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Search for W' bosons decaying to a top and a bottom quark at $\sqrt{s} = 13$ TeV in the hadronic final state

The CMS Collaboration*

Abstract

A search is performed for W' bosons decaying to a top and a bottom quark in the all-hadronic final state, in proton-proton collisions at a center-of-mass energy of 13 TeV. The analyzed data were collected by the CMS experiment between 2016 and 2018 and correspond to an integrated luminosity of 137 fb^{-1} . Deep neural network algorithms are used to identify the jet initiated by the bottom quark and the jet containing the decay products of the top quark when the W boson from the top quark decays hadronically. No excess above the estimated standard model background is observed. Upper limits on the production cross sections of W' bosons decaying to a top and a bottom quark are set. Both left- and right-handed W' bosons with masses below 3.4 TeV are excluded at 95% confidence level, and the most stringent limits to date on W' bosons decaying to a top and a bottom quark in the all-hadronic final state are obtained.

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1 Introduction

The CERN LHC has strengthened the validity of the standard model (SM) of particle physics by providing a large volume of data to be compared with theoretical predictions. The existence of new physics beyond the SM, however, is needed in order to explain several observed phenomena, including the indications for the existence of dark matter, the origin of nonzero neutrino masses, and the baryon asymmetry of the universe. Also, an explanation of the fine tuning required for the insensitivity of the Higgs boson mass to quantum corrections in the SM is one of the important theoretical quests in particle physics. Extensions of the SM, conceived to overcome these limitations, include theories proposing a new spin-1 gauge boson W' , a color singlet with an electric charge of ± 1 . The W' boson appears, for example, in left-right symmetric models [1, 2], in models with extra spatial dimensions [3], and in little Higgs models [4]. Several of these models predict W' bosons having either right-handed or left-handed charged current interactions. In the latter case, interference with SM single top quark production can be present. A model-independent description of such processes can be found in [5]. Some theoretical models, for example [6–8], assume a preferential coupling of a W' boson to the third-generation fermions, which motivates the search for a W' boson decaying to a top and a bottom quark.

The first searches for a W' boson decaying to a top and a bottom quark were conducted by the CDF and D0 experiments at the Tevatron [9, 10] in proton-antiproton collisions, followed by those of the ATLAS and CMS experiments at the LHC using data from proton-proton (pp) collisions [11–16]. In the previous searches for W' bosons in all-hadronic decay modes, the CMS experiment excluded right-handed W' bosons with masses less than 2 TeV at 95% confidence level (CL) at $\sqrt{s} = 8$ TeV, using data corresponding to an integrated luminosity of 19.7 fb^{-1} [14]. The ATLAS experiment excluded right- (left-)handed W' bosons below 3.0 (2.9) TeV at $\sqrt{s} = 13$ TeV using data collected in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb^{-1} [15]. The search performed by the CMS experiment on a similar data set, considering only leptonic final states from the $t \rightarrow bW \rightarrow b\nu$ decay chain, excluded right- (left-)handed W' bosons of masses roughly below 3.6 (3.4) TeV at 95% CL [16].

In this letter, we search for a W' boson decaying to a top and a bottom quark in the all-hadronic final state, where the signature is an excess of events over a smoothly falling background in the invariant mass spectrum of top and bottom quark candidates (m_{tb}) in the range 1–4 TeV.

The main SM background processes from LHC pp collisions that can mimic the final state sought in this search are the production of multijet events due to quantum chromodynamics (QCD) interactions, the production of a top quark-antiquark pair ($t\bar{t}$), and the electroweak production of a single top quark associated with a bottom quark or a W boson. As none of the background processes involve a heavy resonance in the s channel, they result in smoothly falling m_{tb} spectra.

Most of the top quarks in decays of W' bosons with masses greater than 1 TeV have large transverse momentum (p_T), and their subsequent decay products are clustered into a single jet of particles. This requires the use of techniques based on jet substructure [17, 18] and machine learning [19] algorithms for the identification of the jets due to top quark decay (t tagging) that significantly reduce the background from multijet production in QCD in the case of an all-hadronic final state. The jets identified as coming from such highly Lorentz-boosted top quarks are referred to as t -tagged jets. This search makes use of the latest advancements in CMS in bottom-quark tagging [20] as well as top-quark tagging [21] involving a deep neural network (DNN). The study is based on data corresponding to an integrated luminosity of

137 fb^{-1} collected by the CMS experiment in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ from 2016 to 2018. Tabulated results are provided in HEPDATA [22].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and silicon strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass-and-scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage in pseudorapidity (η) provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. In 2017, an additional layer was added in both the barrel and endcap regions of the pixel detector and the number of silicon pixel modules increased to 1856. For nonisolated particles with $1 < p_{\text{T}} < 10 \text{ GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 μm and 25–75 μm in the transverse impact parameter in 2016 and 2017 onwards, respectively, whereas the resolution in the longitudinal impact parameter is 45–150 μm [24, 25].

Events of interest are selected using a two-tiered trigger system [26]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing that reduces the event rate to around 1 kHz before data storage.

3 Object reconstruction

The CMS particle-flow algorithm [27] aims to reconstruct and identify individual particles in an event with an optimized combination of information from the various elements of the CMS detector. The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp interaction vertex. The energy of photons is obtained from ECAL clusters that have no associated track. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track as determined using the tracker and the muon system. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy deposits.

For each event, hadronic jets are clustered from these reconstructed particles (particle-flow candidates) using the infrared- and collinear-safe anti- k_{T} algorithm [28] with distance parameters 0.4 (AK4 jets) and 0.8 (AK8 jets), as implemented in the FASTJET package [29]. The AK4 and AK8 jets are used to identify the bottom quark and the hadronically-decaying top quark, re-

spectively, from a W' boson decay. The distance between two particles in the η - ϕ plane, where ϕ is azimuthal angle in radians, is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the momentum of the particle-level jets reconstructed using stable particles (lifetime > 30 ps), excluding neutrinos, for $p_T > 50$ GeV and rapidity $|y| < 2.5$. Additional pp interactions within the same or nearby bunch crossings (pileup) can result in additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified as originating from pileup vertices are discarded before jet reconstruction. For AK4 jets, an offset correction [30] is applied to correct for remaining pileup contributions [31]. For AK8 jets, the pileup per particle identification (PUPPI) algorithm [32] is used to mitigate the effect of pileup at the reconstructed particle level. It has been shown that the PUPPI algorithm improves the resilience of jet substructure observables against pileup [33].

Additional selection criteria are applied to each jet to remove those potentially dominated by instrumental effects or reconstruction failures [34]. These criteria are the following: the fraction of the jet energy carried by neutral hadrons and photons should be less than 90%, the jet should have at least two constituents, and at least one of those should be a charged hadron. These requirements remove approximately 0.5% of jets selected for analysis, with negligible loss of genuine jets.

Jet energy corrections are derived from simulation so that the average measured energy of jets is the same as that of the corresponding particle-level jets. Measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale (JES) in data and simulation, and appropriate corrections are made [31]. Jet energy correction factors are derived using this methodology for both AK4 and AK8 jets. The jet energy resolution (JER) is obtained from a dijet balance technique [35]. To match the JER in data and simulation, an energy smearing is added to the AK4 and AK8 jets in simulation.

3.1 Identification of jets from bottom quarks

A DNN-based tagger, DEEPJET [20], is used for the b tagging of AK4 jets, utilizing information from the tracks, neutral particles, and the secondary vertices within the jet. This tagger also provides multiple outputs, such as whether the input jet is consistent with a jet initiated from one or more b quarks, one or more c quarks, light quarks, or gluons.

The thresholds used for the DEEPJET b tagger correspond to a mistag rate for jets initiated by light quarks or gluons at a $p_T > 500$ GeV of approximately 5% for data and simulated samples in 2016 and 1% in 2017 and 2018. This choice of threshold corresponds to an efficiency of approximately 75 (60)% at $p_T = 500$ GeV and 65 (50)% at $p_T = 1000$ GeV for jets initiated by b quarks in the barrel (endcap) region. To match the shape of the DEEPJET discriminator in data and simulation, corrections as a function of the p_T and η of AK4 jets, derived using samples enriched in dileptonic $t\bar{t}$ events for the b and c quark-initiated jets, and Z+jets events for the jets initiated by light quarks and gluons, are applied in simulation. The b tagging performance is better in 2017–2018 than in 2016 because of the addition in 2017 of new layers in the pixel detector of the CMS tracker close to the interaction point, in both the barrel and endcap regions.

3.2 Identification of jets from top quarks

The top quark arising from the decay of a heavy W' boson has a large Lorentz boost, and its decay products are expected to be captured within a jet with a large distance parameter. Hence AK8 jets are used to identify t-tagged jets. The key observables for the selection of AK8 jets

resulting from top quark decay are as follows:

- Groomed jet mass: grooming is a procedure for the removal of soft radiation clustered into the jet, which mitigates effects from initial- and final-state radiation, underlying event [36], and pileup interactions. Grooming results in a proportionally larger reduction in the mass of jets from light quarks or gluons with respect to genuine top quarks.
- Substructure of the jet: three dense clusters of energy are expected inside the jet, associated with the b quark and the hadronic decay of the W boson, whereas a jet originated from a light quark or gluon is generally characterized by a single cluster of energy.
- Displaced vertices: the presence of at least one displaced vertex is expected from the decays of b hadrons.

The soft drop algorithm, a generalization of the modified mass drop algorithm [37, 38], with angular exponent $\beta = 0$, soft cutoff threshold $z_{\text{cut}} = 0.1$, and characteristic radius $R_0 = 0.8$ [39] is used to groom the AK8 jets, and the corresponding groomed mass, known as the soft-drop mass (m_{SD}), is required to be within a window of 105–210 GeV for a jet to be t-tagged. In this algorithm, the constituents of the AK8 jets are reclustered using the Cambridge–Aachen algorithm [40, 41] and the relative p_T between the successive clusters of particles merged during the jet clustering is checked to remove soft, wide-angle particles from the jet.

The latter two of the features mentioned above are incorporated in a DNN designed to identify a jet arising from top quark decay. The DNN based t tagging algorithm exploited in this study, henceforth referred to as the DEEPAK8 tagger, has been studied extensively in CMS [21]. This algorithm uses up to a hundred particles (selected in descending order of p_T) in an AK8 jet, incorporating six kinematic variables (p_T , η , ϕ , ΔR from the jet axis, ΔR from the axes of two soft-drop subjets) for each of the particles and also exploits the features of the tracks (quality, displacement, etc.), and properties of secondary vertices associated with the jet. A relative score is assigned to the jet by the DEEPAK8 tagger specifying how likely the jet is to have originated from the decay products of a top quark rather than from a light quark or gluon. A recursive neural network based approach is used to decorrelate the tagger performance from the jet mass.

The threshold used on the DEEPAK8 tagger score corresponds to a rate of incorrectly tagging jets originated from light quarks or gluons, called mistag rate of 0.5%. This choice of threshold corresponds to an efficiency of approximately 35–45%, in the phase space of this analysis, to identify the jets initiated by top quarks. The efficiency of the DEEPAK8 tagger is measured in single-muon events enriched with semileptonic $t\bar{t}$ production, and increases with jet p_T . Corrections based on the p_T of AK8 jets are applied in simulation to match the efficiency of the t tagging algorithm in data [21].

4 Data and simulated samples

The data used in this search are from pp collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment from 2016 to 2018, corresponding to an integrated luminosity of 137 fb^{-1} .

Monte Carlo simulations are used to model the W' boson signal and the background sources relevant to this analysis. Background estimates for $t\bar{t}$ events are taken primarily from simulation, but also include a correction derived from data. Background estimates for multijet production are taken entirely from data; simulated multijet samples are used for cross-checks. The smallest background considered is from single top quark events, and it is estimated purely

from the simulation.

The signal samples are generated at leading order (LO) using the COMPHEP v4.5.2 generator [42]. Signal samples are generated separately for left- and right-handed W' bosons with masses between 1–4 TeV in steps of 100 GeV. The width of the W' boson in all of the generated samples is $\sim 3\%$ [5]. The cross sections of the signal samples are scaled to next-to-leading-order (NLO) accuracy using a K factor of 1.25 [43, 44]. The value of the Λ_{QCD} parameter is taken to be 165.2 MeV in the signal samples.

The POWHEG 2.0 generator [45–47] is used to generate $t\bar{t}$ events at NLO in perturbative QCD [48]. For the normalization of the $t\bar{t}$ sample, the production cross section calculated at next-to-next-to-leading order (NNLO) with the resummation of soft gluons at next-to-next-to-leading logarithmic precision [49] is used. Event generation for the production of a single top quark in the t channel [50] and in association with a W boson [51], is performed with the POWHEG 2.0 generator as well. The sample of events with a single top quark produced in association with a W boson [51] is normalized to the NNLO cross section [52]. Events with the production of a single top quark in the s channel are generated at NLO using MADGRAPH5_aMC@NLO [53], where version 2.2.2 is used for 2016 and version 2.4.2 is used for the 2017 and 2018 data-taking eras, and top quark decays are simulated with MADSPIN [54]. The QCD multijet events are produced with the MADGRAPH5_aMC@NLO generator at LO with up to four outgoing partons in the final state.

Simulated $t\bar{t}$ and single top quark samples in 2016 make use of NNPDF3.0 [55] NNLO parton distribution functions (PDFs), with the strong coupling constant $\alpha_s(M_Z)$ set to 0.118, to describe the momentum distribution of partons inside the colliding protons. The NNPDF3.0 LO PDFs are used in producing simulated multijet samples in 2016. The NNPDF3.1 [56] NNLO PDFs are used to simulate $t\bar{t}$, single top quark, and multijet samples in 2017 and 2018. Simulated signal samples use the CTEQ6L1 [57] LO PDF set.

Generated partons undergo parton showering and hadronization using PYTHIA v8.212 [58]. For the simulated multijet sample, the matching of PYTHIA to MADGRAPH5_aMC@NLO is performed in the MLM [53] schemes. In the case of the samples with $t\bar{t}$ and single top quark production, POWHEG and MADGRAPH5_aMC@NLO are matched to PYTHIA using the FxFx [59] scheme. The underlying event activity in each sample, except for the QCD multijet and W' boson signals in the 2016 era, is simulated using the CP5 tune, which is derived by tuning the model parameters for multiple parton interactions in PYTHIA using minimum bias data collected by the CMS experiment [60]. For the simulated QCD multijet events and W' boson signals in the 2016 era, the underlying event tune is CUETP8M1 [61]. For all samples, in order to match the pileup conditions in data and simulation, a weighting is performed in simulation based on the value of the total inelastic cross section, which is taken to be 69.2 mb [62]. The generated samples are processed through the CMS detector simulation based on GEANT4 [63], using the same reconstruction algorithms as data.

5 Event selection

The trigger criteria chosen in this analysis exploit the large amount of hadronic activity expected in signal events. At L1, a combination of several criteria consisting of requirements on the p_T of AK4 jets or H_T , defined as the scalar p_T sum of all of the AK4 jets in the event with $p_T > 30$ GeV and $|\eta| < 3.0$, is applied to select the events. In the HLT, a set of trigger conditions is applied, selecting events that meet at least one of the following requirements:

- there is at least one AK4 or AK8 jet above a p_T threshold of 450 (500) GeV for the data-taking period 2016 (2017 and 2018);
- there is at least one AK8 jet that has a p_T greater than 360 or 420 GeV in the data-taking periods of 2016 or 2017 and onwards, respectively, and a groomed mass of at least 30 GeV, where a trimming [64] algorithm is used for jet grooming;
- H_T is greater than a threshold that varied between 800 and 1050 GeV depending on the data-taking period and instantaneous luminosity;
- the scalar p_T sum of all of the AK8 jets with $p_T > 150$ (200) GeV and $|\eta| < 2.5$ is greater than 700 (900) GeV in 2016 (2017 and 2018), and at least one of the AK8 jets has a groomed mass of at least 50 GeV.

Events with at least one isolated electron or muon with $p_T > 30$ GeV are rejected, where the condition for electron and muon identification corresponds to approximately 90 and 95% efficiency for a genuine electron or muon, respectively. Events with at least one AK8 and one AK4 jet, both with $p_T > 550$ GeV and $|\eta| < 2.4$, where the AK8 and AK4 jets are separated by $\Delta R \geq 1.2$, are considered for the analysis. The AK8 jet with the highest t tagging score is taken as the top quark candidate jet. As the top quark and bottom quark from W' boson decays are expected to be produced in a back-to-back topology, the AK4 jet with the highest p_T which satisfies $\Delta\phi > \pi/2$ with respect to the top quark candidate jet is taken to be the bottom quark candidate jet. If an AK8 jet is present within $\Delta R < 0.4$ of the b quark candidate jet, it is referred to as the AK8 jet associated with the b quark candidate jet. The p_T thresholds of the top quark and bottom quark candidate jets are chosen such that the triggers used are more than 99% efficient for the selected events. The efficiency of the triggers has been measured in data and simulation with respect to a reference trigger, which requires the event to have at least one muon, and differences between the two are found to be within 0.1% in the phase space of selected events. Therefore, no correction is applied to the simulated samples.

A further selection criterion is applied to reduce the contamination from the $t\bar{t}$ background. After the top and bottom quark candidate jets are selected, if the AK8 jet associated with the bottom quark candidate exists and it has m_{SD} greater than 60 GeV, the event is discarded. This requirement is imposed to reject bottom quark jets from the hadronic decay chain of top quarks.

6 Event categorization and background estimation

After applying the event selection described in Section 5, events are further divided into regions, depending on whether the top or bottom quark candidate jets pass or fail the tagging requirements, for the estimation of multijet background. The following naming convention is used for the phase space division:

- t: top quark candidate AK8 jet;
- b: bottom quark candidate AK4 jet;
- t tagging pass or fail: t passes or fails the threshold on the t tagging score;
- b tagging pass or fail: b passes or fails the threshold on the b tagging score.

The signal region SR is defined by requiring the top quark candidate jet to pass both the m_{SD} and the t tagging score requirement and the bottom quark candidate jet to pass the threshold on the b tagging score. The control region SR' is defined with the same conditions on the top quark candidate jet as in the SR, but the bottom quark candidate jet is required to fail the requirement on the b tagging score. The control regions CR1 and CR1' are similar to the regions SR and SR',

respectively, apart from the m_{SD} requirement on the top quark candidate jet, which is changed as indicated in Table 1. The validation region VR and other control regions VR', CR2 and CR2' are defined by the same criteria used to build SR, SR', CR1, and CR1', respectively, and differ only in the t tagging condition. An overview of the regions used in the analysis is given in Table 1.

Table 1: Regions of parameter space used in the analysis. The m_{SD} and t tagging refer to the soft drop mass and the DEEPAK8 t-tagger score requirements of the top quark candidate AK8 jet. The b tagging refers to the DEEPJET b-tagger score requirement of the bottom quark candidate AK4 jet.

Region	m_{SD}	t tagging	b tagging	Purpose
SR	$\in [105, 210]$ GeV	pass	pass	Signal extraction
SR'	$\in [105, 210]$ GeV	pass	fail	Multijet bkg. estimation in SR
VR	$\in [105, 210]$ GeV	fail	pass	Validation of bkg. estimation
VR'	$\in [105, 210]$ GeV	fail	fail	Multijet bkg. estimation in VR
CR1	< 105 GeV	pass	pass	Extrapolation of multijet bkg.
CR1'	< 105 GeV	pass	fail	from SR' to SR
CR2	< 105 GeV	fail	pass	Extrapolation of multijet bkg.
CR2'	< 105 GeV	fail	fail	from VR' to VR

The criteria on m_{SD} and t tagging score of the top quark candidate jet and b tagging score of the bottom quark candidate jet are chosen to achieve maximum sensitivity to a W' boson signal in the SR, where the multijet background constitutes 85–90% of the total background, whereas $t\bar{t}$ and single top quark production contribute 5–8 and 2–5%, respectively. For a right-handed W' boson of mass 2 TeV, the signal selection efficiency, defined as the fraction of the simulated events with the production of a W' boson decaying into a top and a bottom quark in the all-hadronic final state falling within the SR, is approximately 8% in 2016 and 9% in 2017 and 2018. The efficiency for selecting the signal events with a right-handed W' boson of mass 4 TeV is about 5% in all years. For left-handed W' bosons, the signal selection efficiency is approximately 5% for a 2 TeV resonance mass and decreases to 0.1% for a 4 TeV resonance mass. The large difference between the signal selection efficiency for left-handed and right-handed W' bosons, especially for high resonance masses, is due to the interference with single top quark production in the case of left-handed W' bosons, which results in a larger number of events at low energy that tend to fall outside the acceptance of the SR.

The control regions CR1 and CR1' are used to derive the b tagging pass-to-fail ratio ($R_{\text{p}/\text{f}}$) of the b quark candidate jet. The ratio $R_{\text{p}/\text{f}}$ obtained from CR1 and CR1', and the event yield in the control region SR' are used to estimate the multijet background in the SR. The technique used to estimate the multijet background is cross-checked in the VR, where the multijet background is computed using the regions CR2, CR2', and VR'. The parton flavor composition of the b quark candidate jet has been studied using simulated samples and has been found to be comparable between the SR and the CR1 used to derive $R_{\text{p}/\text{f}}$. The same comparability has been verified for VR and CR2.

The ratios $R_{\text{p}/\text{f}}$ are obtained by dividing the m_{tb} spectrum obtained in CR1 by that from CR1',

and similarly the m_{tb} spectrum in CR2 by that in CR2', as shown in Eq. (1):

$$\begin{aligned} R_{\text{p/f}}^1(m_{\text{tb}}) &= \frac{\text{CR1}}{\text{CR1}'}, \\ R_{\text{p/f}}^2(m_{\text{tb}}) &= \frac{\text{CR2}}{\text{CR2}'}. \end{aligned} \quad (1)$$

The ratios $R_{\text{p/f}}^1$ and $R_{\text{p/f}}^2$, obtained as functions of m_{tb} , are parameterized using a second-order polynomial. The ratios $R_{\text{p/f}}$ are also fitted with a bifurcating function, defined in Eq. (2), to estimate the systematic uncertainty associated with the choice of the parameterization.

$$f_{\text{p/f}}(m_{\text{tb}}) = \begin{cases} a_1 + a_2 (m_{\text{tb}} - a_0) + a_3 (m_{\text{tb}} - a_0)^2, & m_{\text{tb}} < a_0 \\ a_1 + a_2 (m_{\text{tb}} - a_0) + a_4 (m_{\text{tb}} - a_0)^2, & m_{\text{tb}} \geq a_0 \end{cases}. \quad (2)$$

The bifurcating function has five parameters: $a_{0,1,2,3,4}$.

The values of $R_{\text{p/f}}$ are measured in three regions defined by the η of the b quark candidate jet: $|\eta| < 0.5$, $0.5 \leq |\eta| < 1.4$, $1.4 \leq |\eta| < 2.4$, and are multiplied by the event yield in the regions SR' and VR' to obtain the multijet background in the SR and VR, respectively. This is expressed in Eq. (3), where $f_{\text{p/f}}^1$ and $f_{\text{p/f}}^2$ represent the fitted functions for $R_{\text{p/f}}^1$ and $R_{\text{p/f}}^2$ respectively.

$$\begin{aligned} \text{Multijet background in SR} &= f_{\text{p/f}}^1(m_{\text{tb}}) \text{SR}' \\ \text{Multijet background in VR} &= f_{\text{p/f}}^2(m_{\text{tb}}) \text{VR}' \end{aligned} \quad (3)$$

The value of $f_{\text{p/f}}^1$ varies from 10 to 15% in 2016 and 2 to 6% from 2017 onwards, and the value of $f_{\text{p/f}}^2$ ranges from 3 to 12% in 2016 and 1 to 2% from 2017 onwards. Simulated $t\bar{t}$ and single top quark backgrounds are subtracted from the data to calculate the yields in all regions.

In both data and simulation, it is observed that for AK4 jets that pass the threshold on the b tagging discriminator, the associated AK8 jets have a different shape for the m_{SD} distribution compared to the case where AK4 jets fail the b tagging condition. This can affect the multijet m_{tb} spectrum extrapolated from the regions SR' and VR', leading to discrepancies with the SR and VR, respectively. To take this effect into account, multiplicative corrections are applied to Eq. (3). For the estimate of the multijet background in the SR, the correction is derived using the ratio of m_{SD} spectra of the AK8 jets associated with the b quark candidate in CR1 and CR1', and for the background in the VR it is obtained from CR2 and CR2'.

The multijet background estimation procedure is first performed on a simulated QCD multijet sample, and the estimated m_{tb} distribution is obtained in the regions SR, VR, CR1, and CR2. The difference between the extrapolated and predicted m_{tb} spectra in simulation is taken as a systematic uncertainty.

A closure test is performed in the VR by comparing the estimated multijet m_{tb} spectrum to that observed in data, after subtracting simulated $t\bar{t}$ and single top quark backgrounds. The same test is performed in CR1 and CR2. The predicted and observed distributions agree within 1–2% in all cases.

To check the consistency of the simulated $t\bar{t}$ background with data, a control region is selected that satisfies all of the criteria in the SR, but requires that the AK8 jet associated with the b quark candidate jet has m_{SD} in the [105, 210] GeV window and passes the threshold on the DEEPAK8 tagger score. This region is orthogonal to all of the regions specified in Table 1 and is enriched

in $t\bar{t}$ events where both the top quarks decay hadronically, which constitute approximately 80% of the events in this region. The ratio between the m_{tb} spectra in data and simulation is fitted with a first-order polynomial to derive a correction that is applied to the simulated $t\bar{t}$ background. The statistical uncertainties in the linear-fit parameters are used to derive the systematic uncertainty in this data-based correction applied to the simulated $t\bar{t}$ background.

7 Systematic uncertainties

We consider several sources of systematic uncertainty that cover experimental effects, uncertainties due to the extraction of the multijet background, and uncertainties in the predicted $t\bar{t}$ and single top quark backgrounds. These sources and their sizes in the SR are as follows:

- *Fit to $R_{p/f}$* : The impact of the uncertainty in $R_{p/f}$ on the estimated multijet background is computed using the covariance matrix of the fit parameters, and ranges from 2 to 8%.
- *Choice of function describing $R_{p/f}$* : The difference between the multijet background estimated using the default second-order polynomial and that obtained with the bifurcating function is less than 1%. The value of this difference is taken to be the associated uncertainty.
- *Closure*: The uncertainty is taken to be the difference between the estimated multijet background obtained by using $R_{p/f}$ in simulation and the predicted yield in simulation. It ranges from 4 to 8%.
- *b quark candidate m_{SD} correction*: The uncertainty is taken to be half of the difference between the estimated multijet background with and without applying the kinematic correction based on the m_{SD} of the AK8 jet associated with the b quark candidate jet. It is up to 6% in magnitude.
- *JES*: The uncertainty applies to both AK4 and AK8 jets, and affects all of the backgrounds and the W' boson signal. It is taken to be fully correlated between AK4 and AK8 jets, and has a value rising to 5% at high m_{tb} .
- *JER*: The uncertainty is taken into account both for simulation-based backgrounds and signal. It is taken to be fully correlated between AK4 and AK8 jets, and has a value ranging up to 8%.
- *b tagging scale factor*: The uncertainty in the correction applied in simulation to match the shape of the DEEPJET discriminator in data and simulation has a value of up to 30%.
- *t tagging scale factor*: The uncertainty in the correction applied in the simulation to match the efficiency of the DEEPAK8 discriminator in data and simulation has a value of 4%.
- *Trigger timing correction*: During the 2016 and 2017 data taking, a gradual shift in the timing of the inputs of the ECAL hardware level trigger in the region of $|\eta| > 2.0$ caused a specific trigger inefficiency. To take this effect into account, correction factors are computed from data and applied to the simulated samples corresponding to the 2016 and 2017 data taking periods. The uncertainty in this correction is less than 5% over the entire m_{tb} range.
- *Pileup*: The value of the pp total inelastic cross section that is used in the simulation of pileup events is varied upwards and downwards from its assumed value of 69.2 mb by its uncertainty of 4.6% [62]. The difference in yields is taken as the pileup

uncertainty, and is less than 5%.

- *Scale*: The impact of missing higher-order terms in perturbative QCD is evaluated by changing the renormalization (μ_R) and factorization (μ_F) scales in simulation. A six-point scheme is used, where yields are obtained in simulation by scaling the pairs (μ_R, μ_F) by the following combinations: (1, 0.5), (0.5, 1), (1, 2), (2, 1), (0.5, 0.5), and (2, 2). The envelope of the variations as compared to the nominal choice of $(\mu_R, \mu_F) = (1, 1)$ is taken as the scale uncertainty. This reaches up to 20% for $t\bar{t}$ and single top quark backgrounds.
- *PDF*: The parameters that characterize the PDFs are determined from different experiments by fitting the theory prediction to the experimental data. Thus the PDF parameters are affected by the uncertainties from the experimental measurements, modeling, and parameterization assumptions. In this analysis, simulated $t\bar{t}$ and single top quark backgrounds are obtained for each of one hundred replicas of the NNPDF3.1 NNLO PDF set, and the PDF uncertainty is determined from the standard deviation of the yields in each bin of the $m_{t\bar{b}}$ distribution for the $t\bar{t}$ and single top backgrounds. For the W' boson signal sample, the PDF uncertainty is determined using forty-five eigenvectors of the Hessian matrix [65]. The PDF uncertainty size is within 5% for $t\bar{t}$ and single top quark backgrounds and increases up to 20% for a W' boson signal of high mass.
- *$t\bar{t}$ normalization and slope*: The uncertainties in the linear fit parameters used to describe the data-based correction for the $t\bar{t}$ background range from 5% at low- $m_{t\bar{b}}$ to 25% at high- $m_{t\bar{b}}$.
- *Integrated luminosity*: The individual integrated luminosities of the 2016, 2017, and 2018 data-taking periods have uncertainties in the range 2.3–2.5% [66–68]. The total Run 2 (2016–2018) integrated luminosity has an uncertainty of 1.8%, where the improvement in precision reflects the (uncorrelated) time evolution of various systematic effects.
- *$t\bar{t}$ cross section*: This results in an uncertainty of 3.9% [69] in the normalization of the $t\bar{t}$ background.
- *Single top quark cross section*: There is an uncertainty of 12.8% in the single top quark production cross section, averaged between the production in the t channel [70] and production in association with a W boson [71]. This results in a corresponding uncertainty in the normalization of the single top quark background.

Since the multijet background is dominant, the uncertainties in $R_{p/f}$ and in JES are the dominant sources of systematic uncertainty.

Systematic uncertainties corresponding to the $t\bar{t}$ cross section, single top quark cross section, scale, and PDF are taken to be fully correlated, and the uncertainty in the integrated luminosity is taken to be partially correlated between different years of data taking. All other systematic uncertainties are taken to be uncorrelated between the three data-taking eras.

8 Results

The signal and expected background $m_{t\bar{b}}$ distributions are compared with data, and a binned maximum-likelihood fit based on Poisson statistics is applied to measure the W' boson yield. Each source of systematic uncertainty is treated as a nuisance parameter [72]. The nuisance parameters corresponding to the systematic uncertainties that affect only the normalization

of the backgrounds and the signal are assumed to follow log-normal distributions, and those that affect the normalization as well as the shape are described by Gaussian distributions. The expected number, N_{expected} , of W' boson signal events in an m_{tb} bin is given by

$$N_{\text{expected}} = \sigma_{W'} \mathcal{B} \mathcal{L} \epsilon \mathcal{A}, \quad (4)$$

where $\sigma_{W'}$ is the production cross section of the W' boson, \mathcal{B} is the branching fraction of a W' boson decaying to a top and a bottom quark, followed by the hadronic decay of the W boson in the top quark decay chain, \mathcal{L} denotes the integrated luminosity of the data used, and ϵ and \mathcal{A} are the signal detection efficiency and the geometric and kinematic acceptance, respectively.

The expected numbers of events from different background and signal hypotheses and the observed yields in data, after the binned maximum-likelihood fit is performed are shown in Fig. 1 in the VR and SR for the three years of data taking. The agreement within the statistical and systematic uncertainties between the predicted SM background and the observed data in the VR validates the background estimation.

No significant excess is observed over the SM background in the SR. Upper limits on $\sigma_{W'} \mathcal{B}(W' \rightarrow \text{tb})$ at 95% CL are obtained using the asymptotic CL_s method [73, 74] with an asymptotic approximation [75] of the profile likelihood.

Upper limits at 95% CL on the production cross sections times the branching fraction to a top and a bottom quark of right- and left-handed W' bosons including the effects of interference with the SM are calculated after merging the data and backgrounds of all three years and are shown in Fig. 2. There is a difference in the angular distributions of the top quark decay products depending on the chirality of the parent W' boson, which leads to a difference in t tagging efficiency. The theoretical cross section for the production of left-handed W' bosons saturates at high mass because of the interference with single top quark production in the SM, which causes the signal shape to be asymmetric with a pronounced tail at low m_{tb} . This results in a substantial difference between the upper limits on the production cross section of left- and right-handed W' bosons at high m_{tb} .

The current analysis excludes both right- and left-handed W' bosons of masses less than 3.4 TeV at 95% CL. The expected limits are 3.7 and 3.6 TeV for the right- and left-handed W' bosons, respectively. The analysis improves on the expected sensitivity over the previous results [16], and extends the lower exclusion limit on $\sigma_{W'} \mathcal{B}(W' \rightarrow \text{tb})$ over the explored mass spectrum between 1.2 and 4.0 TeV. For right-handed W' bosons, values of $\sigma_{W'} \mathcal{B}(W' \rightarrow \text{tb})$ in the range 60–10 fb are excluded in the 1.2–4.0 TeV mass range.

9 Summary

A search has been performed for heavy W' bosons decaying to a top and a bottom quark in the hadronic final state using data corresponding to an integrated luminosity of 137 fb^{-1} collected by the CMS experiment during the data taking period from 2016 to 2018. The analysis utilizes top quark tagging and bottom quark tagging algorithms based on deep neural networks. No excess above the estimated standard model background is observed. Upper limits on the production cross section times branching fraction of a W' boson decaying to a top and a bottom quark are obtained at 95% confidence level for W' boson masses in the range 1–4 TeV. Left- and right-handed W' bosons with masses below 3.4 TeV are excluded at 95% confidence level. The limits provided on W' bosons decaying to a top and a bottom quark in the all-hadronic decay mode are the most stringent to date.

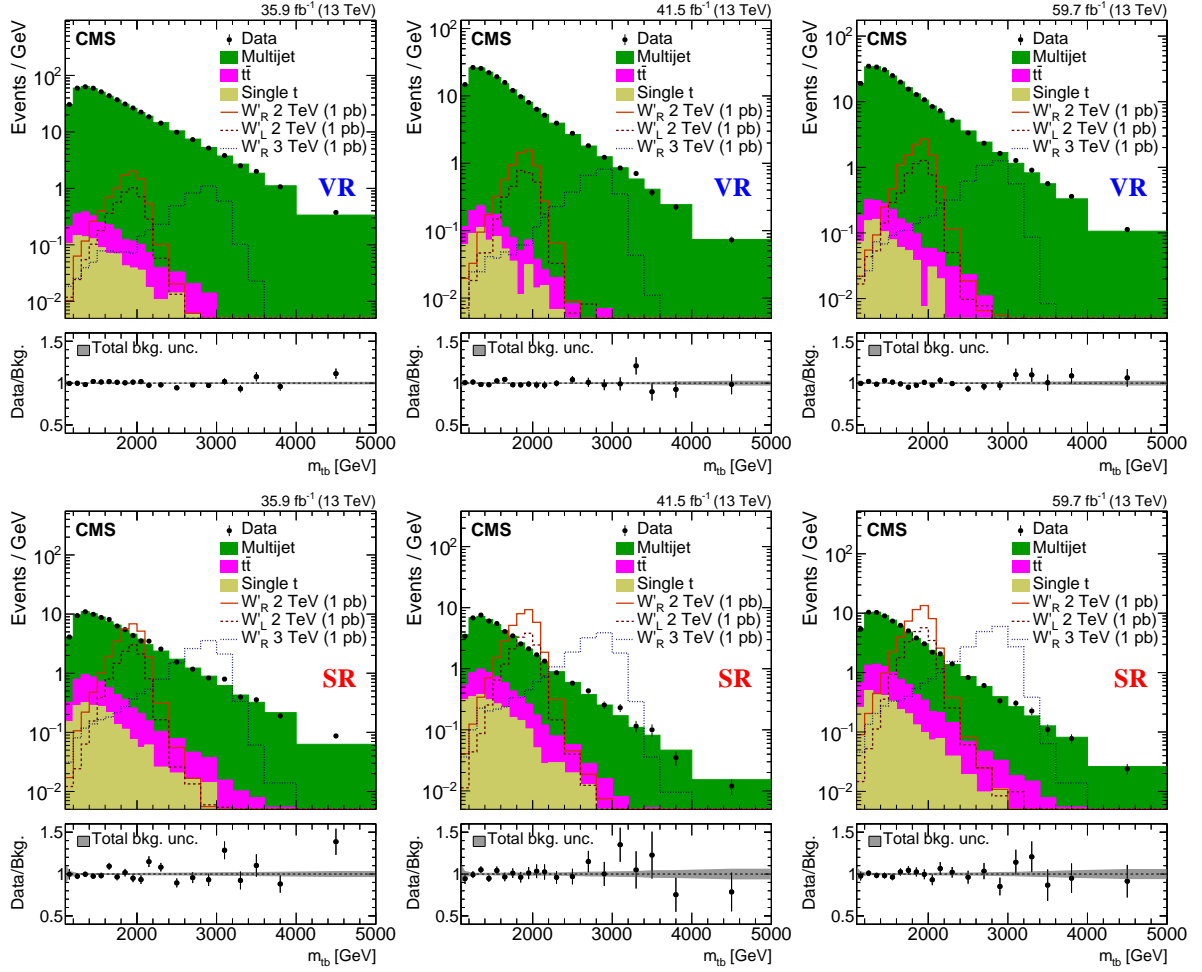


Figure 1: The reconstructed m_{tb} distributions in data (black points with error bars), and backgrounds in the VR (upper row) and SR (lower row) for the data-taking periods of 2016 (left), 2017 (middle), and 2018 (right). The yield in each bin is divided by the corresponding bin width. Distributions expected from right-handed W' bosons of mass 2 and 3 TeV and a left-handed W' boson of mass 2 TeV are shown normalized to the integrated luminosity of the data using a product of cross section and branching fraction of 1 pb. The lower panel in each plot shows the ratio of data to the background prediction. The shaded band indicates the total uncertainty in the estimated background, including both statistical and systematic components.

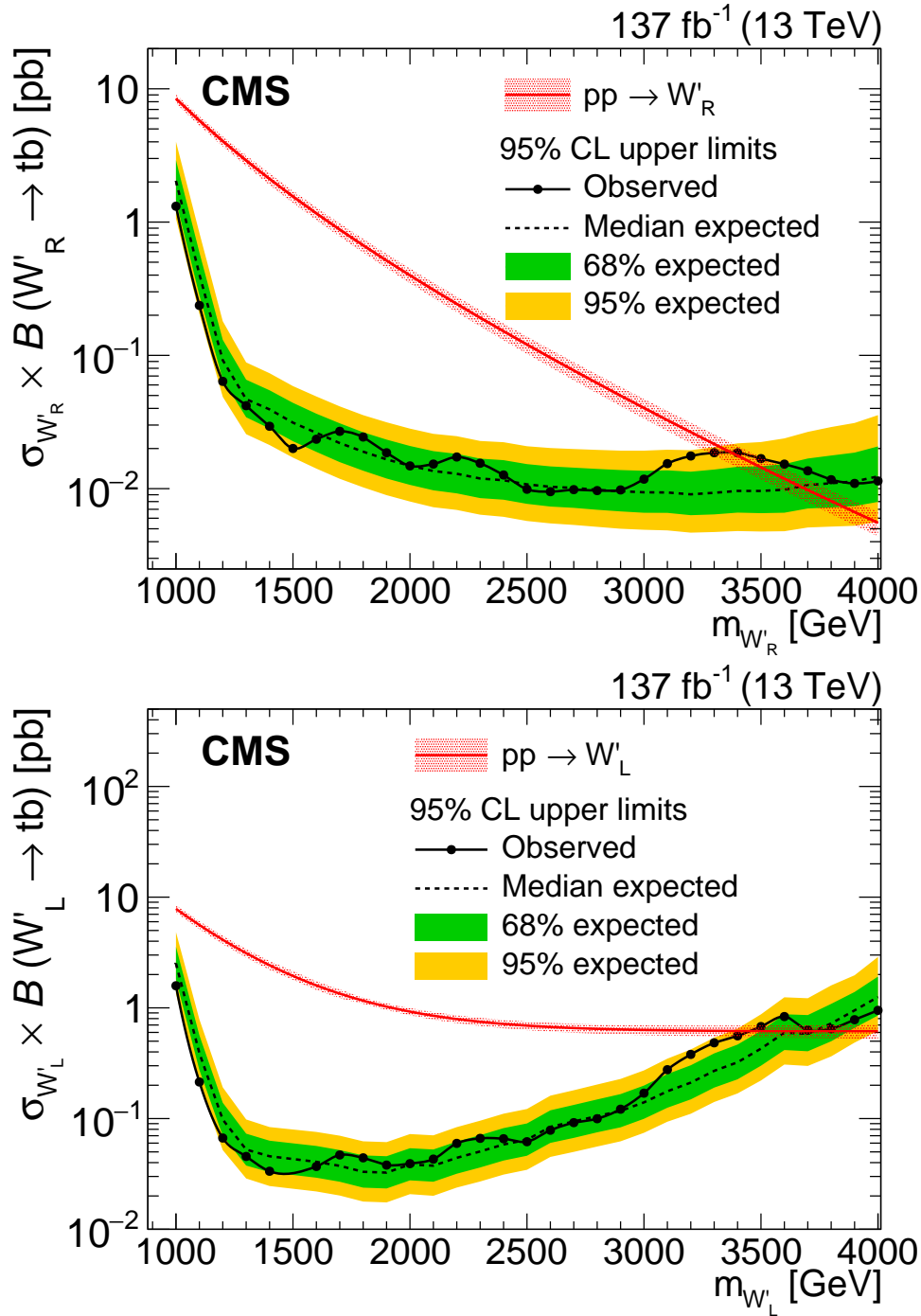


Figure 2: Upper limits at 95% CL on the production cross section and branching fraction of a W'_R boson (upper row) and a W'_L boson with the SM interference (lower row) decaying to a top and a bottom quark, using combined 2016–2018 data and backgrounds. The observed and median expected limits are shown with the black solid and dashed lines, respectively. The inner green and outer yellow bands represent the 68 and 95% confidence level intervals, respectively, of the expected limit, computed using the background-only hypothesis. The theoretical prediction and its uncertainty due to the choice of QCD scale and PDF set are indicated by the red curve and associated red shaded band, respectively.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, I. Mikulec, F.M. Pitters, J. Schieck¹, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish², E.A. De Wolf, X. Janssen, T. Kello³, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, J. D'Hondt, J. De Clercq, M. Delcourt, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. Grebenyuk, A.K. Kalsi, K. Lee, M. Mahdavihorrani, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, M. Gruchala, G. Mestdach, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, C. Hensel, A. Moraes

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

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato⁴, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes^{a,a}, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^{a,b}, D.S. Lemos^a, P.G. Mercadante^{a,b}, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China

T. Cheng, W. Fang³, Q. Guo, T. Javaid⁶, M. Mittal, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen⁷, Z. Hu, J. Martins⁸, Y. Wang, K. Yi^{9,10}

Institute of High Energy Physics, Beijing, China

E. Chapon, G.M. Chen⁶, H.S. Chen⁶, M. Chen, A. Kapoor, D. Leggat, H. Liao, Z.-A. LIU⁶, R. Sharma, A. Spiezia, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, S. Zhang⁶, J. Zhao

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

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China

Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao³, H. Okawa

Zhejiang University, Hangzhou, China

M. Xiao

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov¹¹, T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic

M. Finger¹², M. Finger Jr.¹², A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

S. Abu Zeid¹³, S. Khalil¹⁴, E. Salama^{15,13}

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

A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, J. Pata, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, FranceC. Amendola, M. Besancon, F. Couderc, M. DeJardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁶, M. Titov, G.B. Yu**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, FranceJ.-L. Agram¹⁷, J. Andrea, D. Apparù, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine¹⁷, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove**Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, K. Shchablo, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, GeorgiaA. Khvedelidze¹², Z. Tsamalaidze¹²**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, J. Schulz, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyC. Dziwok, G. Flügge, W. Haj Ahmad¹⁸, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁹, T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras²⁰, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, M.M. Defranchis, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo²¹, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari²², N.Z. Jomhari, H. Jung, A. Kasem²⁰, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²³, T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otariid, D. Pérez Adán, D. Pitzl, A. Raspereza, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger²¹, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, R. Zlebcik

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann¹⁹, C. Heidecker, U. Husemann, I. Katkov²⁴, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Musich, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoii, D. Schäfer, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannelis, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanad, K. Farkas, M.M.A. Gadallah²⁵, S. Lökös²⁶, P. Major, K. Mandal, A. Mehta, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁷, G. Bencze, C. Hajdu, D. Horvath²⁸, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karanicsi²⁷, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, HungaryP. Raics, Z.L. Trocsanyi²⁹, B. Ujvari**Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary**T. Csorgo³⁰, F. Nemes³⁰, T. Novak**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, IndiaS. Bahinipati³¹, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu³², A. Nayak³², P. Saha, N. Sur, S.K. Swain**Panjab University, Chandigarh, India**S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³³, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A.K. Viridi**University of Delhi, Delhi, India**

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, IndiaM. Bharti³⁴, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, B. Gomber³⁵, M. Maity³⁶, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh³⁴, S. Thakur³⁴**Indian Institute of Technology Madras, Madras, India**

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, IndiaD. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar³⁷, P.K. Netrakanti, L.M. Pant, P. Shukla**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

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

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, IranH. Bakhshiansohi³⁸, M. Zeinali³⁹**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani⁴⁰, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, ItalyM. Abbrescia^{a,b}, R. Aly^{a,b,41}, C. Aruta^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, M. Gul^a, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, V. Mastrapasqua^{a,b}, J.A. Merlin^a, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pellecchia^{a,b}, A. Pompili^{a,b},

G. Pugliese^{a,c}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, T. Diotallevi^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, L. Giommi^{a,b}, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,42}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

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

S. Albergo^{a,b,43}, S. Costa^{a,b,43}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,43}, C. Tuve^{a,b}

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

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, F. Fiori^{a,b}, E. Focardi^{a,b}, G. Latino^{a,b}, P. Lenzi^{a,b}, M. Lizzo^{a,b}, M. Meschini^a, S. Paoletti^a, R. Seidita^{a,b}, G. Sguazzoni^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

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

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, F. Brivio^{a,b}, F. Ceteorelli^{a,b}, V. Ciriolo^{a,b,19}, F. De Guio^{a,b}, M.E. Dinardo^{a,b}, P. Dini^a, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi^a, A. Massironi^a, D. Menasce^a, F. Monti^{a,b}, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,19}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, F. Carnevali^{a,b}, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,19}, P. Paolucci^{a,19}, B. Rossi^a, C. Sciacca^{a,b}

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

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, P. Bortignon^a, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, P. De Castro Manzano^a, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, S.Y. Hoh^{a,b}, L. Layer^{a,44}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Presilla^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, G. Strong^a, M. Tosi^{a,b}, H. YARAR^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

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

C. Aimè^{a,b}, A. Braghieri^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, 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

G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, F. Moscatelli^a, A. Piccinelli^{a,b}, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a, T. Tedeschi^{a,b}

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

P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, E. Bossini, R. Castaldi^a,

M.A. Ciocci^{a,b}, R. Dell'Orso^a, M.R. Di Domenico^{a,d}, S. Donato^a, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^{a,d}, A. Venturi^a, P.G. Verdini^a

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

F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^a, M. Diemoz^a, E. Longo^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, C. Quaranta^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^a, R. Tramontano^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, J. Berenguer Antequera^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, R. Salvatico^{a,b}, K. Shchelina^{a,b}, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, M. Tornago^{a,b}, D. Trocino^{a,b}

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

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, G. Sorrentino^{a,b}, F. Vazzoler^{a,b}

Kyungpook National University, Daegu, Korea

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

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

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

J. Goh, A. Gurtu

Sejong University, Seoul, Korea

H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y. Jeong, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait

T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia

V. Veckalns⁴⁵

Vilnius University, Vilnius, Lithuania

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

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

N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

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

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁴⁶, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic⁴⁷, N. Raicevic

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

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

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

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

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, D. Budkouski, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{48,49}, V. Palichik, V. Perelygin, M. Savina,

D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin

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

G. Gavrilov, V. Golovtsov, Y. Ivanov, V. Kim⁵⁰, E. Kuznetsova⁵¹, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov[†], A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko⁵², V. Popov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

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

M. Chadeeva⁵³, A. Oskin, P. Parygin, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

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

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁵⁴, L. Dudko, A. Gribushin, V. Klyukhin, N. Korneeva, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁵⁵, T. Dimova⁵⁵, L. Kardapoltsev⁵⁵, I. Ovtin⁵⁵, Y. Skovpen⁵⁵

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

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

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, V. Okhotnikov, L. Sukhikh

Tomsk State University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁵⁶, M. Dordevic, P. Milenovic, J. Milosevic, V. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez,

J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodriguez Bouza, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Priels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizán Garcia

University of Colombo, Colombo, Sri Lanka

MK Jayananda, B. Kailasapathy⁵⁷, D.U.J. Sonnadara, DDC Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, S.S. Chhibra, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁵⁸, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁵⁹, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁰, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

K. Androsov⁶¹, M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, C. Martin Perez, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann⁶¹, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. Amsler⁶², P. Bäertschi, C. Botta, D. Brzhechko, M.F. Canelli, A. De Wit, R. Del Burgo,

J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶³, C.M. Kuo, W. Lin, A. Roy, T. Sarkar³⁶, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan, P.r. Yu

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

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

F. Boran, S. Damarsecin⁶⁴, Z.S. Demiroglu, F. Dolek, I. Dumanoglu⁶⁵, E. Eskut, G. Gokbulut, Y. Guler, E. Gурpinar Guler⁶⁶, I. Hos⁶⁷, C. Isik, E.E. Kangal⁶⁸, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁶⁹, A. Polatoz, A.E. Simsek, B. Tali⁷⁰, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁷¹, G. Karapinar⁷², K. Ocalan⁷³, M. Yalvac⁷⁴

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya⁷⁵, O. Kaya⁷⁶, Ö. Özçelik, S. Tekten⁷⁷, E.A. Yetkin⁷⁸

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak⁶⁵, Y. Komurcu, S. Sen⁷⁹

Istanbul University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci⁷⁰, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁷⁰

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

University of Bristol, Bristol, United Kingdom

E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸⁰, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸¹, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal⁸², D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁸³, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee¹⁹, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom

J.E. Cole, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, S. Sawant, C. Smith, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, O. Charaf, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio⁸⁴, C. West

Boston University, Boston, USA

A. Akpınar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkle, X. Coubez²⁰, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁸⁵, E. Laird, G. Landsberg, K.T. Lau, J. Lee, J. Luo, M. Narain, S. Sagir⁸⁶, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, USA

C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, M. Tripathi, Y. Yao, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, R. Cousins, A. Dasgupta, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, A. Ovcharova, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, I. Vorobiev

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, K. McDermott, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, J. Lykken, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁵⁴, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, USA

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy¹³, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

The University of Iowa, Iowa City, USA

M. Alhousseini, K. Dilsiz⁸⁷, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁸⁸, A. Moeller, J. Nachtman, H. Ogul⁸⁹, Y. Onel, F. Ozok⁹⁰, A. Penzo, C. Snyder, E. Tiras⁹¹, J. Wetzel

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, B. Maier, A.C. Marini, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Tatar, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Band, R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko⁴⁸, R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, M. Zarucki, L. Zygala

The Ohio State University, Columbus, USA

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar,

M. Liu, G. Negro, N. Neumeister, G. Paspalaki, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic¹⁶, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

J. Dolen, N. Parashar

Rice University, Houston, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], W. Shi, A.G. Stahl Leiton

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban²³, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA

H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁹², M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹³, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, E. Wolfe

Wayne State University, Detroit, USA

P.E. Karchin, N. Poudyal, P. Thapa

University of Wisconsin - Madison, Madison, WI, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, F. Fienga, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased

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

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

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

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

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

6: Also at University of Chinese Academy of Sciences, Beijing, China

- 7: Also at Department of Physics, Tsinghua University, Beijing, China
- 8: Also at UFMS, Nova Andradina, Brazil
- 9: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 10: Now at The University of Iowa, Iowa City, USA
- 11: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
- 12: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 13: Also at Ain Shams University, Cairo, Egypt
- 14: Also at Zewail City of Science and Technology, Zewail, Egypt
- 15: Also at British University in Egypt, Cairo, Egypt
- 16: Also at Purdue University, West Lafayette, USA
- 17: Also at Université de Haute Alsace, Mulhouse, France
- 18: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 19: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 20: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 21: Also at University of Hamburg, Hamburg, Germany
- 22: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- 23: Also at Brandenburg University of Technology, Cottbus, Germany
- 24: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 26: Also at Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
- 27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 28: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 29: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 30: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 31: Also at IIT Bhubaneswar, Bhubaneswar, India
- 32: Also at Institute of Physics, Bhubaneswar, India
- 33: Also at G.H.G. Khalsa College, Punjab, India
- 34: Also at Shoolini University, Solan, India
- 35: Also at University of Hyderabad, Hyderabad, India
- 36: Also at University of Visva-Bharati, Santiniketan, India
- 37: Also at Indian Institute of Technology (IIT), Mumbai, India
- 38: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 39: Also at Sharif University of Technology, Tehran, Iran
- 40: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 41: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy
- 42: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 43: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 44: Also at Università di Napoli 'Federico II', Napoli, Italy
- 45: Also at Riga Technical University, Riga, Latvia
- 46: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 47: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 48: Also at Institute for Nuclear Research, Moscow, Russia
- 49: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

-
- 50: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
 - 51: Also at University of Florida, Gainesville, USA
 - 52: Also at Imperial College, London, United Kingdom
 - 53: Also at P.N. Lebedev Physical Institute, Moscow, Russia
 - 54: Also at California Institute of Technology, Pasadena, USA
 - 55: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
 - 56: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
 - 57: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
 - 58: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
 - 59: Also at National and Kapodistrian University of Athens, Athens, Greece
 - 60: Also at Universität Zürich, Zurich, Switzerland
 - 61: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
 - 62: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
 - 63: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
 - 64: Also at Şırnak University, Sirnak, Turkey
 - 65: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
 - 66: Also at Konya Technical University, Konya, Turkey
 - 67: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
 - 68: Also at Mersin University, Mersin, Turkey
 - 69: Also at Piri Reis University, Istanbul, Turkey
 - 70: Also at Adiyaman University, Adiyaman, Turkey
 - 71: Also at Ozyegin University, Istanbul, Turkey
 - 72: Also at Izmir Institute of Technology, Izmir, Turkey
 - 73: Also at Necmettin Erbakan University, Konya, Turkey
 - 74: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
 - 75: Also at Marmara University, Istanbul, Turkey
 - 76: Also at Milli Savunma University, Istanbul, Turkey
 - 77: Also at Kafkas University, Kars, Turkey
 - 78: Also at Istanbul Bilgi University, Istanbul, Turkey
 - 79: Also at Hacettepe University, Ankara, Turkey
 - 80: Also at Vrije Universiteit Brussel, Brussel, Belgium
 - 81: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
 - 82: Also at IPPP Durham University, Durham, United Kingdom
 - 83: Also at Monash University, Faculty of Science, Clayton, Australia
 - 84: Also at Università di Torino, TORINO, Italy
 - 85: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
 - 86: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
 - 87: Also at Bingol University, Bingol, Turkey
 - 88: Also at Georgian Technical University, Tbilisi, Georgia
 - 89: Also at Sinop University, Sinop, Turkey
 - 90: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
 - 91: Also at Erciyes University, KAYSERI, Turkey
 - 92: Also at Texas A&M University at Qatar, Doha, Qatar
 - 93: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea