are generated with the QBH generator [40] version v3.0 using CTEQ6L [41] PDFs. The signals are generated for masses ranging from 3.0 to 8.5 TeV for the ADD model and from 2.0 to 7.0 TeV for the RS1 model at intervals of 0.5 TeV. The γ +jet mass distribution for QBH is similar between the RS1 and ADD models; therefore, the RS1 simulated sample is used for the ADD model for $M_{\text{th}} < 3$ TeV. The resonance shapes for q^* , b^* , and QBH for the ADD ($n = 6$) and RS1 ($n = 1$) models for a mass of 4 TeV are shown in Fig. 2.

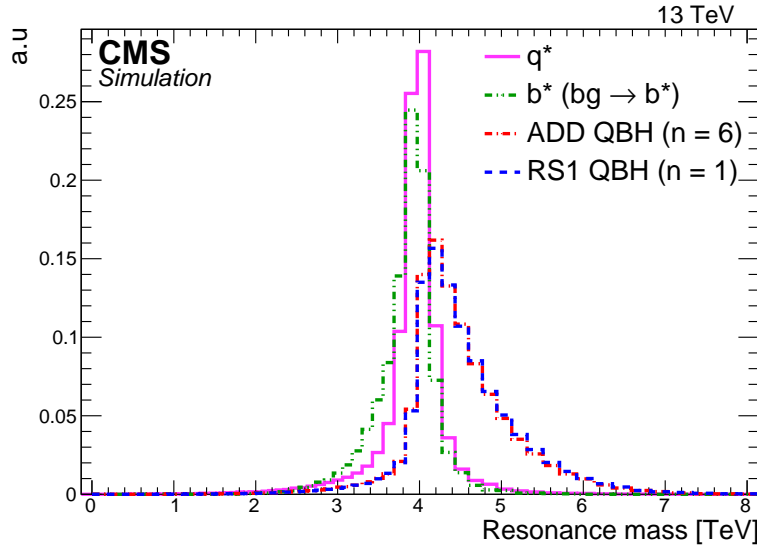


Figure 2: Distributions of reconstructed γ +jet invariant mass for the q^* and b^* signal models with resonance mass of 4 TeV, and for QBH from the ADD and RS1 models with $M_{\text{th}} = 4$ TeV.

Figure 3 shows the product of the cross section (σ) and branching fraction \mathcal{B} for the production at $\sqrt{s} = 13$ TeV of the photon and jet final state as a function of the resonance mass, for excited quark models, or the threshold mass, for QBH models.

The γ +jet, Drell–Yan, and W +jet background are simulated using the MADGRAPH5_aMC@NLO version 2.2.2 (2.4.2) generators for 2016 (2017–2018) [42] at LO in QCD with the MLM matching scheme [43] between jets produced via matrix element calculations and from parton showers. The QCD multijet background simulation is obtained at LO with the PYTHIA generator using version 8.205 (8.230) for 2016 (2017–2018). Hadronization and parton showering of all simulated samples are performed using the PYTHIA program versions 8.205 and 8.230 with the CUETP8M1 and CP5 tunes, respectively.

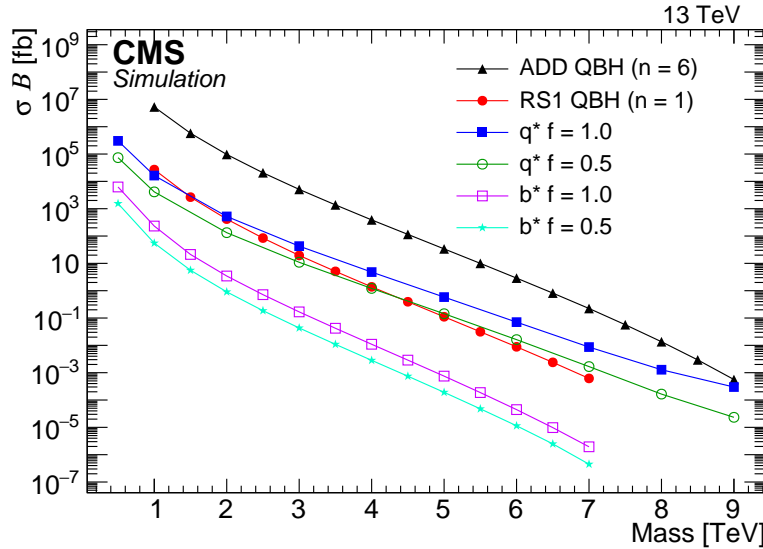


Figure 3: The product of the cross section and branching fraction, $\sigma\mathcal{B}$, as a function of the resonance mass of q^* or b^* signals (M_{q^*} or M_{b^*}) or the threshold mass of QBH signal models (M_{th}).

5 Event reconstruction and selection

The particle-flow (PF) algorithm [44] reconstructs and identifies photons, electrons, muons, charged and neutron hadrons (called PF candidates), with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL detector. The clusters of energy deposited in the ECAL are combined together within a defined geometric area to form a supercluster around the seed cluster [45]. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with their origin from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker with the matched ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are reconstructed from PF candidates using the infrared- and collinear-safe anti- k_T algorithm [46, 47] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. In situ measurements of the momentum balance in dijet, γ +jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [30].

The primary 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. [48].

Candidate events are required to have at least one photon with transverse momentum $p_T^\gamma > 240$ GeV in the barrel region ($|\eta^\gamma| < 1.44$) of the detector. At the p_T^γ threshold of 240 GeV, the trigger is more than 95% efficient. The photon with the highest p_T is selected as the candidate photon in the event. To reject jets misreconstructed as photons, candidate photons are required to satisfy identification and isolation requirements [45] having a selection efficiency of 80% on signal-like events. The requirements placed on the identification and isolation variables are the following:

- The ratio H/E of the energy deposited in the single HCAL tower behind the ECAL supercluster seed crystal over the total supercluster energy in ECAL within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.15$ centered around the supercluster must be less than 0.021.
- The transverse η spread of the shower shape ($\sigma_{i\eta i\eta}$) [45] must be less than 0.01. This variable differentiates between prompt photons and photons from π^0 decays.
- The p_T sum of the charged hadrons within a cone of radius $\Delta R = 0.3$ around the photon must be less than 1.14 GeV.
- The p_T sum of the neutral hadrons within a cone of $\Delta R = 0.3$ around the photon must be less than $1.19 \text{ GeV} + 0.015 p_T^\gamma + 2.26 \times 10^{-5} (p_T^\gamma)^2 / \text{GeV}$.
- The p_T sum of additional photons within a cone of $\Delta R = 0.3$ around the photon candidate must be less than $2.08 \text{ GeV} + 0.0040 p_T^\gamma$.
- An electron veto must also be applied to remove photon candidates in the cases where the candidate's supercluster is matched to a reconstructed electron's track that has no missing hits in the innermost tracker layers.

The observed difference between data and MC simulation in the efficiency for photon identification and isolation is accounted for by applying a data-to-simulation scale factor, as a function of p_T and η [45].

Each candidate event is also required to have at least one jet that passes identification criteria in order to remove spurious jets arising from detector noise [49]. Among the selected jets, a list of jets having at least $p_T^{\text{jet}} > 30$ GeV and $|\eta^{\text{jet}}| < 3.0$ is made in decreasing order of p_T . Setting a minimum value for p_T^{jet} reduces the number of pileup jets in the selected events.

The jets passing all the above criteria and calibrated as discussed above are clustered to form wide jets. The clustering captures final-state radiation and improves the γ +jet invariant mass resolution. To construct wide jets, the highest p_T jet is used as a seed jet, and other jets are merged with it if they are within $\Delta R < 1.1$. The jets are merged by adding the four momenta of jets. The resultant jet is stored as a wide jet and the constituent jets are removed from the jet list. The procedure is repeated with the remaining highest p_T jet as a seed jet to form the next wide jet. These clustered wide jets are ordered in p_T and the highest one is used as the final jet candidate to study signal-like characteristics, such as the invariant mass of the photon and jet. The use of wide jets improves the mass resolution in the q^*/b^* signal by 1.0–1.3% over the entire mass range considered in this analysis. The leading wide jet is required to have $p_T(\text{wide jet}) > 170$ GeV with $|\eta(\text{wide jet})| < 2.4$. The final selected photon and wide-jet candidates are required to be separated by $\Delta R > 1.1$ and to be back-to-back in the azimuthal angle ϕ .

A large reduction in the number of QCD multijet events is achieved by the requirements on photon isolation. To suppress this background further, an additional requirement of $|\Delta\eta| < 1.5$ is imposed on the photon and wide-jet system. This requirement mainly reduces QCD

dijet events produced by t -channel processes, which have a relatively large spread in $\Delta\eta$. If a leading wide-jet (or photon) candidate fails any of the selections described above, the event is discarded. The events selected are assigned to the “inclusive category” for the q^* and QBH signal searches.

The b^* signal search separates the data sets into two categories based on the identification of jets originating from b quarks (b jets). The identification of b jets is performed using the neural network-based DEEPJET tagger [50, 51] at an operating point with 75% b quark efficiency and 1% light quarks misidentification probability. b tag category (events with at least 1 b tagged jet) and 0- b tag category (events without any b tagged jet). The sensitivity of the b^* signal search is improved by combining the results of the 0- b tag category and of the b tag category. This is done to mitigate the effect of a slightly reduced acceptance of the b tag category at higher masses.

The wide-jet, in the case of a b^* , is constructed with the same process described previously, but with an additional requirement that at least one of the constituent jets within $\Delta R < 1.1$ must pass the b tag discriminator selection and fall into the b tag category. This jet will be referred to as a b -tagged jet. In a wide-jet, there could be one, or more b -tagged jets and also light jets. The simulated distributions in both b tag and 0- b tag categories are weighted using scale factors (SF) that account for differences between data and simulation in the b tagging efficiencies.

To avoid the turn-on region in the photon + wide-jet invariant mass distribution that arises due to the various kinematic selections, only events with $m_{\gamma+\text{jet}} > 0.76$ TeV are considered, where $\gamma+\text{jet}$ denotes the photon and wide-jet system. The products of acceptance and efficiency for the q^*/b^* and QBH (ADD/RS1) signals are shown in Fig. 4 for the years 2016, 2017, and 2018. For the ADD and RS1 signals with mass $M_{\text{th}} > 5$ TeV, the reduction in the product of acceptance and efficiency mainly comes from the application of photon isolation criteria. In the following sections, we will refer to wide-jets simply as jets.

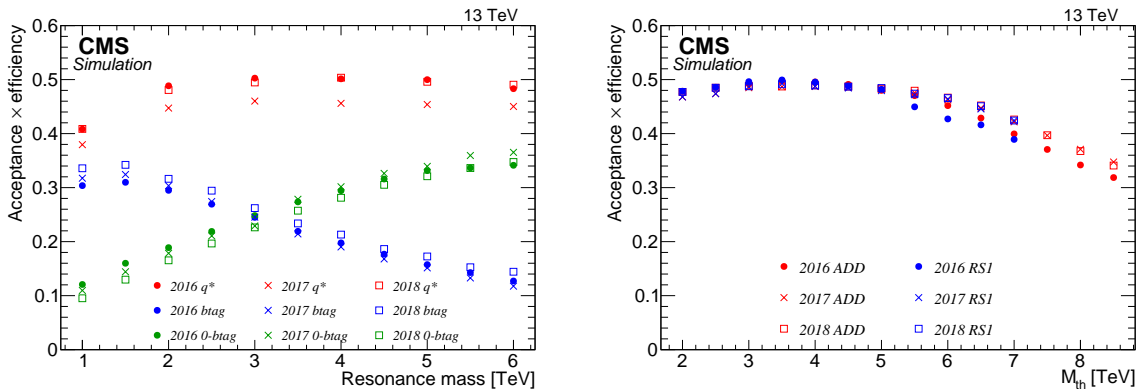


Figure 4: The product of acceptance and efficiency for the q^* signal in the inclusive category and the b^* signal in the b tag and 0- b tag categories, for SM coupling $f = 1.0$ and for different resonance values (left), and the signal for the QBH (ADD/RS1) model in the inclusive category, for different M_{th} values (right), for the years 2016, 2017, and 2018.

6 Signal and background modeling

The background is estimated directly from data. However, MC-simulated background samples are used to perform optimization studies for the event selection and validation of various data distributions.

To extract the background from data, the γ +jet mass spectrum is parameterized with the following empirical functional form

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}} \quad (2)$$

where P_0 , P_1 , P_2 , and P_3 are the fit parameters, and $\sqrt{s} = 13$ TeV. The search uses the signal plus background fit method, where the mass spectrum is fitted with this functional form and the signal template is obtained from simulation. The parameters P_0 , P_1 , P_2 , and P_3 in this functional form are kept floating. This same functional form has also been used in a number of earlier searches [9, 11, 13, 14, 20] to describe the SM background distribution. The fitting range for the q^* , b^* , and RS1 signal is $0.76 < m_{\gamma+\text{jet}} < 8.40$ TeV while for the ADD signal interpretation, where a better signal sensitivity is reached, it is extended up to 9.4 TeV.

The invariant mass distributions for the γ +jet and γ +b jet channels, after all selections, are shown in Figs. 5 and 6, respectively. The bin size of the mass distribution is varied to match the γ +jet mass resolution, which is approximately 4.5% at 1 TeV and 3.3% at 6 TeV.

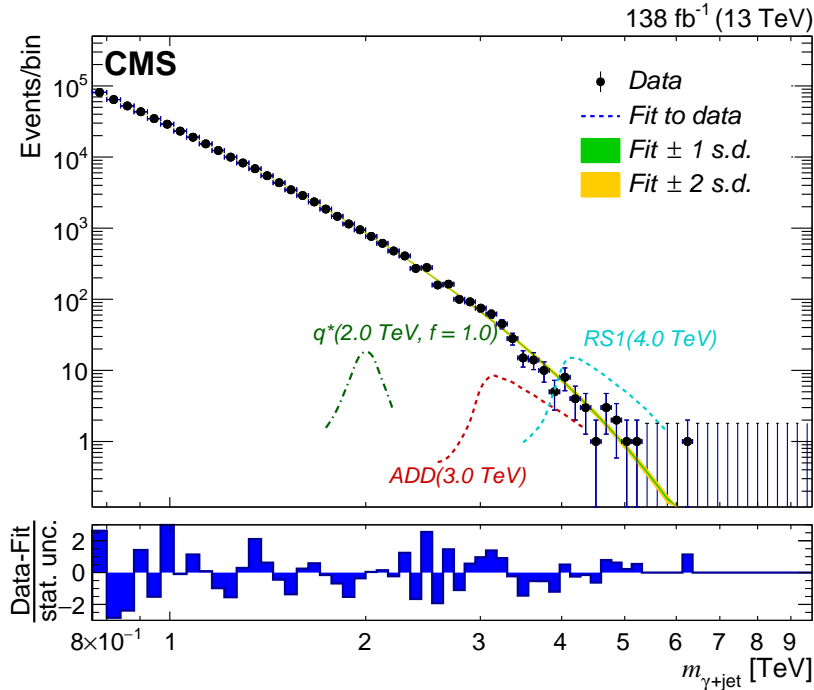


Figure 5: Fit to the γ +jet invariant mass distribution in data with Eq. (2) for the “inclusive” category of q^* and QBH after all selections. Simulations of the q^* signal with a 2 TeV mass and coupling $f = 1.0$, the QBH ADD signal with $M_{\text{th}} = 3$ TeV, and the QBH RS1 signal with $M_{\text{th}} = 4$ TeV are also shown. The lower panel shows the difference between the data yield and the background prediction divided by the statistical uncertainty of the data. The green (inner) and yellow (outer) bands, respectively, represent the 68 and 95% confidence level statistical uncertainties in the fit.

Alternative polynomial functions with 4 and 5 parameters are also considered, to evaluate any possible bias due to the chosen functional form shown in Eq. (2). The choice of the background function is made on the basis of the results of the Fisher test [52]. The procedure used to evaluate the possible bias is the following: pseudo-experiment data distributions are generated for a given alternative function that is fitted to the invariant mass distribution of the SM background and injecting the signal of cross section corresponding to a value of 95% confidence

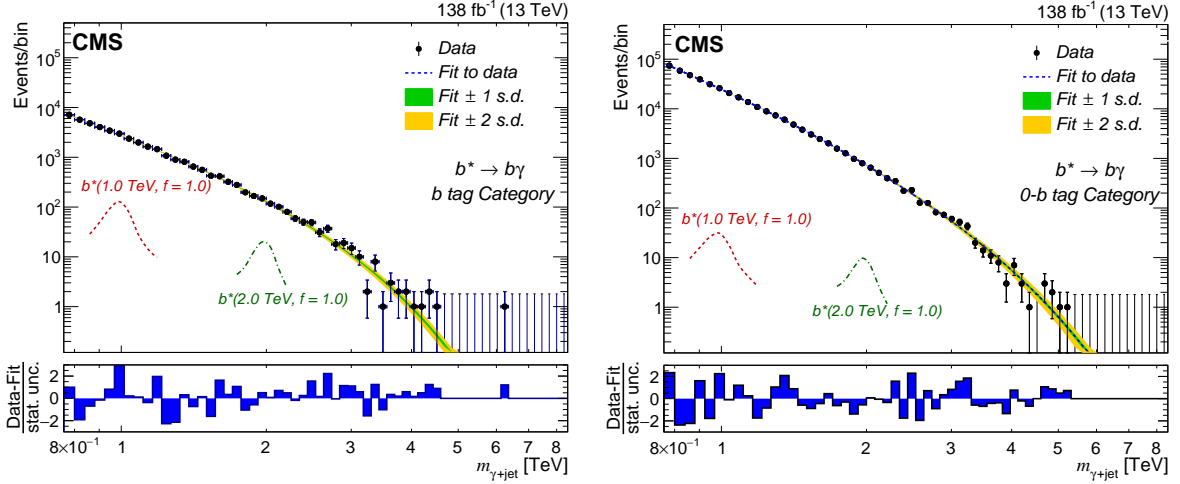


Figure 6: Fits to the γ +jet invariant mass distributions in data with Eq. (2) for the b^* selection for the b tag category (left) and 0 - b tag category (right). Simulations of b^* signals are shown for mass values of 1.0 and 2.0 TeV and for $f = 1.0$. The lower panel shows the difference between the data yield and background prediction divided by the statistical uncertainty of the data. The green (inner) and yellow (outer) bands, respectively, represent the 68 and 95% confidence level statistical uncertainties in the fit.

level (CL) expected limit to it. These pseudo-experiment mass distributions are then fitted with the functional form shown in Eq. (2) using the maximum log likelihood approach to obtain the fitted signal cross section. The possible bias due to the choice of the function is estimated by constructing pull distributions for each mass hypothesis and for each alternative fit function, where the pull is the difference between the injected and extracted signal cross section divided by statistical uncertainty of extracted signal cross section. The pull distributions are found to have a mean bias of less than one half standard deviation for the normalized Gaussian form. A bias of this magnitude is considered acceptable since it contributes $\sim 11\%$ to the total uncertainty when added in quadrature with the statistical uncertainty and has a negligible effect on the sensitivity to signal.

To test the goodness-of-fit for the function used for the alternate fit functions and for the function described in Eq. (2), two different test statistics, the log-likelihood ratio and χ^2 , are used. The test is performed by generating 1000 pseudo-datasets from the best fit model parameters, and each pseudo-dataset is refitted with a maximum log likelihood fit. The estimated p -value [53] for the test statistic is found to be greater than 5% for all the alternative fit functions.

7 Systematic uncertainties

The systematic uncertainties due to various sources can affect both the normalization and the shape of the mass distribution. The dominant source of uncertainty comes from the parametrization of the background fit to data. The background uncertainties are considered as floating nuisance parameters, while the uncertainties in the signal predictions are implemented either as log-normal or Gaussian constraints on the nuisance parameters.

The signal yield and shape are affected by the uncertainties related to the energy or momentum measurements for the reconstructed photons and jets.

To evaluate the effect of uncertainties in wide jets, the jet-related uncertainties are first applied

to the constituent jets. The jet energy scale and jet energy resolution effects are measured by applying the respective ± 1 standard deviation uncertainties in the four-momenta of the constituent jets and reconstructing the mass of the γ -jet system. The effects of the jet energy scale and resolution on the mean and width of the signal shape are found to be in the range 1.0–2.0%.

The photon energy scale and photon energy resolution are measured with $Z \rightarrow e^+e^-$ events, with the electrons reconstructed as photons, using the procedure described in Ref. [45]. The uncertainties in the photon energy scale and photon energy resolution translate into a variation of 1.0–1.5% in the signal mean and width. The uncertainty associated with the photon identification inefficiency due to the extrapolation at very high p_T is taken to be about 10%, which covers all related systematic effects in the procedure used in its measurement.

The b^* signal shape mean and yield have 0.2–3.0% and 7.9–14.3% uncertainties, respectively, obtained by varying the b tagging SF within its ± 1 standard deviation uncertainty. The other sub-dominant uncertainties for the b^* signal shape and normalization are found to be of the order of 1.0–2.0%, as in the case of q^* .

To account for the uncertainty in the HLT inefficiency as discussed in Section 3, a 2.5% systematic uncertainty is used.

The uncertainties associated with the integrated luminosity measurement [54–56] and pileup are also considered. The integrated luminosities of the 2016, 2017, and 2018 data-taking periods are individually known with uncertainties in the 1.2–2.5% range, while the total 2016–2018 integrated luminosity has an uncertainty of 1.6%, used in this paper. The uncertainty due to pileup is calculated by varying the inelastic cross section of 69.4 mb [57] by $\pm 5\%$ and its impact is estimated to be $\sim 0.1\%$ on the signal yield. The uncertainty in the signal shapes due to interpolation for intermediate masses is considered to be $\sim 1\%$, evaluated by comparing the interpolated mass shape with the corresponding generated mass point.

The statistical interpretation considers the systematic uncertainties to be fully correlated among different data-taking years, except for the integrated luminosity uncertainty, which is partially correlated between the years. The effect of uncorrelated systematic uncertainties is also studied by taking the respective uncertainties for each data set separately and obtaining the results again. The results obtained are found to be similar to the case when fully correlated systematic uncertainties are considered for all years.

The details of systematic uncertainties and their relative effects on the shape and normalization are listed in Table 1.

Table 1: Systematic uncertainties in the signal yields for the mass range analyzed.

Source	Type	Uncertainty	Applied to ($q^*/b^*/QBH$)
Integrated luminosity	Normalization	1.6%	All
Jet energy scale	Shape (mean)	$\sim 1.0\%$	All
Jet energy resolution	Shape (width)	0.6–1.9%	All
Photon energy scale	Shape (mean)	$\sim 1.0\%$	All
Photon energy resolution	Shape (width)	0.4–1.2%	All
Pileup	Normalization	0.1%	All
High- p_T photon efficiency	Normalization	$\sim 10.0\%$	All
HLT efficiency	Normalization	2.5%	All
Signal shape interpolation	Shape (mean)	$\sim 1.0\%$	All
b tag SF uncertainty	Shape (mean)	0.2–3.0%	Only b^*
b tag SF uncertainty	Normalization	7.9–14.3%	Only b^*

8 Results and interpretation

The observed mass spectrum is found to be consistent with the background-only prediction. We set limits on potential signals by using a CL_s approach [58, 59] based on an asymptotic approximation [60, 61] of the multibin counting experiment likelihood, taken to be a product of Poisson distributions corresponding to individual bins:

$$\mathcal{L}(\text{data}|\mu, \theta) = \prod_{i=1}^{n_{\text{bin}}} P(x_i | s_i(\mu, \theta) + b_i(\theta)) C(\theta), \quad (3)$$

where P stands for the Poisson probability to observe x_i data events in the i^{th} bin, C represents a constraint term for the nuisance parameters (θ) associated with the systematic uncertainties, μ is the signal strength (parameter of interest), $s_i(\mu, \theta)$ the corresponding signal yield, $b_i(\theta)$ the corresponding background yield, and the product runs over the number of bins (n_{bin}). The systematic uncertainties are considered as nuisance parameters with log-normal constraints on the integrated luminosity and trigger efficiency, and Gaussian constraints on the energy scales and resolutions for the photon and jet. The observed and expected limits are computed and shown in Figs. 7–9 in terms of the product of the cross-section and the branching fraction, $\sigma\mathcal{B}$.

The observed (expected) lower limits on M_{q^*} are found to be 6.0 (6.0), 5.4 (5.2) and 2.4 (2.8) TeV for the coupling strength $f = 1.0, 0.5$, and 0.1 , respectively.

For the b^* resonance search with the process $bg \rightarrow b^* \rightarrow b\gamma$, the observed (expected) lower bounds are 2.2 (2.3) and 1.6 (1.7) TeV for a coupling strength of $f = 1.0$ and 0.5 , respectively. For $f = 0.1$, the analysis did not have sufficient sensitivity to set a mass limit. For b^* production via CI, several processes contribute, with the dominant one being $q\bar{q} \rightarrow \bar{b}b^*$ (or $b\bar{b}^*$) $\rightarrow \bar{b}b\gamma$. Using the same exclusion limit for the $bg \rightarrow b^*$ signal with $f = 1.0$, the observed lower bound on the b^* mass is 3.8 TeV when combining both the processes (b^* produced via gauge interaction and the resonant component of b^* via CI) in the total signal cross section, as shown in Fig. 8 (upper left).

For the QBH search with the ADD (RS1) model with $n = 6$ (1) extra dimensions, the observed lower bound is set to 7.5 (5.2) TeV and the expected exclusion limits are estimated to have the same values. In comparison to q^* , the limits are weaker for b^* resonances and QBH resonances at higher masses.

The two-dimensional representation of the excluded mass region for excited quarks (q^* and b^*) as a function of the coupling strength f , with the assumption $M_{q^*} = \Lambda$, is shown in Fig. 10. The exclusion of the excited quark mass, as a function of M_{q^*}/Λ , is also presented in the same figure on the right hand axis. The excluded M_{q^*} region could also be interpreted in terms of the M_{q^*}/Λ ratio; this interpretation is based on the fact that the detector resolution effects dominate compared to the change in the signal intrinsic width ($\Gamma_{q^*} \sim 0.03f^2M_{q^*}$) [4] arising from the change in the coupling strength f . Consequently, the variation of f effectively changes the production cross section in a similar way to the variations in M_{q^*}/Λ , since both appear as multiplicative factors in the cross section calculation.

9 Summary

A search for resonances in the γ +jet final state has been performed using proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1} . The results are compared with standard model extensions postulating excited quarks, excited b quarks, and quantum black holes.

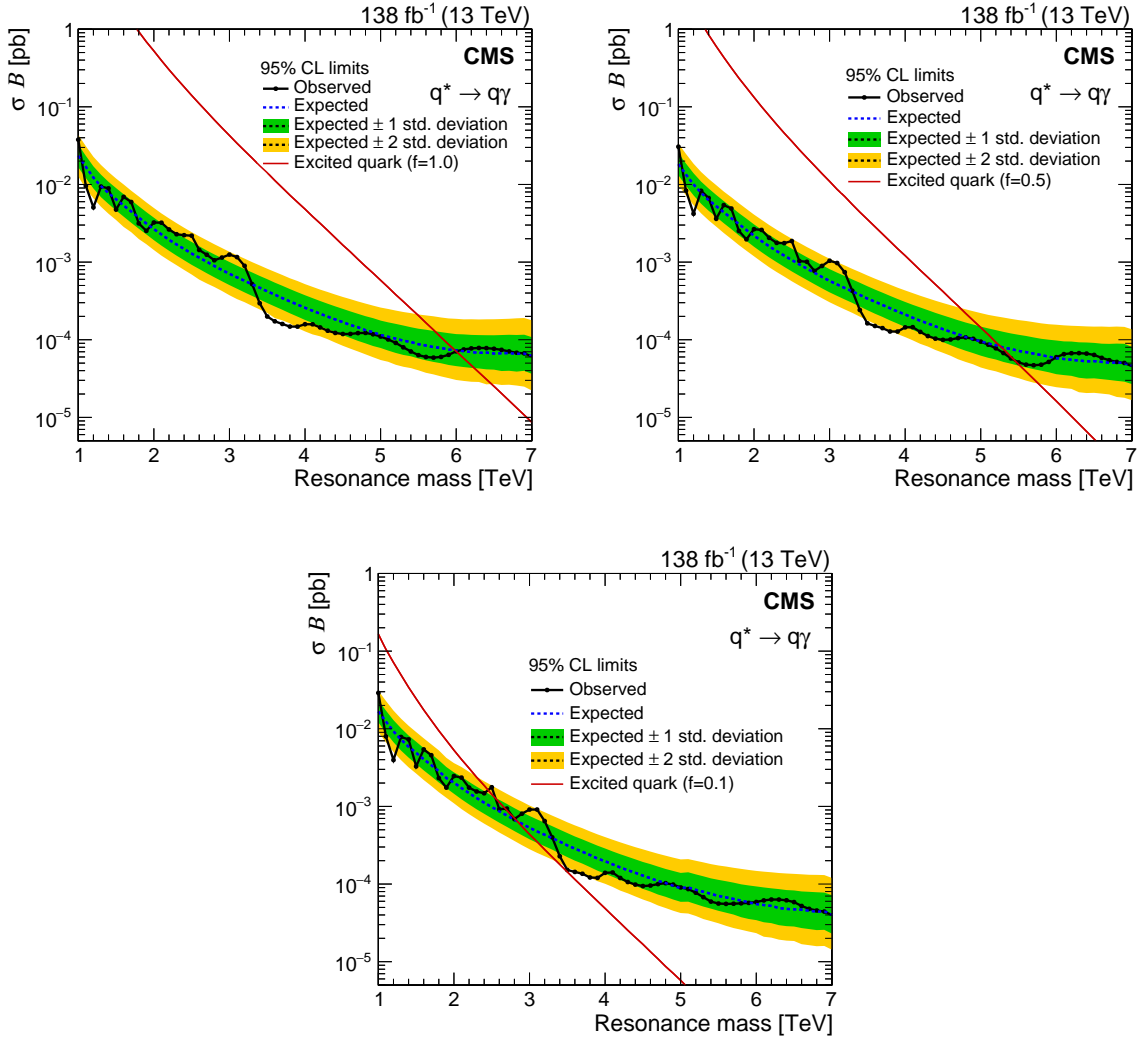


Figure 7: The expected (dashed) and observed (solid) 95% CL upper limits on the product of the cross section and branching fraction, as functions of q^* mass, for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for q^* production for the corresponding coupling strengths.

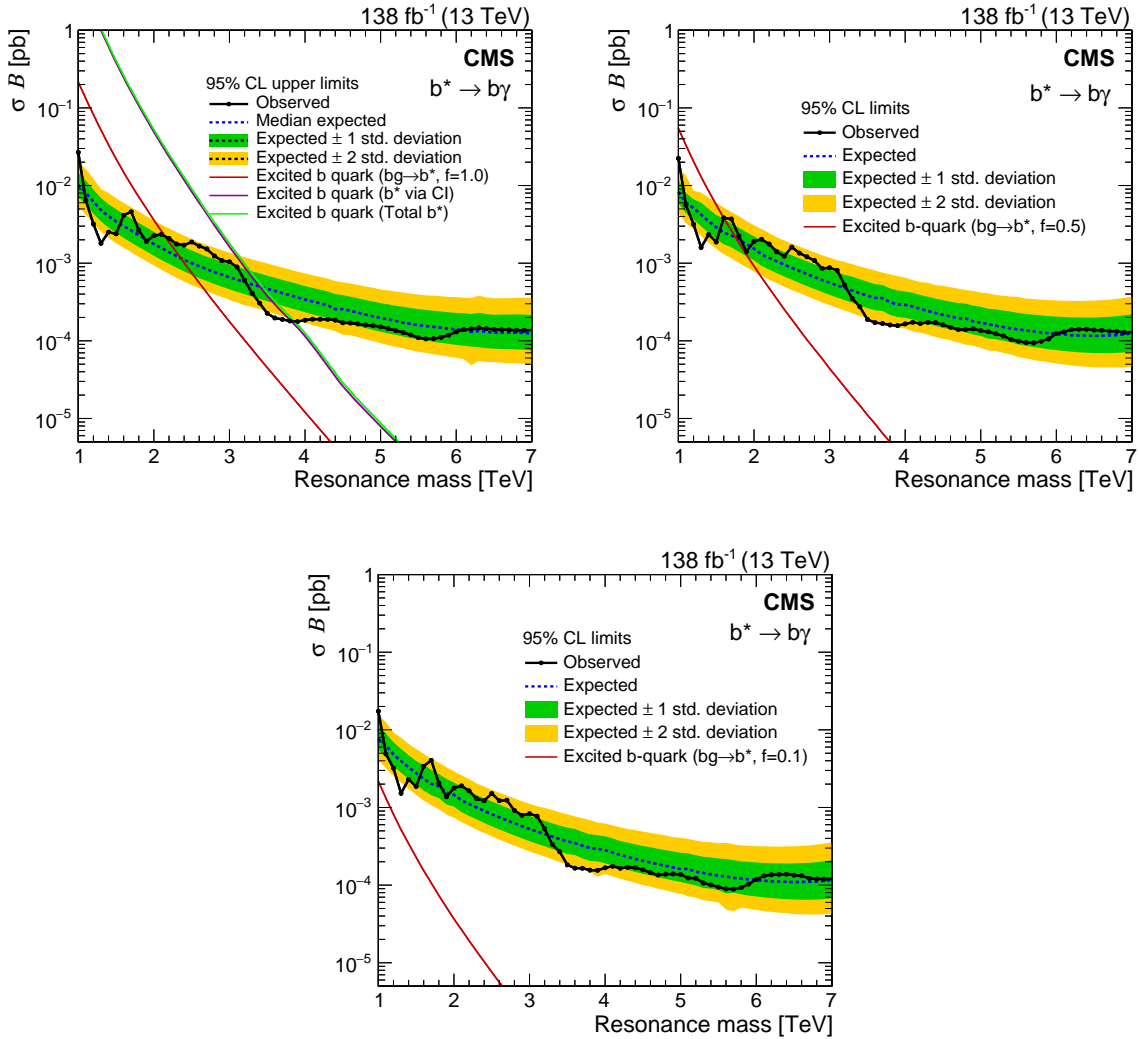


Figure 8: The expected (dashed) and observed (solid) 95% CL upper limits on the product of the cross section and branching fraction, as functions of b^* mass, for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for b^* production for the corresponding coupling strengths. For coupling $f = 1.0$, the limits are compared for b^* production by gauge interactions (red), contact interactions (violet), and total b^* signal by the addition of these two production modes.

For the coupling strength $f = 1.0$, the observed (expected) lower mass bounds on the excited light-flavor quarks and excited bottom quarks from gauge interactions are estimated to be 6.0 (6.0) and 2.2 (2.3) TeV, respectively. For the same coupling strength, the observed lower mass bounds on the excited bottom quarks extends to 3.8 TeV, when the production mode from contact interactions is also considered. For quantum black hole production, observed exclusion limits are estimated to be 7.5 and 5.2 TeV for the Arkani-Hamed–Dimopoulos–Dvali and the Randall–Sundrum models with 6 and 1 extra dimensions, respectively. These lower mass bounds are the most stringent to date among those obtained in the γ -jet final state.

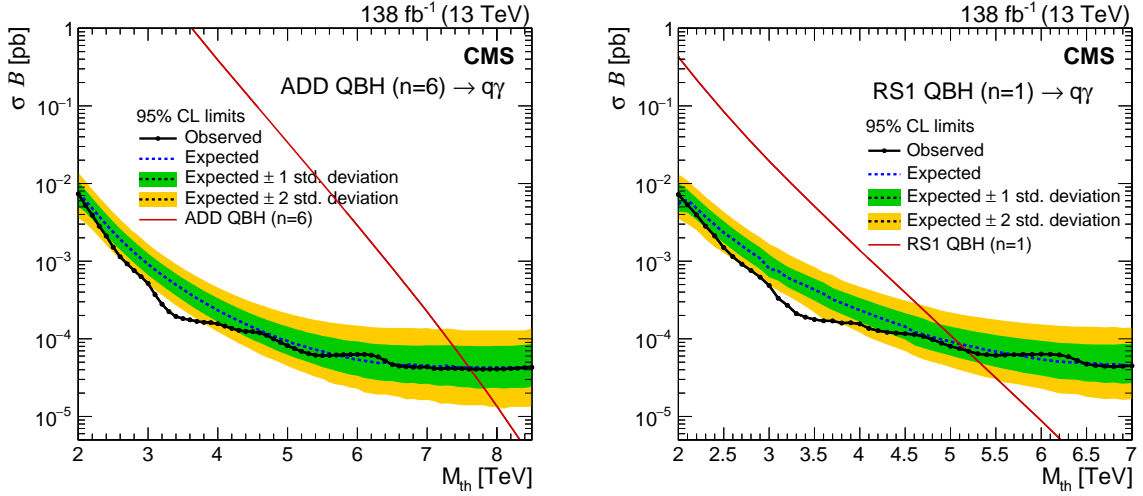


Figure 9: The expected (dashed) and observed (solid) 95% CL upper limit on the product of the cross section and branching fraction as a function of the minimum black hole mass for the ADD ($n = 6$) and RS1 ($n = 1$) models on the left and right, respectively. The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit. The limits are compared with the theoretical predictions for QBH production for ADD ($n = 6$) and RS1 ($n = 1$) models.

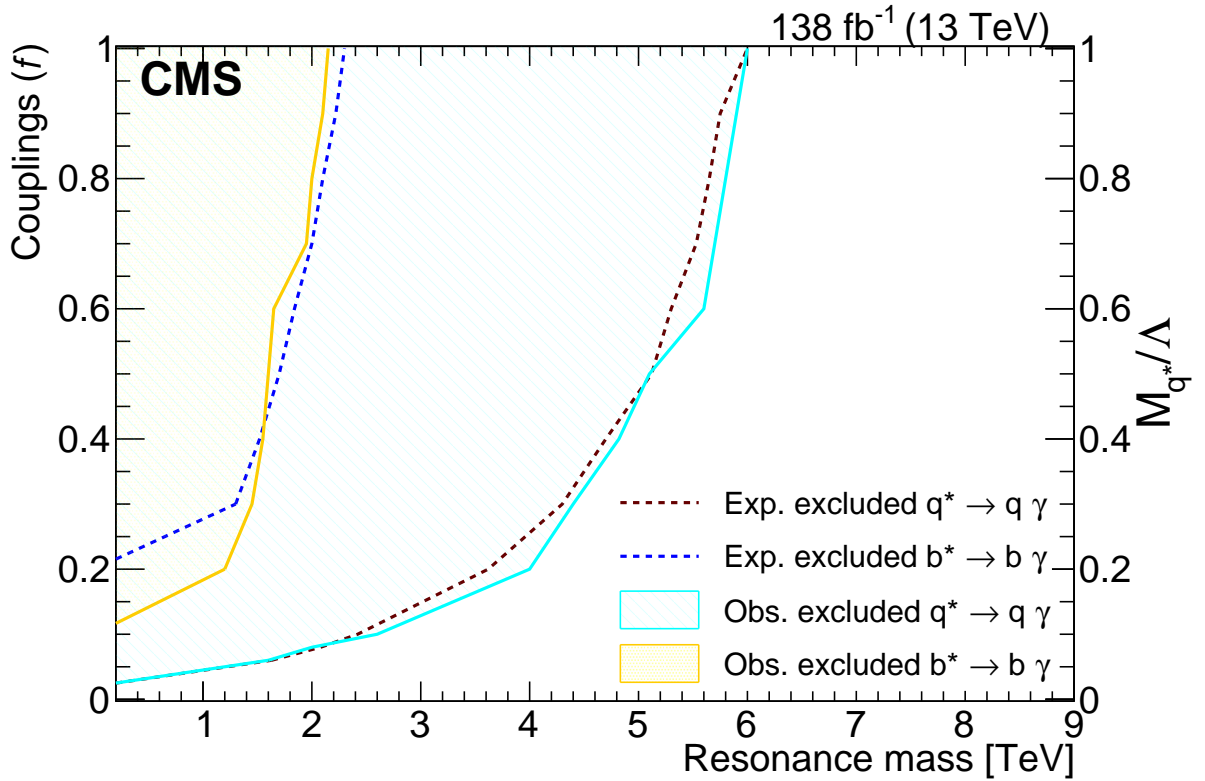


Figure 10: The expected and observed 95% CL exclusion mass limit variation with the SM couplings for the excited q^* and b^* signal models.

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















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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 














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. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch , J. Schieck² , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 


















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , T. Kello⁴ , P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , S. Dansana , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrami , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 






Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , C. Rendón , A. Samalan , K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 






















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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre , K. Mondal , A. Taliercio , T.T. Tran , P. Vischia , S. Wertz 








Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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. Chinellato⁵ , E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , 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. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , 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. Rodozov , 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.Thakur 

Beihang University, Beijing, China

T. Cheng , Q. Guo, T. Javaid⁸ , M. Mittal , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

G. Bauer⁹, Z. Hu , S. Lezki , K. Yi^{9,10} 

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu¹¹ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 


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

A. Agapitos , Y. An , Y. Ban , A. Carvalho Antunes De Oliveira , A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu , 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. Gao⁴ , 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 

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 , I. Puljak 









University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 


Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov¹² , 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. Finger¹² , M. Finger Jr.¹² , 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^{13,14}, S. Elgammal¹⁴

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M. Abdullah Al-Mashad , M.A. Mahmoud 













National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , 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

P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 
















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , 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

C. Amendola , 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-Navarro¹⁵ , 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 , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , 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. Agram¹⁶ , J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom , E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan , P. Van Hove 





Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen¹⁷ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, M. Vander Donckt , P. Verdier , S. Viret


























Georgian Technical University, Tbilisi, Georgia

I. Lomidze , T. Toriashvili¹⁸ , Z. Tsamalaidze¹² 









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 , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , A. Stein , F. Torres Da Silva De Araujo¹⁹ , L. Vigilante, S. Wiedenbeck , S. Zaleski



















RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

C. Dziwok , G. Flügge , W. Haj Ahmad²⁰ , O. Hlushchenko, 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 , P. Asmuss, S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , S. Bhattacharya , F. Blekman²¹ , K. Borrás²² , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Con-suegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²¹ , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²³ , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁴ , W. Lohmann²⁵ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , E. Ranken , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , M. Savitskyi , M. Scham^{26,22} , V. Scheurer, S. Schnake²² , P. Schütze , C. Schwanenberger²¹ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon[†] , F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²² , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , 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 , 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 , J.O. Gosewisch, A. Gottmann , F. Hartmann²⁷ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , M. Link, A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wunsch, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece


M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Pana-

giotou, I. Papavergou , 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 , 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. Gadallah²⁸ , P. Major , K. Mandal , G. Pásztor , A.J. Rádli²⁹ , O. Surányi , G.I. Veres 



Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³⁰ , C. Hajdu , D. Horvath^{31,32} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

G. Bencze, N. Beni , S. Czellar, J. Karancsi³⁰ , J. Molnar, Z. Szillasi, D. Teyssier 

















Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³³ , G. Zilizi 

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo²⁹ , F. Nemes²⁹ , T. Novak 










Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁴ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁵ , 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. Baradia , S. Barman³⁶ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁷ , M. Maity³⁶ , P. Palit , G. Saha , B. Sahu³⁷ , S. Sarkar




Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , S. Chatterjee , P. Kalbhor , J.R. Komaragiri³⁸ , D. Kumar³⁸ , A. Muhammad , L. Panwar³⁸ , R. Pradhan , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 

Bhabha Atomic Research Centre, Mumbai, India

K. Naskar³⁹ 

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

S. Banerjee , M. Guchait , S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Mukherjee , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴⁰ , A.K. Das , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴¹ , A. Nayak⁴¹ , P. Saha , S.K. Swain , S. Varghese , D. Vats⁴¹

Indian Institute of Science Education and Research (IISER), Pune, India

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi^{42,43} , E. Khazaie⁴³ , M. Zeinali⁴⁴ 





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

S. Chenarani⁴⁵ , 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,b,46} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} , L. Cristella^{a,b} , B. D'Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , W. Elmetenawee^{a,b} , F. Errico^{a,b} , 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 , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a









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 , L. Brigliadori^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{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,47} , 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,48} , A. Di Mattia^a , R. Potenza^{a,b} , A. Tricomi^{a,b,48} , 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,b} , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , G. Sguazzoni^a , L. Viliani^a









INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁴⁹ , D. Piccolo 












INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Bozzo^{a,b} , 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 , F. Brivio^{a,b} , F. Cetorelli^{a,b} , 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,b} , 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,b}












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,50} , P. Paolucci^{a,27} , B. Rossi^a , C. Sciacca^{a,b} 
















INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

P. Azzi^a , N. Bacchetta^{a,51} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Gasparini^{a,b} , G. Grosso^a , L. Layer^{a,52} , E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{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} , 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,53} , 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

P. Asenov^{a,54} , 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,54} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 










































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 , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{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 , S. Parolia^a , G. Ramirez-Sanchez^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , 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 , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , 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. Ruspà^{a,c} , K. Shchelina^a , 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} , A. Vagnerini^{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 , G. Della Ricca^{a,b} , G. Sorrentino^{a,b} 




Kyungpook National University, Daegu, Korea

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





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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , S. Jeon , J. Kim , J.S. Kim, S. Ko , H. Kwon , H. Lee , S. 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 , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin, I.C. Park , Y. Roh, D. Song, Watson, I.J. , 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 , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns⁵⁵ 



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 , S.Y. Hoh⁵⁶ , I. Yusuff⁵⁶ , 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 























































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














G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵⁷ , R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico



C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, MexicoI. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada **University of Montenegro, Podgorica, Montenegro**I. Bubanja, J. Mijuskovic⁵⁸, N. Raicevic **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , 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. Szeleper , P. Zalewski **Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski **Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**M. Araujo , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela **Faculty of Physics, University of Belgrade, Belgrade, Serbia**P. Adzic⁵⁹ , P. Milenovic **VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**M. Dordevic , J. Milosevic **Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**M. Aguilar-Benitez, J. Alcaraz Maestre , M. Barrio Luna, 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. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , J. Sastre , 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 **Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , G. Gomez , C. Lasasa García , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , J. Piedra Gomez , C. Prieels, L. Scodellaro , I. Vila , J.M. Vizán Garcia **University of Colombo, Colombo, Sri Lanka**M.K. Jayananda , B. Kailasapathy⁶⁰ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

University of Ruhuna, Department of Physics, Matara, Sri LankaW.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage **CERN, European Organization for Nuclear Research, Geneva, Switzerland**D. Abbaneo , E. Auffray , G. Auzinger , J. Baechler, P. Baillon[†], 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 , S.S. Chhibra , S. Choudhury, M. Cipriani , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita⁶¹, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh⁶² , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabadý , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁶³ , A.G. Stahl Leiton , S. Summers , K. Tatar , D. Treille , P. Tropea , A. Tsirou, D. Walter , J. Wanczyk⁶⁴ , K.A. Wozniak , W.D. Zeuner**Paul Scherrer Institut, Villigen, Switzerland**T. Bevilacqua⁶⁵ , L. Caminada⁶⁵ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶⁵ , L. Noehte⁶⁵ , T. Rohe **ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**T.K. Aarrestad , K. Androsov⁶⁴ , M. Backhaus , A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁶⁴ , F. Nessi-Tedaldi , J. Niedziela , 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. Steggemann⁶⁴ , D. Valsecchi , R. Wallny **Universität Zürich, Zurich, Switzerland**C. Amsler⁶⁶ , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , 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. Adloff⁶⁷, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁸ , S.S. Yu **National Taiwan University (NTU), Taipei, Taiwan**L. Ceard, Y. Chao , K.F. Chen , P.s. Chen, H. Cheng , W.-S. Hou , R. Khurana, G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas, A. Steen , H.y. Wu, E. Yazgan **Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**C. Asawatrangkuldee , N. Srimanobhas , V. Wachirapusanand **Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁸ , E. Eskut , Y. Guler⁶⁹ , E. Gurpinar Guler⁶⁹ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁷⁰ , A. Polatoz , B. Tali⁷¹ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁷², K. Ocalan⁷³ , M. Yalvac⁷⁴ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷⁵ , O. Kaya⁷⁶ , S. Tekten⁷⁷ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁸ , Y. Komurcu , S. Sen⁷⁸ 


Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁷¹ , V. Epshteyn , B. Hacisahinoglu , I. Hos⁷⁹ , B. Isildak⁸⁰ , B. Kaynak , S. Ozkorucuklu , C. Simsek , D. Sunar Cerci⁷¹ 















Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

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 , 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. Stylianou⁸¹ , K. Walkingshaw Pass, R. White 




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁸² , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸³ , Sh. Jain , 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 , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , V. Cepaitis , G.S. Chahal⁸⁴ , 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 , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , D.G. Monk , J. Nash⁸⁵ , M. Pesaresi, B.C. Radburn-Smith , A. Richards, A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁷ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , M. Toms , J. Wilson 

















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 

















The University of Alabama, Tuscaloosa, Alabama, USA

R. Chudasama , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸⁶ , E. Usai , C. West 



















Boston University, Boston, Massachusetts, USA

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













Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²², D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁷ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁸ , E. Simpson , W.Y. Wong, X. Yan , D. Yu , W. Zhang

University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , B. Regnery , W. Wei, Y. Yao , F. Zhang 






















University of California, Los Angeles, California, USA

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, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , O.R. Long , N. Manganelli , W. Si , S. Wimpenny 











University of California, San Diego, La Jolla, California, USA

J.G. Branson, S. Cittolin, S. Cooperstein , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , 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, USA

L. Brennan, C. Campagnari , M. Citron , G. Collura , A. Dorsett , 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 , P. Siddireddy, D. Stuart , S. Wang 













California Institute of Technology, Pasadena, California, USA

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, USA

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, USA

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























Cornell University, Ithaca, New York, USA

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, USA

M. Albrow , M. Alyari , 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 , K.F. Di Petrillo , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , 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 , S. Norberg , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁹ , F. Ravera , A. Reinsvold Hall⁹⁰ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 








University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , P. Chang , V. Cherepanov , R.D. Field , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , E. Kuznetsova⁹¹ , K.H. Lo , K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 


















Florida State University, Tallahassee, Florida, USA

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez , H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang 















Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy⁵³ , M. Hohlmann , R. Kumar Verma , M. Rahmani , F. Yumiceva 












University of Illinois at Chicago (UIC), Chicago, Illinois, USA

M.R. Adams , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 























The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , K. Dilsiz⁹² , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili⁹³ , J. Nachtman , O. Neogi , H. Ogul⁹⁴ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁹⁵ 





Johns Hopkins University, Baltimore, Maryland, USA

O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey , J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 


















Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric, A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 























Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 















University of Maryland, College Park, Maryland, USA

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 , L. Wang , K. Wong 


Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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













University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , D. Mahon , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 




















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , F. Golf , C. Joo , I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 








State University of New York at Buffalo, Buffalo, New York, USA

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , H. Rejeb Sfar, A. Williams 





















Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco



















University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , 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. Musienko¹² , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

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, USA

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, USA

S. Malik 















Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic¹⁵ , J. Thieman , A. K. Viridi , F. Wang , R. Xiao , W. Xie 












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 

Rice University, Houston, Texas, USA

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 , B.P. Padley , R. Redjimi, J. Rotter , S. Yang , E. Yigitbasi , Y. Zhang 

















University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova , R. Taus , G.P. Van Onsem 

The Rockefeller University, New York, New York, USA

K. Goulianos 















Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslowski , O. Karacheban²⁵ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 











Texas A&M University, College Station, Texas, USA

M. Ahmad , O. Bouhali⁹⁶ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁷ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke, S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

Vanderbilt University, Nashville, Tennessee, USA

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, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA

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. Blinov⁹⁸, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , M. Chadeeva⁹⁸ , V. Chekhovsky, M. Danilov⁹⁸ , A. Dermenev , T. Dimova⁹⁸ , I. Dreminev , M. Dubinin⁸⁹ , L. Dudko , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁸ , V. Karjavine , A. Karneyev , V. Kim⁹⁸ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁹ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁸ , N. Krasnikov , A. Lanev , P. Levchenko¹⁰⁰ , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev^{98,101} , V. Murzin , A. Nikitenko^{102,99} , S. Obraztsov , I. Ovtin⁹⁸ , V. Palichik , V. Perelygin , M. Perfilov, S. Petrushanko , S. Polikarpov⁹⁸ , V. Popov, O. Radchenko⁹⁸ , M. Savina , V. Savrin , D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁸ , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , A. Vorobyev[†], N. Voytishin , B.S. Yuldashev¹⁰³, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at Nanjing Normal University Department of Physics, Nanjing, China

¹⁰Now at The University of Iowa, Iowa City, Iowa, USA

¹¹Also at University of Chinese Academy of Sciences, Beijing, China

¹²Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹³Also at Suez University, Suez, Egypt

¹⁴Now at British University in Egypt, Cairo, Egypt

¹⁵Also at Purdue University, West Lafayette, Indiana, USA

¹⁶Also at Université de Haute Alsace, Mulhouse, France

¹⁷Also at Department of Physics, Tsinghua University, Beijing, China

¹⁸Also at Tbilisi State University, Tbilisi, Georgia

¹⁹Also at The University of the State of Amazonas, Manaus, Brazil

²⁰Also at Erzincan Binali Yildirim University, Erzincan, Turkey

²¹Also at University of Hamburg, Hamburg, Germany

-
- ²²Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²³Also at Isfahan University of Technology, Isfahan, Iran
- ²⁴Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁵Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁶Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁷Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²⁸Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ²⁹Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³⁰Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³¹Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³²Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³³Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁴Also at Punjab Agricultural University, Ludhiana, India
- ³⁵Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁶Also at University of Visva-Bharati, Santiniketan, India
- ³⁷Also at University of Hyderabad, Hyderabad, India
- ³⁸Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁹Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴⁰Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴¹Also at Institute of Physics, Bhubaneswar, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Helwan University, Cairo, Egypt
- ⁴⁷Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁸Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁹Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵⁰Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵²Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵³Also at Ain Shams University, Cairo, Egypt
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Riga Technical University, Riga, Latvia
- ⁵⁶Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁷Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁸Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁹Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁶⁰Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁶¹Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁶²Also at Indian Institute of Technology Hyderabad, Hyderabad, India
- ⁶³Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶⁴Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶⁵Also at Universität Zürich, Zurich, Switzerland
- ⁶⁶Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁷Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-

Vieux, France

⁶⁸Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

⁶⁹Also at Konya Technical University, Konya, Turkey

⁷⁰Also at Izmir Bakircay University, Izmir, Turkey

⁷¹Also at Adiyaman University, Adiyaman, Turkey

⁷²Also at Istanbul Gedik University, Istanbul, Turkey

⁷³Also at Necmettin Erbakan University, Konya, Turkey

⁷⁴Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

⁷⁵Also at Marmara University, Istanbul, Turkey

⁷⁶Also at Milli Savunma University, Istanbul, Turkey

⁷⁷Also at Kafkas University, Kars, Turkey

⁷⁸Also at Hacettepe University, Ankara, Turkey

⁷⁹Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁸⁰Also at Ozyegin University, Istanbul, Turkey

⁸¹Also at Vrije Universiteit Brussel, Brussel, Belgium

⁸²Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁸³Also at University of Bristol, Bristol, United Kingdom

⁸⁴Also at IPPP Durham University, Durham, United Kingdom

⁸⁵Also at Monash University, Faculty of Science, Clayton, Australia

⁸⁶Also at Università di Torino, Torino, Italy

⁸⁷Also at Bethel University, St. Paul, Minnesota, USA

⁸⁸Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁹Also at California Institute of Technology, Pasadena, California, USA

⁹⁰Also at United States Naval Academy, Annapolis, Maryland, USA

⁹¹Also at University of Florida, Gainesville, Florida, USA

⁹²Also at Bingol University, Bingol, Turkey

⁹³Also at Georgian Technical University, Tbilisi, Georgia

⁹⁴Also at Sinop University, Sinop, Turkey

⁹⁵Also at Erciyes University, Kayseri, Turkey

⁹⁶Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁷Also at Kyungpook National University, Daegu, Korea

⁹⁸Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁹Also at Yerevan Physics Institute, Yerevan, Armenia

¹⁰⁰Also at Northeastern University, Boston, Massachusetts, USA

¹⁰¹Now at another institute or international laboratory covered by a cooperation agreement with CERN

¹⁰²Also at Imperial College, London, United Kingdom

¹⁰³Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan