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Search for neutral color-octet weak-triplet scalar particles in proton-proton collisions at $\sqrt{s} = 8$ TeV



The CMS collaboration

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

ABSTRACT: A search for pair production of neutral color-octet weak-triplet scalar particles (Θ^0) is performed in processes where one Θ^0 decays to a pair of b quark jets and the other to a Z boson plus a jet, with the Z boson decaying to a pair of electrons or muons. The search is performed with data collected by the CMS experiment at the CERN LHC corresponding to an integrated luminosity of 19.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV. The number of observed events is found to be in agreement with the standard model predictions. The 95% confidence level upper limit on the product of the cross section and branching fraction is obtained as a function of the Θ^0 mass. The 95% confidence level lower bounds on the Θ^0 mass are found to be 623 and 426 GeV, for two different octo-triplet theoretical scenarios. These are the first direct experimental bounds on particles predicted by the octo-triplet model.

KEYWORDS: Exotics, Hadron-Hadron Scattering

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1 Introduction

The CERN LHC is well suited to searches for new colored particles. These searches have targeted particles including vector-like quarks (color triplet spin-1/2 particles), colorons (color octet spin-1 particles), gluinos (color octet Majorana fermions), and color-octet weak-singlet scalars [1–6]. With the recent discovery of a Higgs boson [7–9], so far consistent with being a neutral scalar colorless particle [10, 11], it is also interesting to look for additional scalars, in this case with color charge, with masses close to the electroweak scale. Particles with this combination of spin, charge, and color quantum numbers have not been thoroughly sought at collider experiments. Neutral color-octet spin-0 particles (Θ^0), for example, emerge in the octo-triplet model [12], which includes three particles ($\Theta^+, \Theta^0, \Theta^-$) that transform as a color octet and weak triplet under $SU(3)_c \times SU(2)_W$. The Θ^0 may arise from the sector responsible for breaking extended gauge symmetry associated with colorons [13–15]. Octo-triplets may also be fermion-antifermion bound states [16, 17], or elementary particles from non-minimal grand unified theory. To date, no direct experimental bound has been set for particles predicted by the octo-triplet model.

Octo-triplet particles would be produced in pairs at the LHC either through quark-antiquark annihilation or gluon-gluon interactions, with the former mediated by coloron (G') particles or by gluons (g). If a G' is produced, it can decay to $\Theta^0\Theta^0$, $\Theta^0\phi_I$, or two

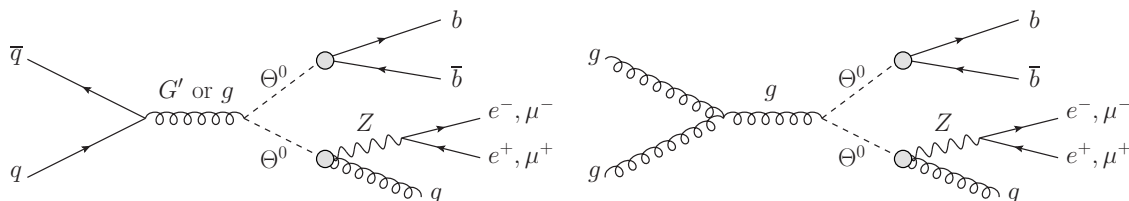


Figure 1. Leading order Feynman diagrams for Θ^0 pair production by quark-antiquark annihilation, through an intermediate G' or gluon (left), and the gluon-gluon interaction (right). In addition to the s -channel gluon process shown in the figure, the gluon-gluon interaction can also proceed directly through $gg \rightarrow \Theta^0\Theta^0$ or a t -channel Θ^0 exchange. The decays of the Θ^0 and Z boson are also included, where the Θ^0 decays are described in the main text.

quarks, where ϕ_I is a color singlet from a general renormalizable coloron model [15]. In the present analysis we are searching for Θ^0 produced in pairs. The ϕ_I mass (m_{ϕ_I}) is a free parameter and has an indirect impact on the Θ^0 pair production cross section, via the G' width.

Unlike color-octet weak-singlet particles, octo-triplet particles do not decay to gluons. However, with a Θ^0 in the loop, one-loop decays to an electroweak boson and a gluon are allowed. There is a potentially similar rate of decays to standard model (SM) quark pairs via mixing through a vector-like quark, which can be as heavy as a few TeV. These heavy vector-like quarks appear in many extensions of the SM, such as composite Higgs models [18] and little Higgs models [19]. In the former, the Higgs boson may be a bound state of a top quark and the heavy vector-like quark, where the binding is provided by the spin-1 G' coloron.

In this paper we assume that one Θ^0 decays to two b quark jets and the other to a Z boson plus a jet originating from a gluon, with $Z \rightarrow \ell\ell$, where ℓ is an electron or muon. With no existing constraints on the ratio of Θ^0 decays to quarks versus those decaying to Zg , we have studied a final state that includes both decay modes. Requiring $Z \rightarrow \ell\ell$ provides a strong experimental signature for event selection and background suppression. The leading order (LO) Feynman diagrams for Θ^0 pair production by quark-antiquark annihilation and gluon-gluon interaction, and the decays explored in this analysis, are shown in figure 1.

The signal production cross section for the octo-triplet model [12] is evaluated at LO with the MADGRAPH v4.5.1 program [20]. Figure 2 shows the values of the cross section in the 2-dimensional plane of G' mass ($m_{G'}$) and Θ^0 mass (m_{Θ^0}). The masses of Θ^0 , G' , and ϕ_I are free parameters in general, but we use $m_{\phi_I} = 125 \text{ GeV} + m_{\Theta^0}/3$ as a benchmark. We explore two distinct mass scenarios: $m_{G'} = 2.3m_{\Theta^0}$ and $m_{G'} = 5m_{\Theta^0}$. The first example corresponds to a scenario in which the signal cross section is enhanced because of the additional contributions from colorons (see figure 2), while the second relation corresponds to a scenario in which the contribution from colorons is negligible. For both mass relations we use Θ^0 masses, ranging from 200 to 900 GeV, which are large enough to allow Θ^0 decay to on-shell Z bosons, but small enough to be within the sensitivity of this search. The first mass relation, $m_{G'} = 2.3m_{\Theta^0}$, results in Θ^0 pair production cross sections from 125 pb down to 2.23×10^{-2} pb, for the range of Θ^0 masses considered. This mass relation also sets

the G' mass sufficiently above Θ^0 pair production threshold, but small enough compared to m_{Θ^0} that production through G' is considerable, at 49 to 86% of the total, depending on m_{Θ^0} . In this case, quark-antiquark annihilation dominates, while gluon-gluon interaction production decreases with increasing Θ^0 (and G') mass, because of the differences in the parton distribution functions (PDF) of quarks and gluons [21]. The second mass relation considered, $m_{G'} = 5m_{\Theta^0}$, results in Θ^0 pair production cross sections from 63.3 pb down to 2.62×10^{-3} pb, for the range of Θ^0 masses considered, which are a factor of two smaller than for the first mass relation. This corresponds to a region where gluon-gluon interactions dominate and production through G' is just 0.6 to 3.6% of the total, depending on the Θ^0 mass. The cross sections discussed above agree with those calculated in ref. [22] where a similar model is considered.

The decay modes $\Theta^0 \rightarrow Zg$ and $\Theta^0 \rightarrow \gamma g$ are invariant under $SU(2)_W$. However, in the Lagrangian, the coefficients of these modes turn out to be much smaller than one. This feature motivates consideration of other decay modes, which can be represented by higher-dimensional operators, and therefore are usually considered as negligible with respect to dominant decay modes. In particular, $q\bar{q}$ decay modes could be as large as the electroweak boson plus gluon modes [12]. In the Θ^0 mass range we consider, the dominant fermion decay mode is either $b\bar{b}$ or $t\bar{t}$ depending on the values of coefficients appearing in different terms of the $\Theta^0 \rightarrow q\bar{q}$ Lagrangian. As a benchmark, we assign half of the branching fraction to $\Theta^0 \rightarrow b\bar{b}$, leaving the other half to the $\Theta^0 \rightarrow Zg$ and $\Theta^0 \rightarrow \gamma g$ decay modes (i.e. $\mathcal{B}(\Theta^0 \rightarrow t\bar{t}) = 0$). The ratio of branching fractions $\mathcal{B}(\Theta^0 \rightarrow Zg)/\mathcal{B}(\Theta^0 \rightarrow \gamma g)$ is set by the mass of the Θ^0 . For the range of Θ^0 masses explored, $\mathcal{B}(\Theta^0 \rightarrow Zg)$ is to 38% and $\mathcal{B}(\Theta^0 \rightarrow \gamma g)$ accounts for the remaining to 17%. The total cross section times branching fraction for the final state studied in this analysis ranges from 2.77 pb down to 5.74×10^{-4} pb for the mass relation $m_{G'} = 2.3m_{\Theta^0}$, and 1.40 pb down to 6.73×10^{-5} pb for the mass relation $m_{G'} = 5m_{\Theta^0}$.

2 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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. 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. [23].

3 Event selection

This analysis uses proton-proton collision data at a center-of-mass energy of 8 TeV collected with dilepton (ee , $\mu\mu$, and $e\mu$) triggers with transverse momentum p_T thresholds of 17 and

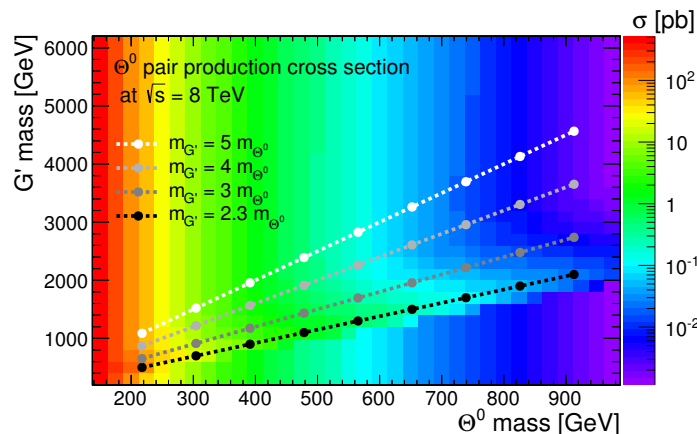


Figure 2. Cross sections for Θ^0 pair production, as a function of the coloron G' and the octo-triplet Θ^0 masses. The dotted lines show a few examples of assumed linear relationship between the two masses.

8 GeV for the two lepton candidates. The $e\mu$ data set is used to estimate $t\bar{t}$ background. The data sample corresponds to an integrated luminosity of 19.7 fb^{-1} . We select events with a final state containing a Z boson and a jet (Z + jet), together with two b quark jets (b jet pair), where the Z boson decays to a pair of electrons or muons.

Electrons are reconstructed using selection criteria that take into account radiated photons [24]. Candidates are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$ where η is the pseudorapidity. Electrons from photon conversions are rejected. An isolation condition is imposed within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the electron. The sum of the p_T of charged particles and transverse energy $E_T = E \sin\theta$ of neutral particles within this cone is corrected in each event for energy deposits due to additional interactions within beam bunch crossings (pileup). The corrected sum must be less than 15% of the electron p_T .

Muons are reconstructed using selection criteria based on quantities measured in the tracker and muon sub-detectors. Candidates are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$. The track associated with the muon candidate is required to have hits in the pixel, silicon strip, and muon systems. An isolation condition requires that the sum of the p_T of charged particles and E_T of neutral particles within a cone of $\Delta R < 0.4$ around the muon is less than 12% of the muon p_T . The pileup correction for muon isolation is similar to the one applied for electrons.

A particle-flow technique [25, 26] is used to identify jet constituents, which are input to the FASTJET algorithm [27, 28] for clustering using the anti- k_T algorithm [29] with a distance parameter of 0.5. The jet energy scale (JES) is measured in data with Z/ γ +jet and dijet events [30, 31], and a correction is applied to both data and simulated samples. The corrected jets must have $p_T > 40 \text{ GeV}$ and $|\eta| < 2.4$. Jets within $\Delta R = 0.3$ from an isolated electron or muon as defined above are not counted as part of the 3 jet requirement. Additional requirements, based on the energy balance between charged and neutral hadronic energy in the jet, are used to reduce contamination from misidentified jets. A jet is considered b tagged, consistent with originating from the hadronization of a bottom

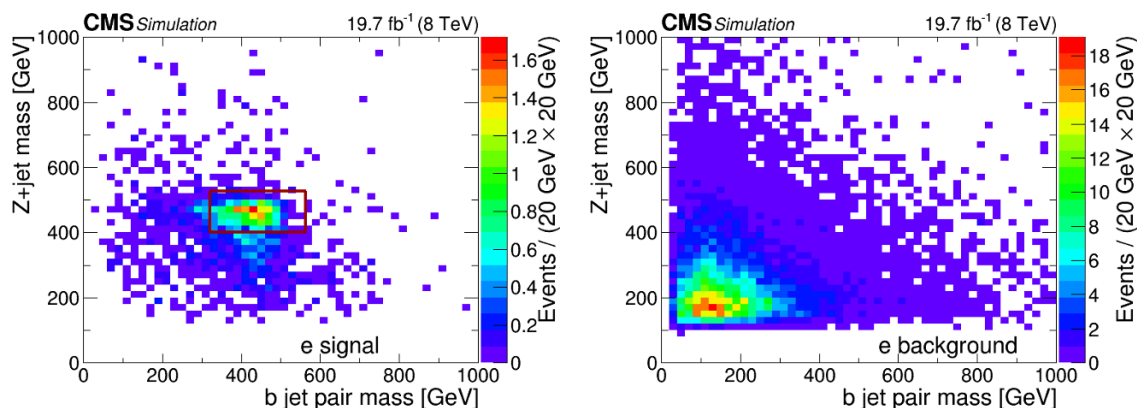


Figure 3. Distributions of Z+jet mass versus b jet pair mass for signal events with $m_{G'} = 1100$ GeV and $m_{\Theta^0} = 478$ GeV (left) and background events (right), in the electron channel (distributions are similar in the muon channel). The open red rectangle on left indicates the signal region, as described in the text.

quark, if it satisfies the “loose operating point” requirements of the combined secondary vertex tagger [32]. The tagging efficiency is about 70–90% and mistagging rate is about 10–20%, depending on p_T and η of the jets.

Candidate events must satisfy the following criteria: at least one reconstructed primary vertex satisfying $|z| < 24$ cm and impact parameter less than 2 cm; an opposite-sign, same-flavor lepton (electron or muon) pair, sharing a primary vertex and with an invariant mass between 80 and 100 GeV to form a Z boson candidate; the two leptons separated from jets by $\Delta R > 0.5$; at least two b-tagged jets forming a b jet pair system (sum of the b jet four-momenta); and at least one additional jet. If more than two b-tagged jets are present in the event, the jets with the largest p_T values are selected for the b jet pair system.

The mass of one Θ^0 candidate is reconstructed from the b jet pair system, and the mass of the other Θ^0 candidate is reconstructed from the combination of the Z boson candidate and the highest p_T jet that is not a part of the b jet pair system. With this prescription, the correct combination of the Z boson and the jet in simulated signal samples is chosen about 65 to 80% of the time, depending on m_{Θ^0} .

For each hypothetical mass point, we consider signal events in a rectangle that is formed in the two-dimensional mass plane defined by the two reconstructed Θ^0 masses. We determine the center, length, and width of the rectangle for each mass point by fitting the b jet pair and Z+jet mass distributions in the simulated signal samples with a modified Gaussian function that has an additional parameter to account for low-mass non-Gaussian tails. The length and width of each rectangle are defined as $\pm 3\sigma_{sd}$ where σ_{sd} is the standard deviation from the modified Gaussian fit. For example, the rectangle is 240 GeV long and 130 GeV wide for the signal with $m_{G'} = 1100$ GeV and $m_{\Theta^0} = 478$ GeV (figure 3 (left)). We choose a $3\sigma_{sd}$ wide window to keep more signal events in middle-high mass regions, since most of the SM background events appear in low-mass region (figure 3 (right)). The signal search regions are defined for the electron and muon channels separately, although these turn out to be very similar.

4 Backgrounds

The dominant background processes are $Z + \text{jets}$ and $t\bar{t} + \text{jets}$. The contributions from other processes, including diboson+jets and multijet, are small. The samples used for all background processes are generated at tree level with the MADGRAPH program, interfaced with PYTHIA v6.4 [33] for showering and hadronization. The $Z + \text{jets}$ background is normalized to the next-to-next-to-leading-order cross section using FEWZ v2.1 [34]. The $t\bar{t} + \text{jets}$ and $tW + \text{jets}$ (single top quark) backgrounds are normalized to the next-to-next-to-leading-logarithm cross sections [35, 36]. The diboson+jets backgrounds are normalized to the next-to-leading-order (NLO) cross section from the MCFM v5.8 [37] calculation. Full simulation of the CMS detector is implemented using the GEANT4 package [38].

4.1 $Z + \text{jets}$

More than half of the background events come from Drell-Yan (DY) production in association with jets. There are two points in estimating the background that require special attention. First, care must be taken in estimating the yield of $Z + \geq 3$ jets events as the simulation may not correctly model the kinematic properties of multijets. Second, the event yield and shape in the $Z + \text{b-jets}$ process, where the kinematic properties of b jet pairs and the fraction of heavy-flavor jets in inclusive $Z + \text{jets}$ might also suffer from mis-modeling in the simulation. The following paragraphs describe how the data are used to improve on the estimates from simulations.

To address the first point, the event yield from the simulation is multiplied by a correction factor to normalize it to data in a control region. This control region is defined such that the dilepton mass is between 80 and 100 GeV and there are at least three jets, none of which is b tagged. The correction factor is found to be 0.98 ± 0.12 (0.91 ± 0.12) for the electron (muon) channel. The correction is applied to all signal rectangle regions. The 12% uncertainty comes from b tagging, JES, and pileup systematic uncertainties in the control region, added in quadrature, while the statistical uncertainty is negligible. The $Z + \text{jet}$ mass in the $Z + \geq 3$ jets (one b tag) control region is plotted in figure 4 after the correction factor has been applied. Agreement between the data and simulated sample is observed in the $Z + \geq 3$ jets (no b tag) and $Z + \geq 3$ jets (one b tag) control regions.

The second point requires a different approach since control regions that include two or more b jets may suffer from signal contamination. We take a two-step approach. First, the simulated $Z + \text{b-jets}$ events are weighted by the ratio of the k-factor (NLO cross section divided by LO cross section) for $Z + 2 \text{b-jets}$ to that of $Z + 2 \text{jets}$, using MCFM [39]. The ratios vary from 1.09 to 2.56 in the b jet pair mass range of 20 GeV to 1.8 TeV. In the simulation, about 20% of $Z + \text{jets}$ events in the signal region have at least two jets originating from b quarks. In the second step, the remaining difference between data and simulation is evaluated as a function of b jet pair mass in the non-signal, off-diagonal regions (sidebands) in the b jet pair mass and $Z + \text{jet}$ mass plane. The uncertainty in the $Z + \text{heavy-flavor jets}$ processes is taken from this difference or from the uncertainty in the CMS cross section measurement [40], whichever is larger. The uncertainty varies from 20 to 50%.

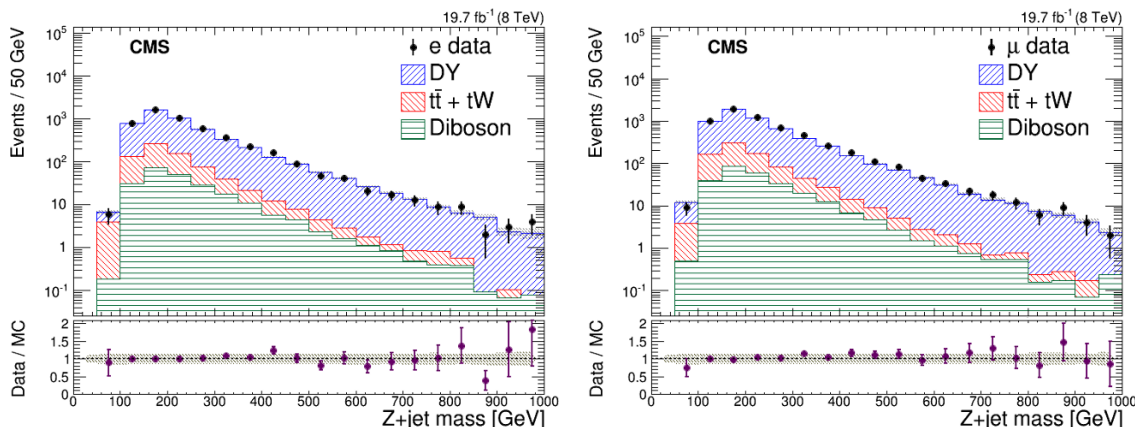


Figure 4. The $Z + \text{jet}$ mass distribution in the $Z + \geq 3$ jet (one b tag) control region after the appropriate correction factor has been applied, for the electron channel (left) and muon channel (right). The panels at the bottom show the ratio of data to background simulation, with the band representing the systematic uncertainty including the normalization uncertainty obtained from the $Z + \geq 3$ jet (no b tag) control region.

The uncertainty in the shape of the other variable that is used to define the signal search regions, the $Z + \text{jet}$ mass distribution, is estimated by comparing the distribution in the simulated $Z + \text{jets}$ sample with those of several MADGRAPH samples that are produced with factorization or renormalization scales and matrix element parton shower matching thresholds varied up and down by a factor of two. The maximum difference between the nominal distribution and the varied distributions is taken as an uncertainty. The uncertainty varies from 2 to 55%.

4.2 $t\bar{t} + \text{jets}$ and $tW + \text{jets}$

After accounting for the $Z + \text{jets}$ background, most of the remaining background events come from $t\bar{t} + \text{jets}$, with a smaller contribution from $tW + \text{jets}$ production.

Both $t\bar{t} + \text{jets}$ and $tW + \text{jets}$ processes can yield final states containing an opposite-sign $e\mu$ pair. In this analysis, we are considering only opposite-sign, same-flavor lepton pairs, and thus the data containing an opposite-sign $e\mu$ pair can be used to calibrate the $t\bar{t} + \text{jets}$ and $tW + \text{jets}$ backgrounds. The overall event yield in the simulation is multiplied by a factor of 1.07 ± 0.13 to normalize it to data in the control region containing an $e\mu$ pair with the mass between 60 and 120 GeV ($Z_{e\mu}$) and at least three jets, at least two of which are b tagged. The uncertainty comes from b tagging, JES, and pileup systematic uncertainties in the control region, added in quadrature, while the statistical uncertainty is negligible. The b jet pair and $Z_{e\mu} + \text{jet}$ mass distributions in this control region are plotted in figure 5 after the normalization factor is applied.

4.3 Diboson + jets

A few percent of the background events come from diboson+jets processes. The simulated diboson cross sections are found to be in agreement with those measured by CMS [41, 42]. Therefore we make no correction to the event yields.

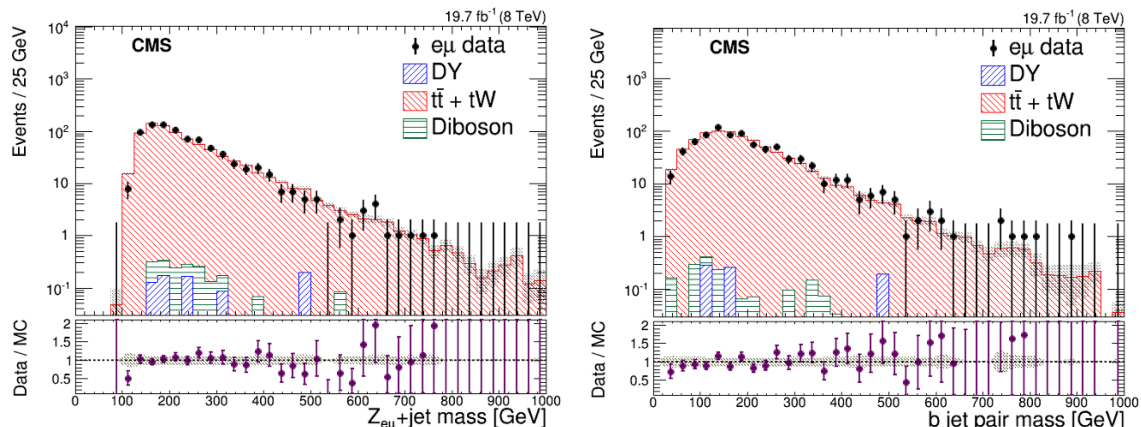


Figure 5. The $Z_{e\mu}+\text{jet}$ (left) and b jet pair mass (right) distributions in the $t\bar{t}$ control region after the appropriate correction factor is applied. The panels at the bottom show the ratio of data to background simulation, with the band representing the systematic uncertainty.

4.4 Multijet events

The estimation of the multijet background with simulated samples is difficult given that the mis-identification rates of jets as electrons or muons are small [24, 43]. Unlike $Z \rightarrow \ell\ell$ and $W^-W^+ \rightarrow \ell\nu\bar{\nu}$ processes, there are about equal amount of like-sign and opposite-sign lepton pairs in the background because the leptons are either misidentified or are non-prompt. In this analysis, we consider only opposite-sign, same-flavor lepton pairs, and thus the data containing like-sign, same-flavor lepton pairs can be used as a control sample to determine the size of the contribution from multijet events. After the Z boson mass window selection and the requirement of at least three jets, with at least two of them being b tagged, and after subtracting events from all other simulated background processes, 27 (13) dielectron (dimuon) events are left in the like-sign dilepton channel. This corresponds to 1.6% (0.7%) of the number of opposite-sign dilepton events. These events are distributed mostly in the lower mass region, as is the case for other backgrounds. Given the small number of like-sign events in the control sample and their mass distribution, the multijet background is found to be negligible.

5 Systematic uncertainties

We organize the sources of systematic uncertainties in three categories: sources affecting both the signal and background; sources affecting only the background; and sources affecting only the signal. A summary of the systematic uncertainties is given in table 1.

Sources affecting both the signal and background:

- *b tagging*

The data-to-simulation correction factor for b tagging is varied by its uncertainties. The resulting uncertainties in the number of predicted signal and background events range from 13 to 25%.

- *Jet energy scale*
The jet energies are varied by the uncertainty in the applied JES correction. The resulting event yield uncertainties range from 0.2 to 2.6% for the signal and 4 to 8% for the background.
- *Lepton trigger and identification (ID)*
The lepton trigger and ID (including isolation) uncertainty is estimated by varying the data-to-simulation correction factor by its uncertainty, which is measured in dilepton data where at least one of the leptons passes stringent identification criteria. The yield uncertainty is about 1%, both for the signal and the background.
- *Pileup modeling*
An uncertainty in the pileup modeling in the signal and background samples is estimated by varying by 5% the total inelastic cross section, as measured at the LHC [44, 45]. The event yield uncertainty is about 1%, somewhat higher for the signal than for the background.

Sources affecting only the background:

- *Z + jet mass shape for Z + jets background*
The uncertainty is evaluated by comparing the varied simulated samples as mentioned in section 4. The shape of the Z + jet mass distribution is much less certain in the high-mass tail than in the low-mass region because of the limited number of simulated events with high masses. The uncertainty in the estimated number of Z + jets events varies from 2 to 55%.
- *b jet pair mass shape for Z + jets background*
The uncertainty from this source is evaluated in the off-diagonal sidebands in the b jet pair mass and Z+jet mass plane, as mentioned in section 4, and takes into account the uncertainty in the CMS cross section measurement of Z + heavy-flavor jets processes. The resultant uncertainty in the Z + jets event yield is in the range 20 to 50%
- *Normalization of Z + jets and $t\bar{t}$ + jets backgrounds*
The uncertainty in the event yield is 12% for Z + jets and 13% for $t\bar{t}$ + jets processes as mentioned in section 4.
- *Diboson cross section*
The uncertainty is taken from the underlying CMS diboson cross section measurements [41, 42], and implies a 10% uncertainty in the estimated number of diboson events.

Sources affecting only the signal:

- *Initial state radiation (ISR) modeling*
For the signal samples, the uncertainty from this source is estimated from the p_T distribution of the $\Theta^0\Theta^0$ system. The distribution generated using MADGRAPH is found to be in agreement with the data for heavy object systems with $p_T < 120$ GeV [46].

Source	Signal [%]	Z + jets [%]	$t\bar{t}$ and tW [%]	Diboson [%]
Signal and background				
b tagging	13–25	15–16	13–15	16–17
Jet energy scale	0.2–2.6	6–8	4–6	5–7
Lepton ID, isolation, trigger	0.9–1.2	0.9–1.2	0.9–1.3	0.9–1.2
Pileup modeling	0.1–1.5	0.3–0.7	0.2–1.0	0.3–0.7
Background only				
Z + jet mass shape	—	2–55	—	—
b jet pair mass shape	—	20–50	—	—
Normalization	—	12	13	—
Diboson cross section	—	—	—	7–10
Signal only				
ISR	1–5	—	—	—
Integrated luminosity	2.6	—	—	—

Table 1. Impact of systematic uncertainties on individual event yields. Ranges show the variation over the search regions that are considered. Dashes indicate cases where a systematic uncertainty is not applied. Sources appearing in more than one process are treated as correlated in the limit setting.

Above 120 GeV, an uncertainty is assigned that varies from 5 to 20%, depending on the p_T . This leads to a 1–5% uncertainty in the yield of signal events for the mass ranges that are considered.

- *Integrated luminosity*

The CMS experiment collected data equivalent to 19.7 fb^{-1} with a 2.6% uncertainty [47]. This uncertainty applies only to yield of signal events. The background events are either normalized in a control region or the normalization is taken from data.

The systematic uncertainties in event yield due to the lepton energy scale, and the lepton and jet energy resolution, are studied and found to be negligible ($<0.1\%$) compared to the other sources of uncertainty.

For the signal samples, the impact on the event yields due to PDF uncertainties are estimated by following the PDF4LHC recommendation [48, 49]. These uncertainties are not used in the limit setting, but are instead included as bands on the theoretical predictions. Since the Z + jets and $t\bar{t}$ + jets backgrounds are normalized in control regions, PDF uncertainties are not applied. Similarly the diboson+jets background normalization is taken from the data [41, 42]. The uncertainty in the signal yield is 7–45%.

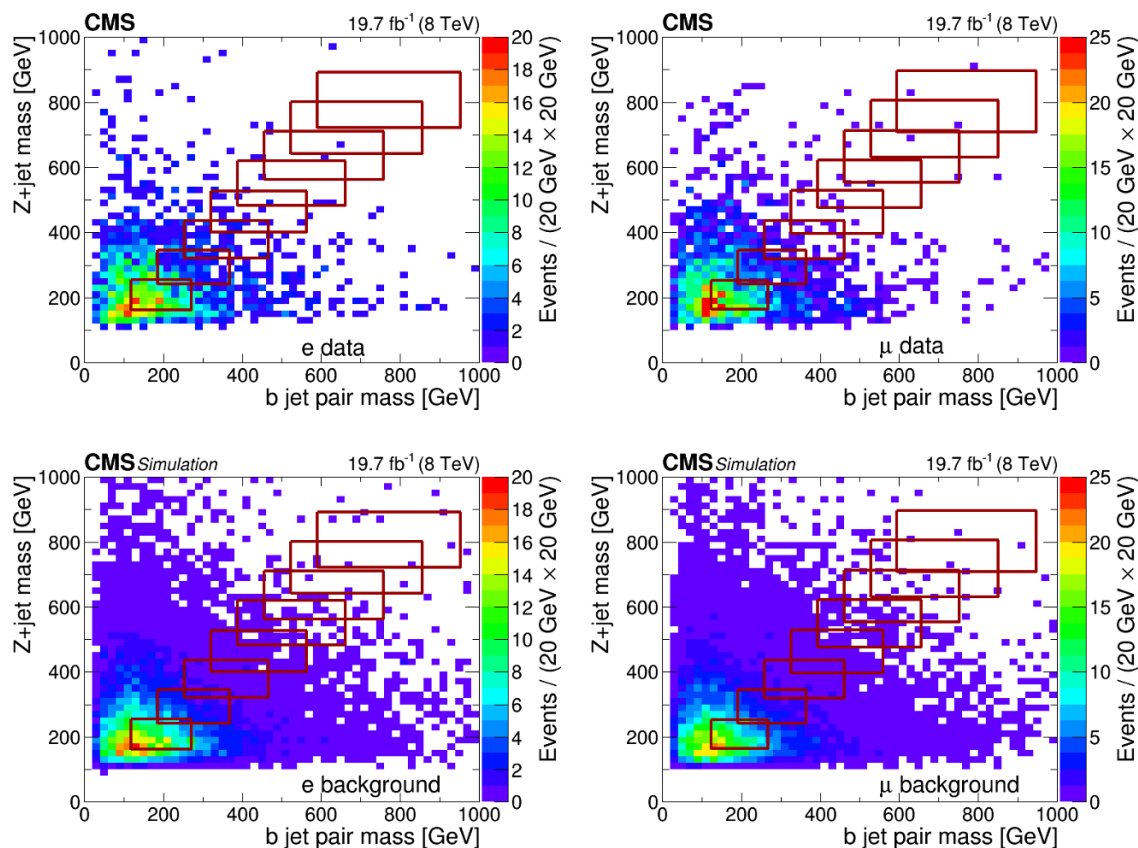


Figure 6. Distributions of the $Z + \text{jet}$ mass versus b jet pair mass in data (top left and right), and estimated background (bottom left and right). The number of signal candidate events is counted in the rectangular boxes defined for each signal mass hypothesis, as discussed in section 3.

6 Results

The numbers of observed data events in each signal region after all of the selection requirements are applied are consistent with the predictions from SM processes within two standard deviations, and are summarized in tables 2 and 3. Table 2 shows the number of events for signal, total background, and observed data, while table 3 shows the detailed breakdown of backgrounds from different sources.

Events observed in the b jet pair and $Z + \text{jet}$ mass plane, together with the predictions from background processes, are plotted in figure 6. The b jet pair and $Z + \text{jet}$ mass distributions are shown separately in figure 7.

Upper limits are calculated on the ratio of the measured Θ^0 pair production cross section times branching fraction $\mathcal{B}(\Theta^0 \rightarrow Zg) \times \mathcal{B}(Z \rightarrow \ell\ell) \times \mathcal{B}(\Theta^0 \rightarrow b\bar{b}) \times 2$, to the theoretically expected cross section times branching fraction, for each search region separately. We have used as a benchmark the case where $\mathcal{B}(\Theta^0 \rightarrow b\bar{b}) = \mathcal{B}(\Theta^0 \rightarrow Zg) + \mathcal{B}(\Theta^0 \rightarrow \gamma g) = 0.5$. The resulting limits placed on octo-triplet particle production cross section and mass can be scaled for different choices of $\mathcal{B}(\Theta^0 \rightarrow b\bar{b})$ and $\mathcal{B}(\Theta^0 \rightarrow Zg)$. The results in the electron and muon channels are consistent and therefore combined. A modified-frequentist approach, CL_s , is used to calculate the limits [50, 51]. For each mass point, pseudo-

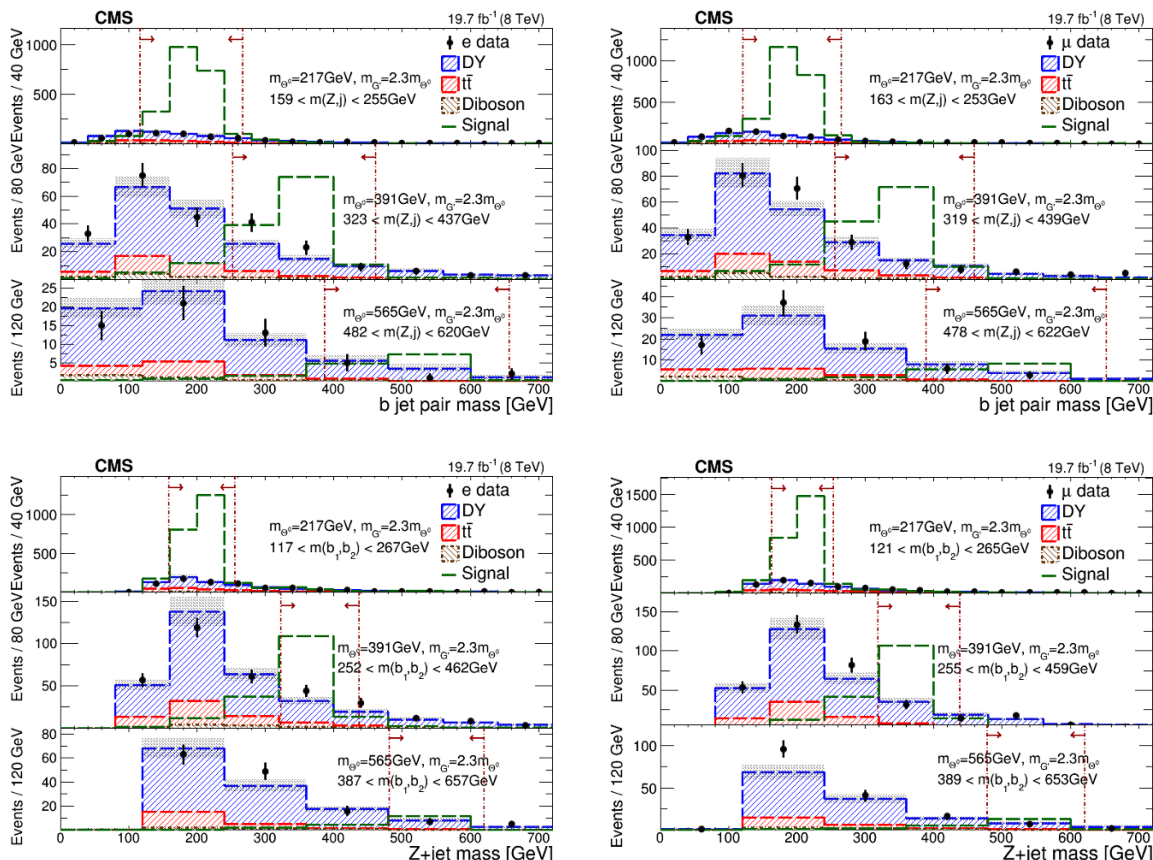


Figure 7. The b jet pair mass distributions for three different ranges of Z + jet mass in the electron channel (top left) and the muon channel (top right); Z + jet mass distributions for three different ranges of b jet pair mass in the electron channel (bottom left) and the muon channel (bottom right). The plotted regions correspond to three of the search regions. Predicted signal distributions are overlaid. The shaded band represents the statistical uncertainty combined with the systematic uncertainty in the simulated samples.

experiments are run for the signal plus background hypothesis, and for the background only hypothesis. The systematic uncertainties discussed in section 5, and their correlations, are included in the limit determinations through a set of nuisance parameters. The results are shown, in figure 8, as a 95% confidence level (CL) observed and expected limit on $\sigma \times \mathcal{B}(\Theta^0 \rightarrow Zg) \times \mathcal{B}(Z \rightarrow \ell\ell) \times \mathcal{B}(\Theta^0 \rightarrow b\bar{b}) \times 2$, as a function of Θ^0 mass. For the case where $m_{G'} = 2.3m_{\Theta^0}$, this result excludes Θ^0 masses below 623 GeV at 95% CL, with an expected exclusion of 639 GeV. For the case where $m_{G'} = 5m_{\Theta^0}$, Θ^0 masses below 426 GeV are excluded at 95% CL, with an expected exclusion of 439 GeV. These plots also include the theoretical predictions, with the band indicating the uncertainty in the signal due to the PDF uncertainty.

7 Summary

A search for pair production of neutral color-octet weak-triplet scalar particles (Θ^0) has been performed based on processes where one Θ^0 decays to a pair of b quark jets and the

m_{Θ^0} [GeV]	Signal		Background	Observed
	$m_{G'} = 2.3m_{\Theta^0}$	$m_{G'} = 5m_{\Theta^0}$		
Electron channel				
217	$2110 \pm 70 \pm 290$	$1110 \pm 40 \pm 160$	$358 \pm 15 \pm 81$	336
304	$448 \pm 12 \pm 70$	$188 \pm 6 \pm 31$	$123 \pm 6 \pm 27$	115
391	$119 \pm 3 \pm 22$	$38.6 \pm 1.3 \pm 7.4$	$42.3 \pm 3.0 \pm 11.0$	59
478	$35.8 \pm 1.0 \pm 6.6$	$9.45 \pm 0.32 \pm 1.90$	$18.9 \pm 2.7 \pm 6.4$	24
565	$11.7 \pm 0.3 \pm 2.4$	$2.37 \pm 0.09 \pm 0.53$	$8.14 \pm 1.94 \pm 3.40$	7
652	$3.96 \pm 0.13 \pm 0.86$	$0.72 \pm 0.03 \pm 0.17$	$3.35 \pm 0.82 \pm 1.50$	4
739	$1.42 \pm 0.06 \pm 0.32$	$0.23 \pm 0.01 \pm 0.05$	$1.02 \pm 0.31 \pm 0.51$	1
826	$0.56 \pm 0.02 \pm 0.13$	0.08 ± 0.02	$0.66 \pm 0.33 \pm 0.36$	0
913	$0.24 \pm 0.01 \pm 0.06$	0.03 ± 0.01	$0.31 \pm 0.14 \pm 0.19$	0
Muon channel				
217	$2360 \pm 70 \pm 310$	$1170 \pm 40 \pm 160$	$348 \pm 11 \pm 74$	355
304	$486 \pm 12 \pm 74$	$185 \pm 6 \pm 31$	$126 \pm 7 \pm 27$	127
391	$118 \pm 3 \pm 20$	$38.7 \pm 1.2 \pm 7.3$	$44.8 \pm 3.1 \pm 11.3$	39
478	$38.7 \pm 1.0 \pm 7.4$	$9.58 \pm 0.32 \pm 1.90$	$17.2 \pm 1.9 \pm 5.7$	15
565	$13.1 \pm 0.4 \pm 2.7$	$2.70 \pm 0.09 \pm 0.58$	$9.52 \pm 1.40 \pm 3.80$	8
652	$4.58 \pm 0.14 \pm 0.99$	$0.74 \pm 0.03 \pm 0.17$	$3.25 \pm 0.84 \pm 1.30$	5
739	$1.63 \pm 0.07 \pm 0.36$	$0.24 \pm 0.01 \pm 0.06$	$1.48 \pm 0.49 \pm 0.58$	3
826	$0.69 \pm 0.03 \pm 0.16$	0.08 ± 0.02	$0.32 \pm 0.17 \pm 0.14$	2
913	$0.26 \pm 0.01 \pm 0.06$	0.03 ± 0.01	$0.14 \pm 0.14 \pm 0.09$	1

Table 2. The number of events after final selection for the signal, total background, and observed data, together with the statistical and systematic uncertainty. For the entries where a single uncertainty is shown, the statistical uncertainty is negligible.

other to a Z boson plus a jet, with the Z boson decaying to a pair of electrons or muons. This analysis is based on data collected with the CMS experiment in proton-proton collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1} . The number of observed events is found to be in agreement with the standard model prediction. The CL_s method is used to set a 95% confidence level limit on the cross section of octo-triplet particles, assuming $\mathcal{B}(\Theta^0 \rightarrow b\bar{b}) = 0.5$, with the remaining Θ^0 branching fraction shared between Zg and γg . By comparing the theoretical predictions of the octo-triplet model and the observed limits, masses of Θ^0 below 623 GeV for $m_{G'} = 2.3m_{\Theta^0}$, and below 426 GeV for $m_{G'} = 5m_{\Theta^0}$, are excluded at 95% confidence level. These are the first direct experimental bounds on the Θ^0 production model.

m_{Θ^0} [GeV]	Z + jets	$t\bar{t}$ and tW	Diboson
Electron channel			
217	$256 \pm 15 \pm 79$	$91.3 \pm 2.2 \pm 18.0$	$11.1 \pm 0.9 \pm 2.2$
304	$90.5 \pm 5.7 \pm 26.0$	$27.5 \pm 1.2 \pm 5.3$	$4.55 \pm 0.60 \pm 0.90$
391	$33.6 \pm 2.9 \pm 11.0$	$6.55 \pm 0.60 \pm 1.30$	$2.10 \pm 0.35 \pm 0.42$
478	$16.9 \pm 2.7 \pm 6.4$	$1.24 \pm 0.25 \pm 0.24$	$0.78 \pm 0.21 \pm 0.16$
565	$7.36 \pm 1.90 \pm 3.30$	$0.36 \pm 0.11 \pm 0.07$	$0.42 \pm 0.17 \pm 0.08$
652	$3.08 \pm 0.81 \pm 1.50$	$0.04 \pm 0.03 \pm 0.01$	$0.23 \pm 0.12 \pm 0.05$
739	$1.02 \pm 0.31 \pm 0.51$	< 0.04	< 0.01
826	$0.65 \pm 0.33 \pm 0.36$	< 0.04	0.01 ± 0.01
913	$0.27 \pm 0.13 \pm 0.19$	< 0.04	$0.04 \pm 0.04 \pm 0.01$
Muon channel			
217	$244 \pm 10 \pm 72$	$91.5 \pm 2.2 \pm 18.0$	$12.7 \pm 1.0 \pm 2.4$
304	$92.2 \pm 7.2 \pm 27.0$	$28.7 \pm 1.2 \pm 5.5$	$5.57 \pm 0.59 \pm 1.10$
391	$35.1 \pm 3.0 \pm 11.0$	$7.51 \pm 0.62 \pm 1.40$	$2.20 \pm 0.36 \pm 0.42$
478	$15.0 \pm 1.8 \pm 5.7$	$1.20 \pm 0.26 \pm 0.23$	$1.00 \pm 0.24 \pm 0.19$
565	$8.89 \pm 1.40 \pm 3.80$	$0.36 \pm 0.13 \pm 0.07$	$0.26 \pm 0.11 \pm 0.05$
652	$3.03 \pm 0.84 \pm 1.30$	$0.08 \pm 0.07 \pm 0.01$	$0.14 \pm 0.05 \pm 0.03$
739	$1.27 \pm 0.48 \pm 0.58$	$0.12 \pm 0.07 \pm 0.02$	$0.09 \pm 0.04 \pm 0.02$
826	$0.23 \pm 0.16 \pm 0.14$	$0.05 \pm 0.05 \pm 0.01$	$0.05 \pm 0.03 \pm 0.01$
913	$0.14 \pm 0.14 \pm 0.09$	< 0.05	< 0.05

Table 3. The number of background events, from all sources, after final selection, together with the statistical and systematic uncertainty. For the entries where a single uncertainty is shown, the systematic uncertainty is negligible.

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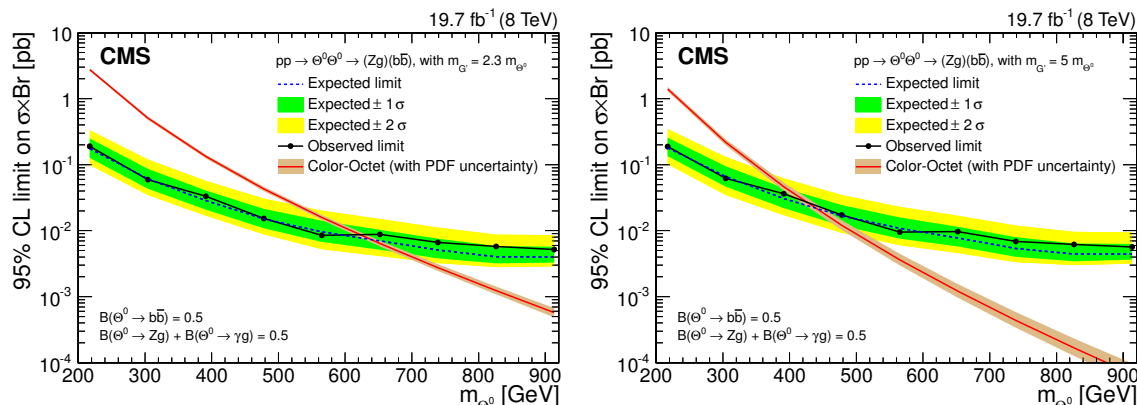


Figure 8. The 95% CL expected and observed upper limits on the cross section times branching fraction, $\sigma \times \mathcal{B}(\Theta^0 \rightarrow Zg) \times \mathcal{B}(Z \rightarrow \ell\ell) \times \mathcal{B}(\Theta^0 \rightarrow b\bar{b}) \times 2$, as a function of Θ^0 mass, for the case where $m_{G'} = 2.3m_{\Theta^0}$ (left) and $m_{G'} = 5m_{\Theta^0}$ (right) with the band on the color octet theoretical prediction indicating uncertainty in the signal yield due to PDF. These results assume $\mathcal{B}(\Theta^0 \rightarrow b\bar{b}) = 0.5$ and $\mathcal{B}(\Theta^0 \rightarrow Zg) + \mathcal{B}(\Theta^0 \rightarrow \gamma g) = 0.5$.

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The CMS collaboration**Yerevan Physics Institute, Yerevan, Armenia**

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè, A. Randleconde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni, F. Zhang³

Ghent University, Ghent, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi⁴, O. Bondu, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco⁵, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁶, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium

N. Belyi, T. Caebergs, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁷, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁷, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja, C.A. Bernardes^b, A. De Souza Santos, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^{a,8}, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁹, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

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

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, L. Sudic

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger¹⁰, M. Finger Jr.¹⁰

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt**

A. Ali^{11,12}, R. Aly¹³, S. Aly¹³, S. Elgammal¹², A. Ellithi Kamel¹⁴, A. Lotfy¹⁵,
M.A. Mahmoud¹⁵, R. Masod¹¹, A. Radi^{12,11}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén,
P. Luukka, T. Mäenpää, J. Pekkanen, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovi-
nen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro,
F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci,
M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau,
France**

S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms,
O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mas-
trotorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini,
S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Univer-
sité de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram¹⁶, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert,
N. Chanon, C. Collard, E. Conte¹⁶, J.-C. Fontaine¹⁶, D. Gelé, U. Goerlach, C. Goetzmann,
A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique
des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut
de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, N. Beaupere, C. Bernet⁹, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo
Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni,
J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito,
A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini,
M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov⁶

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁷, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁷, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁷, R. Mankel, I. Marfin¹⁷, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo², T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², U. Husemann, F. Kassel², I. Katkov⁶, A. Kornmayer², P. Lobelle Pardo,

M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók²¹, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, N. Nishu, J.B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²², R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²³, G. Kole, S. Kumar, B. Mahakud, M. Maity²²,

G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar²², K. Sudhakar, N. Sur, B. Sutar, N. Wickramage²⁴

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

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁵, A. Fahim²⁶, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana², A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, CSFNSM ^c, Catania, Italy

G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,c}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}, L. Viliani^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

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

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, R. Gerosa^{a,b}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, B. Marzocchi^{a,b,2}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{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, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}, C. Sciacca^{a,b}, F. Thyssen

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

P. Azzi^{a,2}, N. Bacchetta^a, D. Bisello^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b,2}, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, M. Sgaravatto^a, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, S. Ventura^a, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b,2}, G. Zumerle^{a,b}

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

A. Braghieri^a, M. Gabusi^{a,b}, A. Magnani^a, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^{a,28}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,28}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, L. Foà^{a,†}, A. Giassi^a, M.T. Grippo^{a,28}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,29}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,28}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b,2}, D. Del Re^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b}, P. Traczyk^{a,b,2}

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}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a, P.P. Trapani^{a,b}

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

S. Belforte^a, V. Candelise^{a,b,2}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a,
C. La Licata^{a,b}, M. Marone^{a,b}, A. Schizzi^{a,b}, T. Umer^{a,b}, A. Zanetti^a

Kangwon National University, Chunchon, Korea

S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

H. Kim, T.J. Kim, M.S. Ryu

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

S. Song

Korea University, Seoul, Korea

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee,
S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

H.D. Yoo

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

A. Juodagalvis, J. Vaitkus

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur,
Malaysia**

Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³⁰, F. Mohamad Idris, W.A.T. Wan
Abdullah

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³¹,
A. Hernandez-Almada, R. Lopez-Fernandez, G. Ramirez Sanchez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³², P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, T. Toriashvili³³, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁴, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁵, I. Dremin³⁵, M. Kirakosyan, A. Leonidov³⁵, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin³⁶, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³⁷, M. Ekmedzic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³⁸, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, T. du Pree, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot,

H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi³⁹, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁰, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres¹⁹, N. Wardle, H.K. Wöhri, A. Zagozdzińska⁴¹, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov⁴², M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴³, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng, R. Wilken

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, S. Cerci⁴⁴, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴⁵, A. Kayis Topaksu, G. Onengut⁴⁶, K. Ozdemir⁴⁷, S. Ozturk⁴⁸, B. Tali⁴⁴, H. Topakli⁴⁸, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan⁴⁹, B. Isildak⁵⁰, G. Karapinar⁵¹, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, TurkeyE.A. Albayrak⁵², E. Gülmez, M. Kaya⁵³, O. Kaya⁵⁴, T. Yetkin⁵⁵**Istanbul Technical University, Istanbul, Turkey**K. Cankocak, Y.O. Günaydin⁵⁶, F.I. Vardarli**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine**

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United KingdomR. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵⁷, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith**Rutherford Appleton Laboratory, Didcot, United Kingdom**K.W. Bell, A. Belyaev⁵⁸, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm**Imperial College, London, United Kingdom**M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁵⁷, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴², J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, P. Sharp[†], A. Tapper, K. Uchida, M. Vazquez Acosta⁵⁹, T. Virdee, S.C. Zenz**Brunel University, Uxbridge, United Kingdom**

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, U.S.A.

A. Borzou, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough

The University of Alabama, Tuscaloosa, U.S.A.

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, U.S.A.

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, U.S.A.

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

University of California, Davis, Davis, U.S.A.

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, U.S.A.

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, U.S.A.

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, H. Wei, S. Wimpenny

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁶⁰, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, U.S.A.

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, U.S.A.

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooperman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶¹, G. Mitselmakher, L. Muniz, D. Rank, L. Shchutska, M. Snowball, D. Sperka, S.J. Wang, J. Yelton

Florida International University, Miami, U.S.A.

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, U.S.A.

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, U.S.A.

B. Bilki⁶², W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶³, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵², A. Penzo, S. Sen⁶⁴, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

The University of Kansas, Lawrence, U.S.A.

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, U.S.A.

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, U.S.A.

D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, K. Pedro, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, U.S.A.

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. McGinn, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, U.S.A.

B. Dahmes, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, U.S.A.

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³², T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, U.S.A.

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Purdue University, West Lafayette, U.S.A.

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University Calumet, Hammond, U.S.A.

N. Parashar, J. Stupak

Rice University, Houston, U.S.A.

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, U.S.A.

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti, D. Vishnevskiy

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

L. Demortier

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, U.S.A.

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, U.S.A.

O. Bouhali⁶⁵, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶⁶, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer²

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderu, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, U.S.A.

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, U.S.A.

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, U.S.A.

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomer, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

7: Also at Universidade Estadual de Campinas, Campinas, Brazil

8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France

9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

10: Also at Joint Institute for Nuclear Research, Dubna, Russia

11: Also at Ain Shams University, Cairo, Egypt

12: Now at British University in Egypt, Cairo, Egypt

13: Now at Helwan University, Cairo, Egypt

14: Also at Cairo University, Cairo, Egypt

15: Now at Fayoum University, El-Fayoum, Egypt

16: Also at Université de Haute Alsace, Mulhouse, France

17: Also at Brandenburg University of Technology, Cottbus, Germany

18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

19: Also at Eötvös Loránd University, Budapest, Hungary

20: Also at University of Debrecen, Debrecen, Hungary

21: Also at Wigner Research Centre for Physics, Budapest, Hungary

22: Also at University of Visva-Bharati, Santiniketan, India

23: Now at King Abdulaziz University, Jeddah, Saudi Arabia

24: Also at University of Ruhuna, Matara, Sri Lanka

25: Also at Isfahan University of Technology, Isfahan, Iran

- 26: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at Purdue University, West Lafayette, U.S.A.
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at CONSEJO NACIONAL DE CIENCIA Y TECNOLOGIA, MEXICO, Mexico
- 32: Also at Institute for Nuclear Research, Moscow, Russia
- 33: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
- 34: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 35: Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 36: Also at California Institute of Technology, Pasadena, U.S.A.
- 37: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 38: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 39: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
- 40: Also at University of Athens, Athens, Greece
- 41: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 42: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 43: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 44: Also at Adiyaman University, Adiyaman, Turkey
- 45: Also at Mersin University, Mersin, Turkey
- 46: Also at Cag University, Mersin, Turkey
- 47: Also at Piri Reis University, Istanbul, Turkey
- 48: Also at Gaziosmanpasa University, Tokat, Turkey
- 49: Also at Anadolu University, Eskisehir, Turkey
- 50: Also at Ozyegin University, Istanbul, Turkey
- 51: Also at Izmir Institute of Technology, Izmir, Turkey
- 52: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 53: Also at Marmara University, Istanbul, Turkey
- 54: Also at Kafkas University, Kars, Turkey
- 55: Also at Yildiz Technical University, Istanbul, Turkey
- 56: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
- 57: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 58: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 59: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 60: Also at Utah Valley University, Orem, U.S.A.
- 61: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 62: Also at Argonne National Laboratory, Argonne, U.S.A.
- 63: Also at Erzincan University, Erzincan, Turkey
- 64: Also at Hacettepe University, Ankara, Turkey
- 65: Also at Texas A&M University at Qatar, Doha, Qatar
- 66: Also at Kyungpook National University, Daegu, Korea