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Author(s):

CMS Collaboration; Chatrchyan, Serguei; Bäni, Lukas; Bortignon, Pierluigi; Buchmann, Marco A.; Casal, Bruno; Chanon, Nicolas; Deisher, Amanda; Dissertori, Günther; Dittmar, Michael; Dünser, Marc; Eugster, Jürg; Freudenreich, Klaus; Grab, Christoph; Hits, Dmitry; Lecomte, Pierre; Lustermann, Werner; Marini, Andrea C.; Martinez Ruiz del Arbol, Pablo; Mohr, Dirk; Moortgat, Filip; Nägeli, Christoph; Nef, Pascal; Nessi-Tedaldi, Francesca; Pandolfi, Francesco; Pape, Luc; Paus, Felicitas; Peruzzi, Marco; Ronga, Frédéric J.; Rossini, Marco; Sala, Leonardo; Sanchez, Ann-Karin; Starodumov, Andrey; Stieger, Benjamin; Takahashi, Maiko; Tauscher, Ludwig; Thea, Alessandro; Theofilatos, Konstantinos; Treille, Daniel; Urscheler, Christina; Wallny, Rainer; Weber, Hannsjörg A.; Wehrli, Lukas; et al.

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Search for high-mass resonances decaying into τ -lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV[☆]

CMS Collaboration^{*}

CERN, Switzerland

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ABSTRACT

A search for high-mass resonances decaying into $\tau^+\tau^-$ is performed using a data sample of pp collisions at $\sqrt{s} = 7$ TeV. The data were collected with the CMS detector at the LHC and correspond to an integrated luminosity of 4.9 fb^{-1} . The number of observed events is in agreement with the standard model prediction. An upper limit on the product of the resonance cross section and branching fraction into τ -lepton pairs is calculated as a function of the resonance mass. Using the sequential standard model resonance Z'_{SSM} and the superstring-inspired E_6 model with resonance Z'_ψ as benchmarks, resonances with standard model couplings with masses below 1.4 and 1.1 TeV, respectively, are excluded at 95% confidence level.

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1. Introduction

The standard model (SM) of elementary particles [1–3] provides a successful framework that describes a vast range of particle processes involving weak, electromagnetic, and strong interactions. It is widely believed, however, that the SM is incomplete since, e.g., it fails to incorporate the gravitational force, has no dark matter candidate, and has too many parameters whose values cannot be deduced from the theory. Many models of physics beyond the SM have been proposed to address these problems. A simple way of extending the SM gauge structure is to include an additional $U(1)$ group, which requires an associated neutral gauge boson, usually labeled as Z' [4–7]. Although most studies have assumed generation-independent gauge couplings for Z' , models in which the Z' couples preferentially to third generation fermions have also been proposed [7–10]. The sensitivity of the traditional searches for Z' production using e^+e^- and $\mu^+\mu^-$ final states may be substantially reduced in such non-universal scenarios, motivating the exploration of other allowed final states. The sequential SM (SSM) includes a neutral gauge boson, Z'_{SSM} , with the same couplings to quarks and leptons as the SM Z boson. Although not gauge invariant, this model has been traditionally considered by experiments studying high-mass resonances. Other models, such as the superstring-inspired E_6 model, have more complex group structures, $E_6 \rightarrow SO(10) \times U(1)_\psi$, with a corresponding neutral gauge

boson denoted as Z'_ψ [11]. In this Letter we present a search for heavy resonances that decay into pairs of τ leptons using the Z'_{SSM} and Z'_ψ models as benchmarks. A previous search reported by the CDF Collaboration has ruled out a Z'_{SSM} decaying into $\tau^+\tau^-$ with SM couplings with mass below 399 GeV [12].

About one-third of the time τ leptons decay into lighter charged leptons plus neutrinos, whereas the other two-thirds of the time τ leptons decay into a hadronic system with one, three, or five charged mesons, which can be accompanied by neutral pions in addition to the τ neutrino. We refer to the leptonic and hadronic decay channels as τ_ℓ ($\ell = e, \mu$) and τ_h , respectively. Four $\tau^+\tau^-$ final states, $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$, are studied using a sample of proton–proton collisions at $\sqrt{s} = 7$ TeV recorded by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The data sample corresponds to an integrated luminosity of $4.94 \pm 0.11 \text{ fb}^{-1}$.

2. The CMS experiment

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the lead-tungstate (PbWO_4) crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

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^{*} E-mail address: cms-publication-committee-chair@cern.ch.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, ϕ , is measured in the x - y plane.

The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$; muons are measured within $|\eta| < 2.4$.

A more detailed description of the CMS detector can be found elsewhere [13].

3. Lepton reconstruction and identification

Electrons are reconstructed by combining clusters in the ECAL with tracks in the inner tracker fitted with a Gaussian sum filter algorithm [14]. Electron candidates are required to have good energy-momentum and spatial match between the ECAL cluster and the inner track. In addition, the ratio of the energies measured in HCAL and ECAL must be consistent with an electron signature.

Muons are reconstructed by matching hits found in the muon detectors to tracks in the inner tracker [15]. Quality requirements, based on the minimum number of hits in the silicon, pixel, and muon detectors, are applied to suppress backgrounds from punch-through and decay-in-flight pions. A requirement on the maximum transverse impact parameter with respect to the beamspot (2 mm) largely reduces the contamination from cosmic-ray muons.

A particle-flow (PF) technique [16] is used for the reconstruction of hadronically decaying τ candidates. In the PF approach, information from all subdetectors is combined to reconstruct and identify all final-state particles produced in the collision. The particles are classified as either charged hadrons, neutral hadrons, electrons, muons, or photons. These particles are used to reconstruct τ_h candidates using the hadron plus strip (HPS) algorithm [17], which is designed to optimize the performance of τ_h identification and reconstruction by considering specific τ -lepton decay modes.

4. Signal and background MC samples

Signal and background Monte Carlo (MC) samples are produced with the PYTHIA 6.4.22 [18] and MADGRAPH [19] generators using the Z2 tune [20] and the CTEQL1 parton distribution function (PDF) set [21]. The TAUOLA package [22] is used to decay the generated τ leptons. All generated objects are input into a detailed GEANT4 [23] simulation of the CMS detector.

The Z'_{SSM} and Z'_ψ signal samples are generated with seven different masses: 350, 500, 750, 1000, 1250, 1500, and 1750 GeV. Their corresponding cross sections are calculated to leading order.

The most important sources of background are the irreducible Drell-Yan process ($Z \rightarrow \tau^+\tau^-$), production of W bosons in association with one or more jets (W + jets), $t\bar{t}$, dibosons (WW, WZ), and QCD multijet production. Although the $Z \rightarrow \tau^+\tau^-$ background peaks around the Z mass, its tail extends to the region where a high-mass resonance might present itself. The W + jets events are characterized by an isolated lepton from the decay of the W boson and an uncorrelated jet misidentified as a light lepton or a τ_h . Background from $t\bar{t}$ events is usually accompanied by one or two b jets, in addition to genuine, isolated leptons or τ_h . Background from diboson events produces both genuine, isolated leptons, when the gauge bosons decay leptonically, and a misidentified τ_h when they decay hadronically. Finally, QCD events are characterized by non-collimated jets with a high-multiplicity of particles, which can be misidentified as charged light leptons and τ_h .

Table 1

Lepton p_T , η , and isolation requirements for each $\tau^+\tau^-$ final state.

Selection		$\tau_e \tau_\mu$	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$
τ_e	Min p_T (GeV)	15	20	–	–
	Max $ \eta $	2.1	2.1	–	–
	Iso ΔR	0.3	0.4	–	–
	Max TrkIso (GeV)	3.5	3.0	–	–
	Max EcallIso (GeV)	3.0	4.5	–	–
τ_μ	Min p_T (GeV)	20	–	20	–
	Max $ \eta $	2.1	–	2.1	–
	Iso ΔR	0.5	–	0.5	–
	Max TrkIso (GeV)	3.5	–	1.0	–
	Max EcallIso (GeV)	3.0	–	1.0	–
τ_h	Min p_T (GeV)	–	20	20	35
	Max $ \eta $	–	2.1	2.1	2.1
	Iso ΔR	–	0.5	0.5	0.5
	Iso definition	–	Medium	Medium	Loose

5. Event selection

A new heavy neutral gauge boson decaying into τ pairs is characterized by two high- p_T , oppositely charged, isolated, and almost back-to-back (in the transverse plane) τ candidates.

CMS uses a two-level trigger system consisting of the so-called level one (Level-1) and the high-level trigger (HLT). The events selected for this analysis are required to have at least two trigger objects: an electron and a muon, a τ_h candidate and a light charged lepton, or two τ_h candidates for the $\tau_e \tau_\mu$, $\tau_e \tau_h$, and $\tau_h \tau_h$ final states, respectively. Details of the electron and muon triggers can be found in Refs. [14,15]. The τ_h trigger algorithm requires the presence of jets reconstructed at Level-1 using a 3×3 combination of calorimeter trigger regions. Those jets are considered as seeds for the HLT where a simplified version of the PF algorithm is used to build the HLT τ_h candidate. The HLT τ_h four-momentum is reconstructed as a sum of the four-momenta of all particles in the jet with p_T above 0.5 GeV in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the direction of the leading particle.

The event selection requirements are optimized, for each individual final state, to maximize the sensitivity reach of the search. Events are required to have at least two τ candidates satisfying the p_T , η , and isolation requirements presented in Table 1. The isolation requirement is the strongest discriminator between genuine τ candidates and those from misidentified QCD jets. The leptonic τ candidates (τ_e , τ_μ) are required to pass both track and ECAL isolation requirements. Track isolation (TrkIso) is defined as the sum of the p_T of the tracks, as measured by the tracking system, within an isolation cone of radius ΔR centered around the charged light lepton track. Similarly, ECAL isolation (EcallIso) measures the amount of energy deposited in the ECAL within the isolation cone. In both cases the contribution from the charged light lepton candidate is removed from the sum. For τ_h candidates, the HPS algorithm provides three isolation definitions. The “loose” τ definition rejects a τ candidate if one or more charged hadrons with $p_T \geq 1.0$ GeV or one or more photons with transverse energy $E_T \geq 1.5$ GeV are found within the isolation cone. The “medium” and “tight” definitions require no charged hadrons or photons with p_T greater than 0.8 and 0.5 GeV within the isolation cone, respectively. Additionally, τ_h candidates are required to fail electron and muon requirements.

Pairs are formed from oppositely charged τ candidates with $\Delta R > 0.7$. In addition, a back-to-back requirement on the τ pairs is imposed by selecting candidates with $\cos \Delta\phi(\tau_1, \tau_2) < -0.95$, where $\Delta\phi(\tau_1, \tau_2)$ is the difference in the azimuthal angle between

Table 2
Signal selection efficiency for Z'_{SSM} decaying into $\tau_e \tau_\mu$, $\tau_e \tau_h$, $\tau_\mu \tau_h$, and $\tau_h \tau_h$ final states.

Z'_{SSM} mass (GeV)	$\tau_e \tau_\mu$	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$
350	0.142 ± 0.007	0.050 ± 0.004	0.08 ± 0.01	0.014 ± 0.001
500	0.199 ± 0.008	0.064 ± 0.005	0.13 ± 0.01	0.022 ± 0.001
750	0.257 ± 0.008	0.083 ± 0.007	0.15 ± 0.01	0.030 ± 0.001
1000	0.281 ± 0.009	0.087 ± 0.007	0.17 ± 0.01	0.034 ± 0.001

the τ candidates. The presence of neutrinos in the final state precludes a full reconstruction of the mass of the $\tau^+ \tau^-$ system. We use the visible τ -decay products and the missing transverse energy, E_T^{miss} , defined as the magnitude of the negative of the vector sum of the transverse momentum of all PF objects in the event [24], to reconstruct the effective visible mass:

$$M(\tau_1, \tau_2, E_T^{\text{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_T^{\text{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{E}_T^{\text{miss}})^2}. \quad (1)$$

When compared with the mass obtained by using only the visible decay products of the $\tau^+ \tau^-$ system, the effective mass provides better discrimination against backgrounds. The width and central value of the effective visible mass distribution, which is offset from the true resonance mass, depend on the true mass of the new resonance. The width-to-mass ratio of the effective mass distribution reconstructed using Eq. (1) varies from $\sim 25\%$ for a Z' with a generated mass of 350 GeV to $\sim 50\%$ for a Z' with generated mass of 1750 GeV.

Further selection requirements are applied to suppress background contributions. To discriminate against QCD jets, E_T^{miss} is required to be greater than 20 GeV for the $\tau_e \tau_\mu$ final state and greater than 30 GeV for the $\tau_e \tau_h$, $\tau_\mu \tau_h$, and $\tau_h \tau_h$ final states. Furthermore, we consider only one-prong τ_h candidates in the $\tau_h \tau_h$ final state.

To reduce the contamination from collisions in which W bosons are produced, events are required to be consistent with the signature of a particle decaying into two τ leptons. We define a unit vector ($\hat{\zeta}$) along the bisector defined by the p_T vector of the tau candidates, and two projection variables [25]:

$$p_\zeta^{\text{vis}} = \vec{p}_{\tau_1}^{\text{vis}} \cdot \hat{\zeta} + \vec{p}_{\tau_2}^{\text{vis}} \cdot \hat{\zeta}, \quad (2)$$

$$p_\zeta = p_\zeta^{\text{vis}} + \vec{E}_T^{\text{miss}} \cdot \hat{\zeta}. \quad (3)$$

We require that $(1.25 \times p_\zeta^{\text{vis}}) - p_\zeta < 10$ GeV for the $\tau_e \tau_\mu$ final state and $(0.875 \times p_\zeta^{\text{vis}}) - p_\zeta < 7$ GeV, for the $\tau_\mu \tau_h$, $\tau_e \tau_h$, and $\tau_h \tau_h$ final states. Hereafter, we will refer to the inequalities based on the p_ζ and p_ζ^{vis} variables as the p_ζ requirements.

Any remaining contribution from $t\bar{t}$ events is minimized by selecting events where none of the jets has been identified as a b jet. A jet is identified as a b jet if it has at least two tracks with impact parameter significance, defined as the ratio between the impact parameter and its estimated uncertainty, greater than 3.3 [26]. In order to further reduce the $t\bar{t}$ contribution in the $\tau_e \tau_\mu$ final state, an additional requirement is imposed on the difference in the azimuthal angle between the highest- p_T (leading) lepton (ℓ^{lead}) and the E_T^{miss} vector ($\cos \Delta\phi(\ell^{\text{lead}}, E_T^{\text{miss}}) < -0.6$).

Table 2 summarizes the signal selection efficiency after all requirements have been applied for various Z'_{SSM} masses. The uncertainties in the selection efficiencies are statistical only. The Z'_ψ model has comparable efficiencies.

6. Background estimation

The estimation of the background contributions in the signal region is derived from data wherever possible. The general strategy

is to modify the standard selection requirements to select samples enriched with background events. These control regions are used to measure the efficiencies for background candidates to pass the signal selection requirements. In cases where the above approach is not feasible, data-to-MC scale factors, defined as a ratio of efficiencies, are used to correct the expected contributions obtained from the simulation samples.

The number of QCD events in the signal region for the $\tau_h \tau_h$ and $\tau_\ell \tau_h$ final states is estimated from a sample of like-sign $\tau\tau$ candidates scaled by the opposite-sign to like-sign ratio ($R_{OS/LS}$) observed in the data. For the $\tau_h \tau_h$ final state, $R_{OS/LS}$ is measured for events with transverse mass $M_T(\tau_h^{\text{lead}}, E_T^{\text{miss}})$ between 15 and 90 GeV, where τ_h^{lead} is the highest- p_T τ_h candidate and

$M_T(\tau_h^{\text{lead}}, E_T^{\text{miss}}) = \sqrt{2p_{\tau_h^{\text{lead}}}^{\text{lead}} E_T^{\text{miss}} (1 - \cos \Delta\phi)}$. For the $\tau_\ell \tau_h$ final states $R_{OS/LS}$ is measured from a sample in which the muon TrkIso is between 4 and 15 GeV. For the $\tau_e \tau_\mu$ final state, the QCD background is estimated using a sample of non-isolated electrons and muons. The isolation efficiency, needed to extrapolate into the signal region, is measured from a sample of like-sign candidates.

An enhanced sample of W +jets events is obtained by removing the $\Delta\phi(\tau_1, \tau_2)$ and p_ζ requirements from the standard selections. Further enhancement of W events is obtained by requiring that the transverse mass of the lepton and E_T^{miss} system to be between 50 and 100 GeV. The number of W +jets events in the signal region is estimated from the number of events in the W +jets enhanced sample passing the $\Delta\phi(\tau_1, \tau_2)$ and p_ζ requirements divided by the efficiency of the transverse mass requirement measured from a sample of events passing the complement of both the $\Delta\phi(\tau_1, \tau_2)$ and p_ζ requirements.

A high-purity sample of $t\bar{t}$ events is obtained by requiring the presence of at least one reconstructed b jet with $p_T > 20$ GeV and removing the $\Delta\phi(\tau_1, \tau_2)$ and p_ζ requirements. The $t\bar{t}$ contribution in the signal region is estimated from the number of events with one or more b jets passing the $\Delta\phi(\tau_1, \tau_2)$ and p_ζ requirements multiplied by the ratio of events passing the zero b-jet requirement and those events with one or more b jets. This ratio is measured from a sample with at least two additional jets in the events, which is dominated by $t\bar{t}$ events.

Control samples dominated by $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ background events are obtained by removing the E_T^{miss} requirement and requiring the τ candidates to be compatible with charged light-lepton signatures. The number of events in each control sample is compared with the expected contributions as determined from the simulation and are found to be in agreement. Since the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ backgrounds are well described by the simulation, the estimated background contribution from these sources is taken directly from the number of simulated events passing the standard selection requirements normalized to the recorded integrated luminosity and the next-to-next-leading order cross-section value.

The contamination from diboson production is estimated directly from the number of simulated events that pass the analysis requirements normalized to the integrated luminosity with next-to-leading order (NLO) cross-section values.

Table 3

Number of observed events in data and estimated background events for the whole mass range. The first and second uncertainties are the statistical and systematic, respectively.

Process	$\tau_e \tau_\mu$	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$
$Z \rightarrow \tau^+ \tau^-$	$816 \pm 58 \pm 44$	$462 \pm 56 \pm 24$	$804 \pm 53 \pm 44$	$30.9 \pm 3.6 \pm 4.3$
$Z \rightarrow \mu^+ \mu^-$	–	–	$20.8 \pm 8.3 \pm 1.1$	–
$Z \rightarrow e^+ e^-$	–	$220 \pm 24 \pm 11$	–	$0.66 \pm 0.33 \pm 0.22$
W + jets	$83 \pm 15 \pm 7$	$181 \pm 36 \pm 13$	$459 \pm 26 \pm 29$	$5.8 \pm 1.7 \pm 1.1$
WW	$55.6 \pm 1.4 \pm 1.9$	–	$24.59 \pm 0.80 \pm 0.80$	–
WZ	$5.60 \pm 0.35 \pm 0.22$	–	–	–
$t\bar{t}$	$9.6 \pm 1.2 \pm 0.7$	$10.8 \pm 2.8 \pm 0.9$	$46.2 \pm 6.9 \pm 3.7$	$0.00^{+0.76+0.15}_{-0.00}$
QCD	$45.1 \pm 3.3 \pm 9.0$	$185 \pm 31 \pm 19$	$72 \pm 18 \pm 8$	$467 \pm 26 \pm 67$
Total	$1015 \pm 60 \pm 45$	$1058 \pm 77 \pm 35$	$1427 \pm 63 \pm 53$	$504 \pm 26 \pm 67$
Observed	1044	1043	1422	488

Table 4

Number of observed events in data and estimated background events obtained from the integration of the $M(\tau_1, \tau_2, E_T^{\text{miss}})$ distribution for masses above 300 GeV. The statistical and systematic uncertainties have been added in quadrature.

Process	$\tau_e \tau_\mu$	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$
$Z \rightarrow \tau^+ \tau^-$	2.76 ± 0.25	12.5 ± 1.7	18.0 ± 1.5	3.41 ± 0.62
$Z \rightarrow \mu^+ \mu^-$	–	–	3.0 ± 1.2	–
$Z \rightarrow e^+ e^-$	–	6.94 ± 0.83	–	–
W + jets	4.86 ± 0.97	0.23 ± 0.05	9.58 ± 0.81	1.83 ± 0.69
WW	8.53 ± 0.36	–	4.01 ± 0.18	–
WZ	1.34 ± 0.10	–	–	–
$t\bar{t}$	1.57 ± 0.23	0.93 ± 0.25	6.6 ± 1.1	–
QCD	–	0.13 ± 0.03	0.16 ± 0.04	18.0 ± 2.9
Total	19.1 ± 1.1	20.8 ± 1.9	41.3 ± 2.4	23.3 ± 3.0
Observed	20	10	32	13

Finally, high-purity samples of $Z \rightarrow \tau_\ell \tau_h$ events in which the data-to-MC scale factor can be evaluated are obtained by removing the E_T^{miss} selection and requiring that the τ_ℓ transverse momentum be less than 40 GeV. Contamination from W + jets events in these samples is reduced after requiring $M_T(\tau_\ell, E_T^{\text{miss}}) < 40$ GeV. For the $\tau_e \tau_\mu$ final state the data-to-MC scale factor is evaluated for $M(\tau_e, \tau_\mu, E_T^{\text{miss}}) < 150$ GeV.

Table 3 lists the number of estimated background events compared with the total number of observed events in data for each final state. The statistical and systematic uncertainties are quoted separately. Only the uncertainties on the cross section and background estimation methods are included in the systematic uncertainties. Other effects, such as the uncertainty of the luminosity measurement, are not included in Table 3. The $\tau^+ \tau^-$ effective visible mass distributions, $M(\tau_1, \tau_2, E_T^{\text{miss}})$, for all four final states are shown in Fig. 1. The largest background sources are from W + jet(s) and Drell–Yan production for $\tau_e \tau_\mu$ and $\tau_\ell \tau_h$ final states, and QCD processes for $\tau_h \tau_h$. We use the background shapes normalized to the values obtained from the background estimation methods to search for a broad enhancement in the $M(\tau_1, \tau_2, E_T^{\text{miss}})$ spectrum consistent with the production of a high-mass resonance state. The background shapes are taken from the MC simulation and parametrized to extrapolate to the high-mass regions. Table 4 lists the number of observed events in data and the estimated background contributions for events with $M(\tau_1, \tau_2, E_T^{\text{miss}}) > 300$ GeV.

7. Systematic uncertainties

The main source of systematic uncertainty results from the estimation of the background contributions that are dominated by the statistical uncertainty of the data used in the control regions. These uncertainties are in the range of 6 to 14%. The contamination from other backgrounds in these control regions has a negligible effect on the systematic uncertainty. The efficiencies for electron

and muon reconstruction and identification are measured with the “tag-and-probe” method [14,15] with a resulting uncertainty of 4.5% for electrons and up to 3% for muons. The hadronic τ trigger efficiency is measured from $Z \rightarrow \tau_\mu \tau_h$ events selected by single-muon triggers. This leads to a relative uncertainty of 4.0% and 6.4% per τ_h candidate for the $\tau_\ell \tau_h$ and $\tau_h \tau_h$ final states, respectively. Systematic effects associated with τ_h identification are extracted from a fit to the $Z \rightarrow \tau^+ \tau^-$ visible mass distribution, $M(\tau_1, \tau_2)$. The fit constrains the Z production cross section to the measured cross section in $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ decay channels, leading to a relative uncertainty of 6.8% per τ_h candidate [27]. The simulation is used to verify that τ_h identification efficiency remains constant as a function of p_T up to the high-mass signal region.

Uncertainties that contribute to the $M(\tau_1, \tau_2, E_T^{\text{miss}})$ shape variations include the τ_h (2%) and charged light-lepton (1%) energy scales, and the uncertainty on the E_T^{miss} scale, which is used for the $M(\tau_1, \tau_2, E_T^{\text{miss}})$ mass calculation. The E_T^{miss} scale uncertainties contribute via the jet energy scale (2–5% depending on η and p_T) and unclustered energy scale (10%), where unclustered energy is defined as the energy not associated with the reconstructed leptons and jets with $p_T > 10$ GeV. The unclustered energy scale uncertainty has a negligible systematic effect on the signal acceptance and $M(\tau_1, \tau_2, E_T^{\text{miss}})$ shape. In addition, the limited sizes of the simulated samples in the high-mass regions lead to systematic uncertainties in the background shape parametrization at high mass. The uncertainty on the probability for a light quark or gluon jet to be misidentified as a b jet (20%) also has a negligible effect on the signal acceptance and $M(\tau_1, \tau_2, E_T^{\text{miss}})$ mass shape.

The uncertainty on signal acceptance due to the PDF set included in the simulated samples is evaluated by comparing CTEQ6.6L, MRST2006, and NNPDF10 PDF sets [28–30] with the default PDF set. The systematic effect due to imprecise modeling of initial- and final-state radiation is determined by reweighting events to account for effects such as missing α terms in the soft-collinear approach [31] and missing NLO terms in the parton shower approach [32]. Finally, the uncertainty in the luminosity measurement is 2.2% [33]. Table 5 summarizes the sources of systematics considered.

8. Results

The observed mass spectra shown in Fig. 1 do not reveal any evidence for $Z' \rightarrow \tau^+ \tau^-$ production. A fit of the expected mass spectrum to the data based on the CL_s criterion [34,35] is used to calculate an upper limit on the product of the resonance cross section and its branching fraction into τ -lepton pairs at 95% CL as a function of the Z' mass for each $\tau^+ \tau^-$ final state taking into account all systematic uncertainties shown in Table 5. The final limits are obtained from the combination of all four final states.

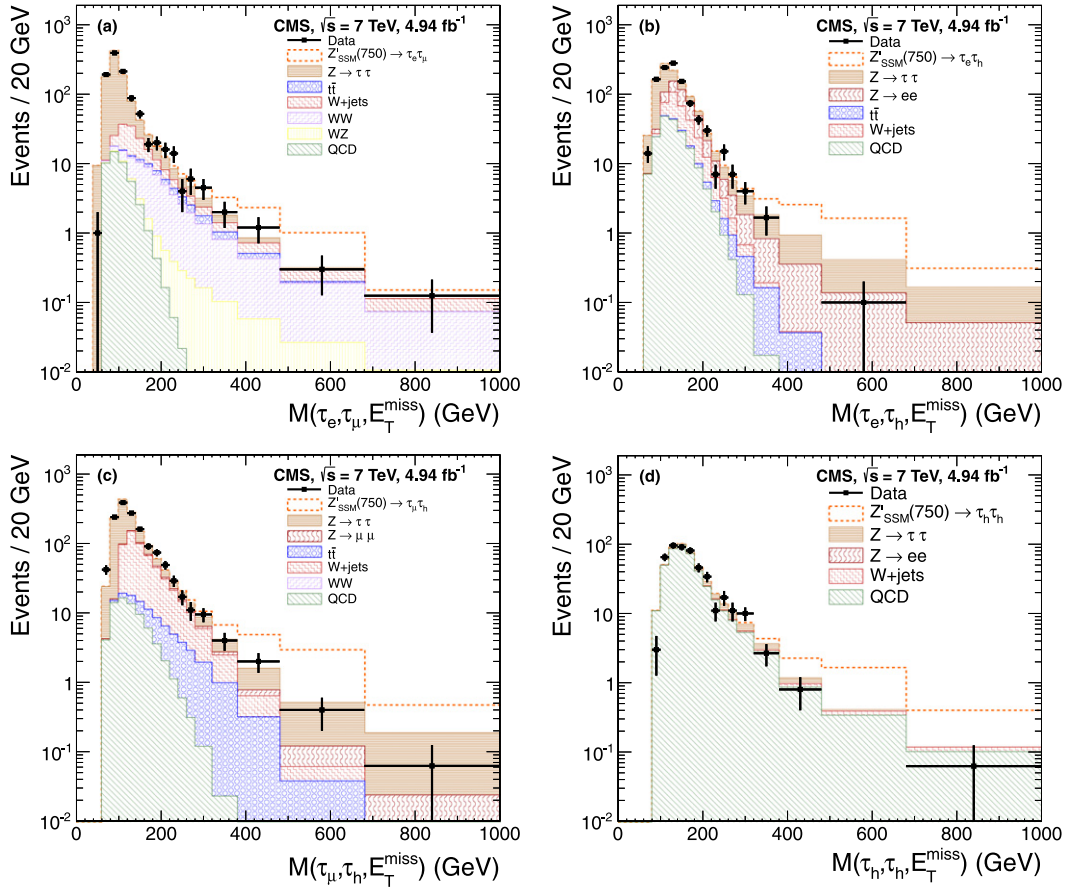


Fig. 1. $M(\tau_1, \tau_2, E_T^{\text{miss}})$ distributions for all four final states: (a) $\tau_e \tau_\mu$, (b) $\tau_e \tau_h$, (c) $\tau_\mu \tau_h$, and (d) $\tau_h \tau_h$. The dashed line represents the mass distribution for a $Z'_{\text{SSM}} \rightarrow \tau^+ \tau^-$ with a mass of 750 GeV.

Table 5
Summary of the sources of systematic uncertainties.

Source of systematic	$\tau_e \tau_\mu$	$\tau_e \tau_h$	$\tau_\mu \tau_h$	$\tau_h \tau_h$
Background estimation	7.4%	8.0%	5.8%	14.3%
Muon id	3.0%	–	1.1%	–
Electron id	4.5%	4.5%	–	–
Tau id	–	6.8%	6.8%	9.6%
Tau energy scale	–	2.1%	2.1%	3.0%
Tau trigger	–	4.0%	4.0%	9.0%
Jet energy scale			4.0%	
Luminosity			2.2%	
Parton distribution functions			4.0–6.5%	
Initial-state radiation			3.1%	
Final-state radiation			2.2%	

Fig. 2 shows the combined expected and observed limits as well as the theoretical cross section times the branching fraction to τ -lepton pairs for the SSM (Z'_{SSM}) and E_6 (Z'_ψ) models as functions of the Z' resonance mass. The bands on the expected limits represent the one and two standard deviations obtained using a large sample of pseudo-experiments based on the background-only hypothesis. The upper limit on $\sigma(\text{pp} \rightarrow Z') \times \text{Br}(Z' \rightarrow \tau^+ \tau^-)$ corresponds to the point where the observed limit crosses the theoretical line. We exclude a Z'_{SSM} with mass below 1.4 TeV and a Z'_ψ with mass less than 1.1 TeV. The $\tau_e \tau_h$ and $\tau_\mu \tau_h$ final states contribute the most to the limits. A downward fluctuation in the number of observed events with respect to the number of expected events leads to a limit that is about 1.5 standard deviations higher than expected in the region above 600 GeV.

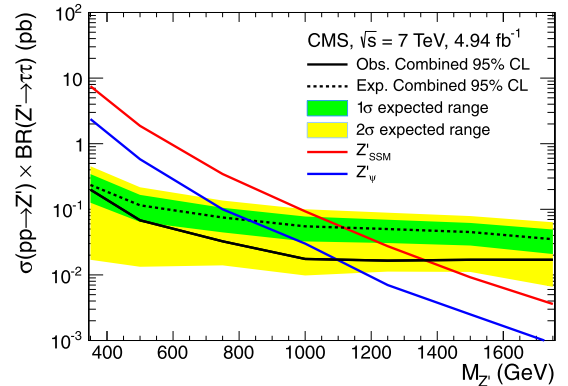


Fig. 2. Combined upper limit at the 95% CL on the product of the cross section and branching fraction into τ pairs as a function of the Z' mass. The bands represent the one and two standard deviations obtained from the background-only hypothesis.

9. Summary

A search for new heavy Z' bosons decaying into τ -lepton pairs using data corresponding to an integrated luminosity of $4.94 \pm 0.11 \text{ fb}^{-1}$ collected by the CMS detector in proton–proton collisions at $\sqrt{s} = 7 \text{ TeV}$ was performed. The observed mass spectrum did not reveal any evidence for $Z' \rightarrow \tau^+ \tau^-$ production, and an upper limit, as a function of the Z' mass, on the product of the resonance cross section and branching fraction into $\tau^+ \tau^-$ was calculated. The Z'_{SSM} and Z'_ψ resonances decaying to τ -lepton pairs were excluded for masses below 1.4 and 1.1 TeV, respectively, at

95% CL. These represent the most stringent limits on the production of a new heavy resonance decaying into τ -lepton pairs published to date.

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haeevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

O. Charaf, B. Clerboux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderren, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaître, J. Liao, O. Militaru, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

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

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

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

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

C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatrangkuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

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

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, M. Karim¹⁴, A.-C. Le Bihan, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

F. Fassi, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, H. Brun, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze¹⁵

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

M. Bontenackels, V. Cherepanov, M. Davids, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung⁵, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, H. Stadie, G. Steinbrück, J. Thomsen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹⁶, J.R. Komaragiri, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott,

G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas⁵, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu⁵, P. Hidas, D. Horvath¹⁸, K. Krajczar¹⁹, B. Radics, F. Sikler⁵, V. Veszpremi, G. Vesztergombi¹⁹

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karacsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

Panjab University, Chandigarh, India

S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi²², S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari²², M. Khakzad, A. Mohammadi²⁴, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁵, M. Zeinali²³

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

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c},
N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a,
B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b},
L. Silvestris^a, G. Singh^{a,b}, R. Venditti, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b},
P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b},
D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5},
A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b},
G. Siroli^{a,b}, R. Travaglini^{a,b}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

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

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a,
S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,5}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁶, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

A. Benaglia^{a,b,5}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a,
R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a,
S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,5}, N. Cavallo^{a,27}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,27},
A.O.M. Iorio^a, L. Lista^a, S. Meola^{a,28}, M. Merola^{a,b}, P. Paolucci^{a,5}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli "Federico II", Napoli, Italy

P. Azzi^a, N. Bacchetta^{a,5}, D. Bisello^{a,b}, A. Branca^{a,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a,
U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a,
I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,5}, J. Pazzini^a, L. Perrozzi^a,
N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b,5}, S. Vanini^{a,b},
A. Zucchetta^a, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento (Trento), Padova, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, A. Lucaroni ^{a,b,5}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Nappi ^{a,b}, F. Romeo ^{a,b}, A. Saha, A. Santocchia ^{a,b}, S. Taroni ^{a,b,5}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

P. Azzurri ^{a,c}, G. Bagliesi ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, R.T. D’Agnolo ^{a,c}, R. Dell’Orso ^a, F. Fiori ^{a,b,5}, L. Foà ^{a,c}, A. Giassi ^a, A. Kraan ^a, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,29}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, A.T. Serban ^{a,30}, P. Spagnolo ^a, P. Squillacioti ^{a,5}, R. Tenchini ^a, G. Tonelli ^{a,b,5}, A. Venturi ^{a,5}, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, D. Del Re ^{a,b,5}, M. Diemoz ^a, M. Grassi ^{a,b,5}, E. Longo ^{a,b}, P. Meridiani ^{a,5}, F. Micheli ^{a,b}, S. Nourbakhsh ^{a,b}, G. Organtini ^{a,b}, R. Paramatti ^a, S. Rahatlou ^{a,b}, M. Sigamani ^a, L. Soffi ^{a,b}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma “La Sapienza”, Roma, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, C. Biino ^a, C. Botta ^{a,b}, N. Cartiglia ^a, M. Costa ^{a,b}, N. Demaria ^a, A. Graziano ^{a,b}, C. Mariotti ^{a,5}, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, M. Musich ^{a,5}, M.M. Obertino ^{a,c}, N. Pastrone ^a, M. Pelliccioni ^a, A. Potenza ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, V. Sola ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a, A. Vilela Pereira ^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte ^a, V. Candelise ^{a,b}, F. Cossutti ^a, G. Della Ricca ^{a,b}, B. Gobbo ^a, M. Marone ^{a,b,5}, D. Montanino ^{a,b,5}, A. Penzo ^a, A. Schizzi ^{a,b}

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

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

H.Y. Jo

Konkuk University, Seoul, Republic of Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarquen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

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

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Soltan Institute for Nuclear Studies, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, M. Fernandes, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

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

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov⁵, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin

Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic³¹, M. Djordjevic, M. Ekmedzic, D. Krpic³¹, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez³²

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³³, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³⁴, T. Rommerskirchen, C. Rovelli³⁵, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist,

P. Silva, M. Simon, P. Sphicas^{36,*}, D. Spiga, M. Spiropulu⁴, M. Stoye, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁷, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁸

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Luster, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁹, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov⁴⁰, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci⁴¹, S. Cerci⁴², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴³, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴², B. Tali⁴², H. Topakli⁴¹, L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁶, S. Ozkorucuklu⁴⁷, N. Sonmez⁴⁸

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁷, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso⁴⁹, K.W. Bell, A. Belyaev⁴⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko⁴⁰, A. Papageorgiou, J. Pela⁵, M. Pesaresi, K. Petridis, M. Pioppi⁵⁰, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev, M. Weber

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵¹, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵², F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, L. Lueking, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵³, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, S. Hamdan, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

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

U. Akgun, E.A. Albayrak, B. Bilki⁵⁵, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemour, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Mississippi, University, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, P. Jindal, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

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, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, A. Richards, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

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

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁷, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, P.R. Duderer, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, D. Engh, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.

† Deceased.

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

² Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

³ Also at Universidade Federal do ABC, Santo Andre, Brazil.

⁴ Also at California Institute of Technology, Pasadena, USA.

⁵ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

⁶ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

⁷ Also at Suez Canal University, Suez, Egypt.

⁸ Also at Zewail City of Science and Technology, Zewail, Egypt.

⁹ Also at Cairo University, Cairo, Egypt.

¹⁰ Also at Fayoum University, El-Fayoum, Egypt.

¹¹ Also at Ain Shams University, Cairo, Egypt.

¹² Now at British University, Cairo, Egypt.

¹³ Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.

¹⁴ Also at Université de Haute-Alsace, Mulhouse, France.

¹⁵ Now at Joint Institute for Nuclear Research, Dubna, Russia.

¹⁶ Also at Moscow State University, Moscow, Russia.

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 Tata Institute of Fundamental Research – HECR, Mumbai, India.

²¹ Also at University of Visva-Bharati, Santiniketan, India.

²² Also at Sharif University of Technology, Tehran, Iran.

²³ Also at Isfahan University of Technology, Isfahan, Iran.

²⁴ Also at Shiraz University, Shiraz, Iran.

²⁵ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.

²⁶ Also at Facoltà Ingegneria Università di Roma, Roma, Italy.

²⁷ Also at Università della Basilicata, Potenza, Italy.

²⁸ Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

²⁹ Also at Università degli Studi di Siena, Siena, Italy.

³⁰ Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.

³¹ Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.

³² Also at University of Florida, Gainesville, USA.

³³ Also at University of California, Los Angeles, Los Angeles, USA.

³⁴ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

³⁵ Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy.

³⁶ Also at University of Athens, Athens, Greece.

- ³⁷ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ³⁸ Also at The University of Kansas, Lawrence, USA.
- ³⁹ Also at Paul Scherrer Institut, Villigen, Switzerland.
- ⁴⁰ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁴¹ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁴² Also at Adiyaman University, Adiyaman, Turkey.
- ⁴³ Also at The University of Iowa, Iowa City, USA.
- ⁴⁴ Also at Mersin University, Mersin, Turkey.
- ⁴⁵ Also at Ozyegin University, Istanbul, Turkey.
- ⁴⁶ Also at Kafkas University, Kars, Turkey.
- ⁴⁷ Also at Suleyman Demirel University, Isparta, Turkey.
- ⁴⁸ Also at Ege University, Izmir, Turkey.
- ⁴⁹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁵⁰ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
- ⁵¹ Also at University of Sydney, Sydney, Australia.
- ⁵² Also at Utah Valley University, Orem, USA.
- ⁵³ Also at Institute for Nuclear Research, Moscow, Russia.
- ⁵⁴ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁵⁵ Also at Argonne National Laboratory, Argonne, USA.
- ⁵⁶ Also at Erzincan University, Erzincan, Turkey.
- ⁵⁷ Also at Kyungpook National University, Daegu, Republic of Korea.