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Measurement of differential cross sections for Z bosons produced in association with charm jets in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Measurements are presented of differential cross sections for the production of Z bosons in association with at least one jet initiated by a charm quark in pp collisions at $\sqrt{s} = 13$ TeV. The data recorded by the CMS experiment at the LHC correspond to an integrated luminosity of 35.9 fb^{-1} . The final states contain a pair of electrons or muons that are the decay products of a Z boson, and a jet consistent with being initiated by a charm quark produced in the hard interaction. Differential cross sections as a function of the transverse momentum p_T of the Z boson and p_T of the charm jet are compared with predictions from Monte Carlo event generators. The inclusive production cross section $405.4 \pm 5.6 \text{ (stat)} \pm 24.3 \text{ (exp)} \pm 3.7 \text{ (theo)} \text{ pb}$, is measured in a fiducial region requiring both leptons to have pseudorapidity $|\eta| < 2.4$ and $p_T > 10 \text{ GeV}$, at least one lepton with $p_T > 26 \text{ GeV}$, and a mass of the pair in the range 71–111 GeV, while the charm jet is required to have $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$. These are the first measurements of these cross sections in proton-proton collisions at 13 TeV.

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1 Introduction

The CERN LHC produced a large number of events at $\sqrt{s} = 13$ TeV in proton-proton (pp) collisions containing a Z boson accompanied by one or more jets initiated by charm quarks (c jets). The differential cross sections for inclusive Z+c jet production, as functions of the transverse momenta p_T of the Z boson and of the c jet, are used to verify quantum chromodynamics (QCD) models, provide information on the parton distribution function (PDF) of the charm quark, and investigate the possibility of observing the intrinsic charm quark (IC) component in the nucleon [1–3]. An IC component would enhance the rate of Z+c jet production, especially at large values of p_T of the Z boson and of the c jet.

Associated production of a Z boson and a c jet is an important background in searches for physics beyond the standard model (SM). For example, in supersymmetry models a top scalar quark ($\tilde{t}$) could decay into a charm quark and an undetected lightest supersymmetric particle, providing thereby a large p_T imbalance [4]. One of the background sources for such a process is Z+c jet production with the Z boson decaying into neutrinos. Better modelling of Z+c jet production through studies of visible decay modes can enhance the sensitivity in searches for new physics. An example of a Feynman diagram corresponding to the Z+c jet process is shown in Fig. 1.

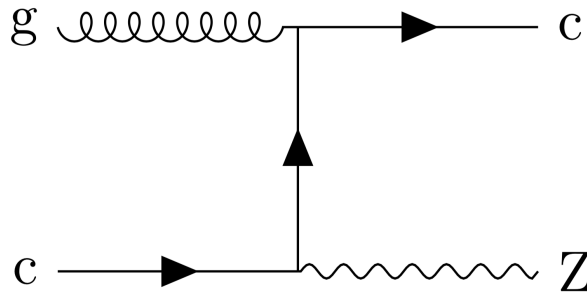


Figure 1: Example Feynman diagram for the Z+c jet process.

A previous measurement of the Z+c jet cross section at 8 TeV is reported in Ref.[5]. In this paper the Z boson is formed from an identified electron or muon pair, and the c jet is identified by applying charm tagging criteria [6] to reconstructed jets. This achieves a higher selection efficiency than in the 8 TeV measurement, where c jets were identified by reconstructed $D^*(2010)$ mesons or low-momentum muons inside the jets.

Measurements of the fiducial total and differential cross sections of Z+c jet production are presented as functions of the p_T of the Z boson and of the c jet p_T . To provide a direct comparison with predictions from Monte Carlo (MC) event generators (generator level), we unfold the detector effects.

The data, corresponding to an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV, were recorded by the CMS experiment during pp collisions in 2016. The minimum proton bunch spacing is 25 ns with 24 interactions on average per beam crossing.

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. A silicon pixel and strip tracker, covering a pseudo-rapidity region $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a

brass and scintillator hadron calorimeter, with each system composed of a barrel and two endcap sections, lie within the solenoid volume. Forward calorimeters, made of steel and quartz fibers, extend η coverage provided by the barrel and endcap detectors to $|\eta| < 5$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid that cover $|\eta| < 2.4$. Events of interest are selected using a two-tiered trigger system [7]. The first level, composed of specialized hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of ≈ 100 kHz within a fixed latency of about $4 \mu\text{s}$. The second level, known as the high-level trigger, consists of a farm of processors running full event reconstruction software optimized for fast processing, that reduces the event rate to ≈ 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [8].

3 Data and simulated events

Various MC generators are used to simulate the Z+jets background and the signal processes. The MADGRAPH5_aMC@NLO version 2.2.2 [9] (MG5_aMC) generator is used to simulate Drell-Yan (DY) processes, including the Z+c jet signal, calculated at next-to-leading order (NLO). Background DY events include those with a Z boson and a jet initiated by a bottom quark (b jet), or a jet initiated by a light quark or a gluon (light jet). Samples are made for Z+n jet processes ($n \leq 2$), calculated at NLO in perturbative QCD. A second signal model is provided by using MG5_aMC to calculate leading order (LO) matrix elements for $pp \rightarrow Z + n$ jets ($n \leq 4$). For a third signal model, SHERPA v2.2 [10, 11] is used to generate $pp \rightarrow Z + n$ jets events, with $n \leq 2$ at NLO and $n \leq 4$ at LO. All three signal models are normalized to the value of the inclusive Z + jets cross section calculated at next-to-next-to-leading order with FEWZ v3.1 [12]. These samples are generated using the NNPDF 3.0 [13] PDF set.

In addition to events with light and b jets, there are contributions to the background from processes producing top quark pairs [14, 15] and single top quarks [16, 17]. These samples are generated using NLO POWHEG v2.0 [18–20] or MG5_aMC. There is also background from vector boson pair production, which is simulated using PYTHIA 8 v8.212 [21].

All samples, except SHERPA, use PYTHIA 8 to model the initial- and final-state parton showers and hadronization, with the CUETP8M1 [22] or CUETP8M2T4 [23] (top pair sample) tune that includes the NNPDF 2.3 [24] LO PDFs and the value of the strong coupling at the mass of the Z boson is $\alpha_s(m_Z) = 0.119$. Matching between the matrix element generators and the parton shower is done using the k_T -MLM [25, 26] scheme with the matching scale set at 19 GeV for the LO MG5_aMC samples, and the FxFx [27] scheme with the matching scale set to 30 GeV for the NLO MG5_aMC events.

GEANT4 [28] is used for CMS detector simulation. The simulation includes additional pp interactions (pileup) in the current and nearby bunch crossings.

The simulated events are reconstructed with the same algorithms used for the data.

4 Object reconstruction and event selection

The particle flow (PF) algorithm [29] is used to reconstruct and identify individual particle candidates (physics objects) in an event, through an optimized combination of information from the various elements of the CMS detector. Energy depositions are measured in the calorimeters, and charged particles are identified in the central tracking and muon systems.

Electrons are reconstructed from tracks, fitted with a Gaussian sum filter, matching energy deposits in the ECAL [30]. Identification requirements are applied based on the ECAL shower shape, matching between the track and the ECAL deposits, and observables characterizing the emission of bremsstrahlung radiation along the electron trajectory. Electrons are required to originate from the primary vertex, which is the vertex candidate with the largest value of summed physics-object p_T^2 . Longitudinal and transverse impact parameters with respect to the primary vertex for barrel (endcap) are required to be <0.10 (0.20) and <0.05 (0.10) cm, respectively. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \rightarrow ee$ decays ranges from 1.7 to 4.5%. The dielectron mass resolution for $Z \rightarrow ee$ decays when both electrons are in the ECAL barrel is 1.9%, degrading to 2.9% when both electrons are in the endcaps.

Muons are reconstructed by combining signals from the inner tracker and the muon detector subsystems. They are required to satisfy standard identification criteria based on the number of hits in each detector, the track fit quality, and the consistency with the primary vertex by requiring the longitudinal and transverse impact parameters to be less than 0.5 and 0.2 cm, respectively. The efficiency to reconstruct and identify muons is greater than 96% [31]. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $20 < p_T < 100$ GeV of 1% in the barrel and 3% in the endcaps.

To reduce the misidentification rate, electrons and muons are required to be isolated. The isolation of electron or muon is defined as the sum of the p_T of all additional PF candidates within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ (0.4) around the electron (muon) track, where ϕ is the azimuthal angle in radians. After compensating for the contribution from pile-up [32], the resultant sum is required to be less than 25% of the lepton p_T .

Jets are clustered from PF candidates using the infrared- and collinear-safe anti- k_T algorithm with a distance parameter of 0.4, as implemented in the FASTJET package [33, 34]. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and, based on simulation, is within 5 to 10% of the true momentum over the entire p_T spectrum and detector acceptance. To mitigate the effects of pileup, charged particle candidates identified as originating from pileup vertices are discarded and a correction [32] is applied to remove remaining contributions. The reconstructed jet energy scale (JES) is corrected using a factorized model to compensate for the nonlinear and nonuniform response in the calorimeters. Corrections are derived from simulation to bring the measured response of jets to that of generator-level jets on average. In situ measurements of the momentum balance in dijet, multijet, photon+jet, and leptonically decaying Z+jet events are used to correct any residual differences between the JES in data and simulation [35]. The jet energy in simulation is degraded to match the resolution observed in data. The jet energy resolution (JER) amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Additional selection criteria are applied to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [36]. Jets identified as likely coming from pileup [37] are also removed.

Events are selected online through a single electron trigger requiring at least one electron candidate with $p_T > 27$ GeV (electron channel), or a single muon trigger requiring at least one muon candidate with $p_T > 24$ GeV (muon channel). Offline, we require a pair of oppositely charged electrons or muons each satisfying identification and isolation criteria, with $p_T > 10$ GeV and $|\eta| < 2.4$, and with an invariant mass close to the mass of the Z boson: $71 < m_{ee \text{ or } \mu\mu} < 111$ GeV. To exceed the trigger threshold in the electron channel at least one electron must have $p_T > 29$ GeV, and in the muon channel at least one muon must have

$p_T > 26$ GeV. Small residual differences in the trigger, identification, and isolation efficiencies between data and simulation are measured using tag-and-probe methods [38], and corrected by applying scale factors to simulated events.

The event must contain at least one jet with $p_T > 30$ GeV and $|\eta| < 2.4$, satisfying tight c tagging criteria using the deep combined secondary vertices algorithm [6]. This algorithm discriminates c jets from b and light jets based on jet properties such as the presence of displaced vertices (secondary vertices) and tracks with large impact parameter with respect to the primary vertex. Data from W+jets, $t\bar{t}$, and inclusive jet production are used to measure the c tagging efficiency for c jets, and mistag rates for b and light jets. These are compared with the simulation, where the reconstructed jet flavor is known from its hadron content. Small differences between data and simulation are corrected by applying scale factors to the simulation. The threshold applied in this analysis gives a c tagging efficiency of about 30%, and misidentification probabilities of 1.2% for light jets and 20% for b jets, with relative uncertainties between 5% and 15% depending on the p_T of the jet. If several c-tagged jets occur in the event, the one with the highest p_T is selected.

The simulated events are classified according to generator-level information. Generator-level jets are made by clustering all stable particles resulting from hadronization using the anti- k_T algorithm with a distance parameter of 0.4, and the jet flavor is defined by the flavor of the hadrons within the jet. If an event contains a generator-level jet with $p_T > 10$ GeV containing a b hadron, the event is defined as a Z+b jet event. If there is no such generator-level b jet in the event and there is at least one generator-level jet with $p_T > 10$ GeV containing a c hadron, the event is defined as a Z+c jet event. Other events in the DY sample are classified as Z+light jet events. The generator-level leptons are dressed by adding the momenta of all photons within $\Delta R = 0.1$ around the lepton directions.

5 Signal determination and data unfolding

Measurement of the differential cross sections of Z+c jet production as a function of the p_T of the Z boson (p_T^Z) and as a function of the c jet p_T ($p_T^{c\text{ jet}}$) are performed in several steps. The first step is to select c jet-enriched samples of $Z \rightarrow ee$ (electron channel) or $Z \rightarrow \mu\mu$ (muon channel) candidate events. The second step is to split the sample into different bins according to the p_T of the Z boson or c-tagged jet ($p_T^{c\text{-tagged jet}}$), and to measure the number of Z+c jet events in each bin. The third step is to unfold the data, using the simulation of the signal to construct response matrices to relate the observed distributions to those at the generator level. The final step is to combine the resulting unfolded electron and muon channel p_T distributions, and compare them with predictions from different MC event generators.

Charm hadrons can decay at points displaced from the primary vertex. This secondary vertex is reconstructed using the inclusive vertex finder algorithm [39]. The invariant mass of charged particles associated with the secondary vertex (m_{SV}) in the c-tagged jet [6] is used to discriminate between signal and background. Figure 2 shows the observed distributions of m_{SV} in the electron and muon channels, compared with the different signal and background contributions predicted by the simulation. Although m_{SV} is an ingredient in the c tagging algorithm, there are sufficient differences remaining in the distributions for the c-tagged samples to provide information on the flavor composition. The normalized distributions of m_{SV} for Z+light jet, Z+c jet and Z+b jet components are compared in Fig. 3.

The top quark and diboson background predictions are taken directly from simulation. The normalizations for the Z+c jet, Z+b jet and Z+light jet components are then obtained by fitting

templates of the m_{SV} distribution obtained from simulation to the observed data. A maximum likelihood template fit is performed separately in each bin of Z boson candidate or c-tagged jet p_T .

The values of the scale factors for the light (SF_l), charm (SF_c), and bottom (SF_b) components, defined as the ratio of the fitted normalization to the prediction from simulation, are presented in Tables 1–4 for each p_T bin for each Z+q jet process. The correlation coefficients between errors of different flavor SFs, found in the fit, are approximately equal to -0.8 , -0.35 and -0.25 for SF_c and SF_b , SF_l and SF_b , SF_c and SF_l respectively. Sources of systematic uncertainty are discussed in Sec. 6. Figure 4 shows the distributions of the Z boson candidate and c-tagged jet p_T after applying these scale factors, assuming they are constant across the p_T range in which they are determined. The post-fit m_{SV} distributions are presented in Appendix A. Good agreement is observed between simulation and data after applying these factors.

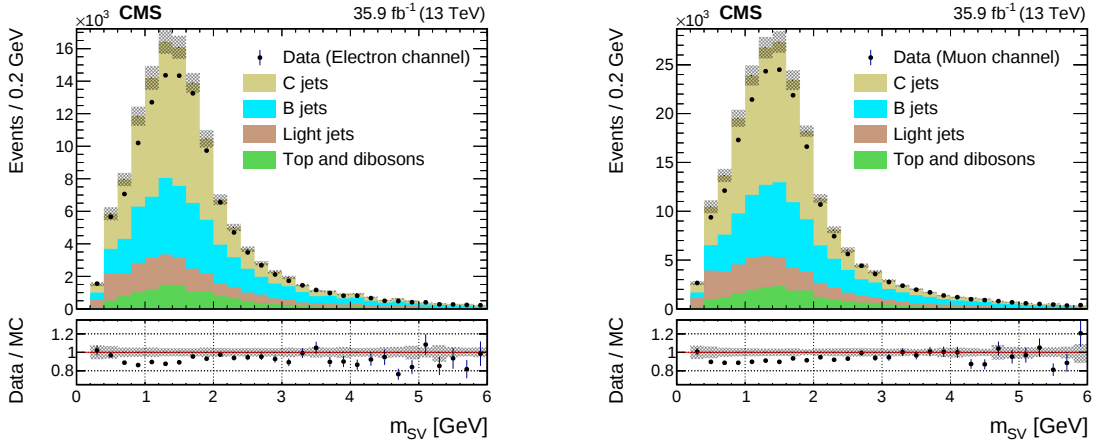


Figure 2: Distribution of the secondary vertex mass m_{SV} of the highest- p_T c-tagged central jet, for electron (left) and muon (right) channels. The observed data is compared with the different signal and background components in simulation, before normalization scale factors are applied. Dashed area represents MC systematic uncertainties. The vertical bars on the data points represent statistical uncertainties. Bottom panels on each plot represent the data to MC ratio.

Table 1: Values of Z+light jet SF_l , Z+c jet SF_c , and Z+b jet SF_b scale factors measured in the electron channel, as a function of c-tagged jet p_T . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

c-tagged jet p_T (GeV)	SF_l	SF_c	SF_b
30–37	$1.16 \pm 0.05^{+0.29}_{-0.21}$	$0.70 \pm 0.04^{+0.09}_{-0.11}$	$1.06 \pm 0.05^{+0.16}_{-0.12}$
37–45	$0.79 \pm 0.06^{+0.26}_{-0.18}$	$0.89 \pm 0.03^{+0.10}_{-0.08}$	$0.92 \pm 0.05^{+0.16}_{-0.16}$
45–60	$0.97 \pm 0.06^{+0.23}_{-0.19}$	$0.74 \pm 0.03^{+0.08}_{-0.06}$	$1.07 \pm 0.06^{+0.09}_{-0.09}$
60–90	$0.99 \pm 0.07^{+0.24}_{-0.18}$	$0.87 \pm 0.04^{+0.08}_{-0.08}$	$0.95 \pm 0.07^{+0.09}_{-0.12}$
90–250	$0.92 \pm 0.07^{+0.27}_{-0.19}$	$0.98 \pm 0.05^{+0.11}_{-0.10}$	$1.04 \pm 0.07^{+0.08}_{-0.08}$

The generator-level signal is defined to be Z+c jet events with two oppositely charged generator-level electrons or muons with $p_T > 10$ GeV (at least one with $p_T > 26$ GeV), $|\eta| < 2.4$, and an invariant mass $71 < m_{ee \text{ or } \mu\mu} < 111$ GeV. There must also be at least one generator-level c jet

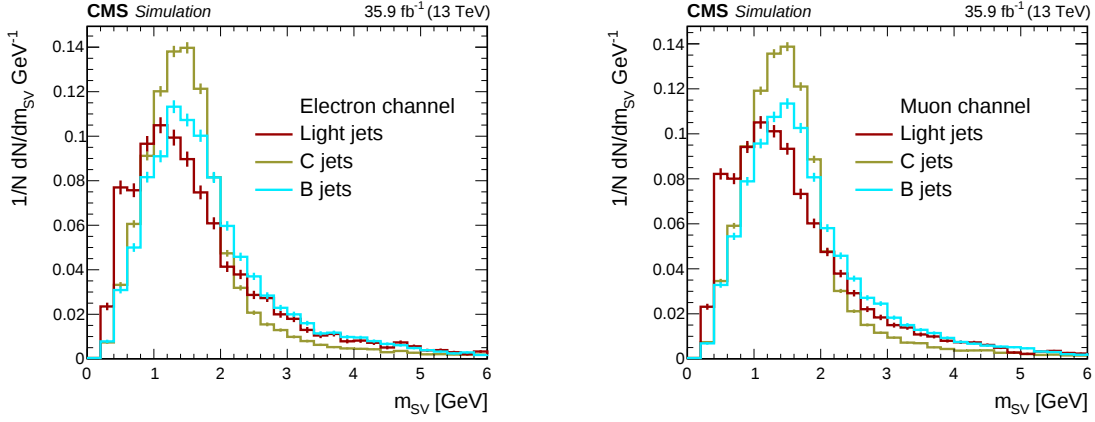


Figure 3: Distribution of the secondary vertex mass of the highest- p_T c-tagged central jet, for electron (left) and muon (right) channels for Z+light jet, Z+c jet and Z+b jet components, normalized to 1. Vertical bars represent statistical uncertainties.

Table 2: Values of Z+light jet SF_l , Z+c jet SF_c , and Z+b jet SF_b scale factors measured in the electron channel, as a function of Z candidate p_T . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

Z candidate p_T (GeV)	SF_l	SF_c	SF_b
0–30	$0.86 \pm 0.05^{+0.24}_{-0.18}$	$0.76 \pm 0.04^{+0.11}_{-0.09}$	$1.25 \pm 0.07^{+0.17}_{-0.18}$
30–50	$0.98 \pm 0.05^{+0.23}_{-0.17}$	$0.80 \pm 0.03^{+0.08}_{-0.08}$	$0.91 \pm 0.05^{+0.10}_{-0.08}$
50–65	$0.85 \pm 0.07^{+0.21}_{-0.16}$	$0.78 \pm 0.04^{+0.15}_{-0.11}$	$1.04 \pm 0.06^{+0.17}_{-0.17}$
65–95	$1.14 \pm 0.08^{+0.30}_{-0.22}$	$0.97 \pm 0.04^{+0.08}_{-0.07}$	$0.76 \pm 0.06^{+0.09}_{-0.11}$
95–300	$1.01 \pm 0.07^{+0.26}_{-0.20}$	$0.83 \pm 0.05^{+0.07}_{-0.07}$	$1.13 \pm 0.07^{+0.08}_{-0.08}$

with $p_T > 30$ GeV and $|\eta| < 2.4$. To avoid double counting, jets within $\Delta R = 0.4$ of one of the two leptons from the Z candidate are removed.

A fraction of Z+c jet events that are outside the signal phase space will migrate into the reconstructed signal region, primarily events with c jets with generated $p_T < 30$ GeV but reconstructed $p_T > 30$ GeV due to the finite detector resolution. The fraction of Z+c jet events that are inside the signal phase space is estimated from the number of selected events in which the c-tagged jet and lepton pair match within $\Delta R < 0.3$ to a generator-level highest- p_T c jet and lepton pair satisfying the phase space requirements. Figure 5 shows this fraction as functions of Z boson and c-tagged jet p_T , for electron and muon channels, calculated using MADGRAPH5_aMC@NLO sample.

Response matrices are constructed using the Z+c jet events in the DY sample that is simulated using the MG5_aMC (NLO) generator, and cross-checked using the MG5_aMC (LO) generator. Each matrix entry represents the probability for an event generated in the signal phase space within a certain c jet (or Z boson) p_T range to end up within a certain reconstructed c jet (or Z boson candidate) p_T range. The unfolding was done with 5 detector-level p_T bins and 4 generator-level p_T bins. The TUNFOLD package v17.5 [40], which is based on a least-squares fit, is then used to invert the response matrices and unfold the distribution of the measured number of Z+c jet events.

Table 3: Values of Z+light jet SF_l , Z+c jet SF_c , and Z+b jet SF_b scale factors measured in the muon channel, as a function of c-tagged jet p_T . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

c-tagged jet p_T (GeV)	SF_l	SF_c	SF_b
30–37	$0.95 \pm 0.04^{+0.24}_{-0.17}$	$0.82 \pm 0.03^{+0.12}_{-0.07}$	$1.04 \pm 0.05^{+0.11}_{-0.19}$
37–45	$0.93 \pm 0.05^{+0.26}_{-0.23}$	$0.82 \pm 0.03^{+0.06}_{-0.06}$	$0.96 \pm 0.05^{+0.12}_{-0.09}$
45–60	$0.81 \pm 0.04^{+0.20}_{-0.15}$	$0.79 \pm 0.03^{+0.09}_{-0.06}$	$1.10 \pm 0.04^{+0.08}_{-0.07}$
60–90	$0.88 \pm 0.04^{+0.23}_{-0.17}$	$0.80 \pm 0.03^{+0.06}_{-0.08}$	$1.25 \pm 0.05^{+0.12}_{-0.10}$
90–250	$0.92 \pm 0.05^{+0.24}_{-0.17}$	$0.79 \pm 0.04^{+0.07}_{-0.06}$	$1.16 \pm 0.06^{+0.12}_{-0.12}$

Table 4: Values of Z+light jet SF_l , Z+c jet SF_c , and Z+b jet SF_b scale factors measured in the muon channel, as a function of Z candidate p_T . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

Z candidate p_T (GeV)	SF_l	SF_c	SF_b
0–30	$0.97 \pm 0.04^{+0.24}_{-0.20}$	$0.82 \pm 0.03^{+0.09}_{-0.08}$	$1.09 \pm 0.05^{+0.11}_{-0.10}$
30–50	$0.91 \pm 0.04^{+0.21}_{-0.16}$	$0.80 \pm 0.02^{+0.07}_{-0.06}$	$0.99 \pm 0.04^{+0.05}_{-0.06}$
50–65	$0.63 \pm 0.06^{+0.17}_{-0.13}$	$0.73 \pm 0.03^{+0.09}_{-0.06}$	$1.24 \pm 0.05^{+0.09}_{-0.10}$
65–95	$0.96 \pm 0.05^{+0.25}_{-0.18}$	$0.85 \pm 0.03^{+0.09}_{-0.06}$	$1.04 \pm 0.05^{+0.13}_{-0.14}$
95–300	$0.89 \pm 0.05^{+0.23}_{-0.17}$	$0.78 \pm 0.04^{+0.07}_{-0.07}$	$1.33 \pm 0.06^{+0.08}_{-0.08}$

Figure 6 shows the efficiency (defined as the fraction of signal events generated in the fiducial phase space that pass all selection criteria after reconstruction) as a function of the generator-level Z boson or c jet p_T for electron and muon channels, calculated using the MG5_aMC (NLO) sample. The dominant losses are due to the c tagging and lepton selection efficiencies.

6 Systematic uncertainties

The systematic uncertainties are estimated by varying relevant parameters and then repeating the unfolding procedure, recalculating the values of the efficiency, response matrix, and number of Z+c jet and background events in each case. The differences observed between the unfolded distributions are assumed as the uncertainties. The following uncertainties are included:

- *QCD renormalization and factorization scales:* The ambiguity in the choice of QCD renormalization scale (μ_R) and factorization scale (μ_F) leads to uncertainty in theoretical predictions for the DY process. This uncertainty is estimated by changing the values of μ_R and μ_F by factors of 0.5 and 2 relative to the default values, $\mu_F = \mu_R = m_Z$, excluding the $(0.5\mu_F, 2\mu_R)$ and $(0.5\mu_R, 2\mu_F)$ combinations. Largest deviations from the central values were used as uncertainty.
- *PDF:* The unfolding is performed with different PDF replicas and compared with the nominal distribution.
- *c tagging efficiency:* The effect of uncertainties in the c tagging rates is estimated by varying tagging and mistagging scale factors for the different jet flavors. Scale factors for tagging c jets, and mistagging b jets and light jets are varied up and down by one standard deviation. The combined c tagging uncertainty is then calculated

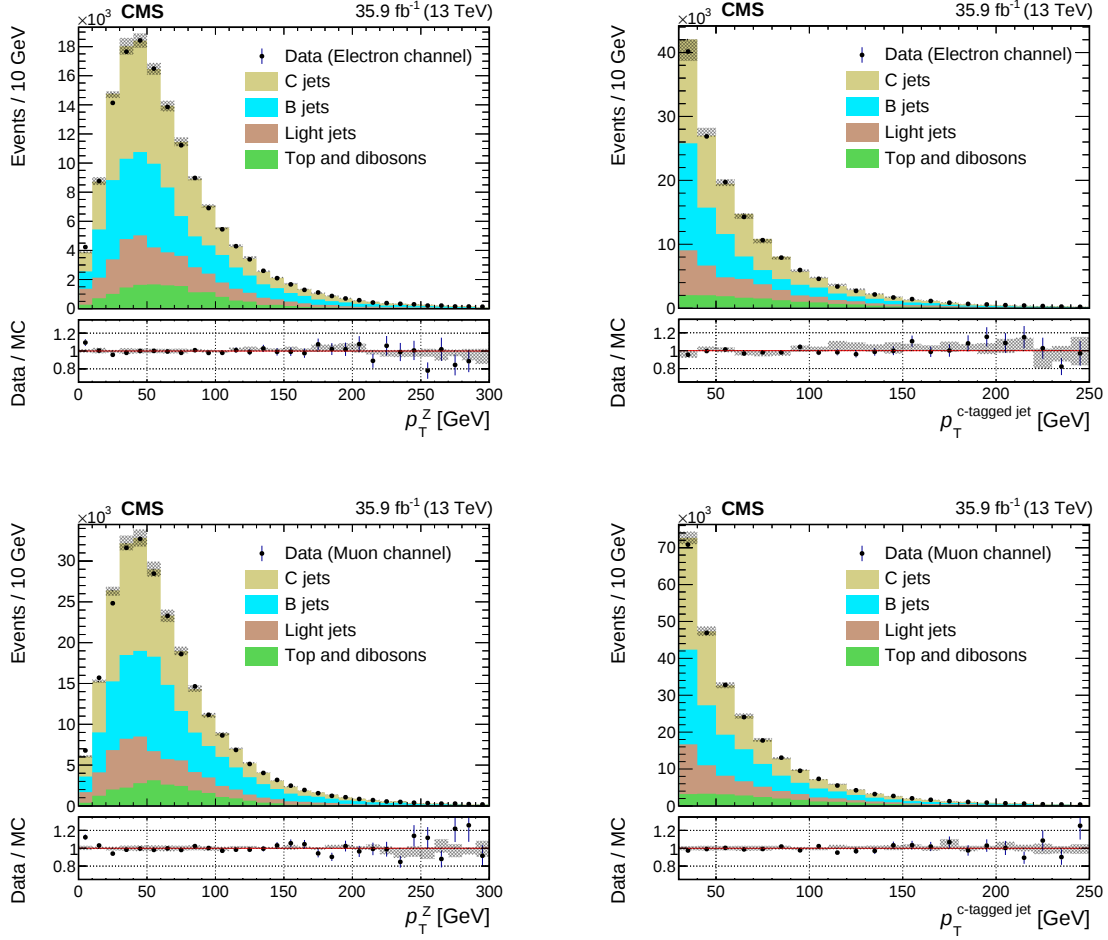


Figure 4: The distributions of p_T in data and corrected simulation, after applying the fitted scale factors to the Drell-Yan components. The upper plots show distributions for the electron channel, with the p_T of the electron pair (left) and c-tagged jet (right). The lower plots show distributions for the muon channel with the p_T of the muon pair (left) and c-tagged jet (right). Dashed area represents MC systematic uncertainties. The vertical bars on the data points represent statistical uncertainties. Bottom panels on each plot represent the data to MC ratio.

as the sum in quadrature of these variations. The variation of scale factors is $\approx 15\%$ for light jets, and $\approx 5\%$ for charm and bottom jets.

- *Jet energy resolution and scale:* Both the JES and JER corrections can affect jet p_T and the m_{SV} distributions used in the SF_b and SF_l measurements. The uncertainty resulting from JES corrections is estimated by varying the p_T - and η -dependent scale factors within their uncertainty (up to $\approx 4\%$). The JER uncertainty is estimated by varying the amount of jet p_T resolution degradation applied to the simulation up and down by one standard deviation ($\approx 10\%$).
- *Pileup:* The corresponding uncertainty is estimated by changing the total inelastic cross section by $\pm 4.6\%$ [41].
- *Lepton identification and isolation:* Uncertainties resulting from the modeling of the identification and isolation of muons and electrons are estimated by varying the corresponding scale factors within their uncertainties. For electrons the uncertainty is less than 3%, while for muons uncertainties in identification and isolation are less

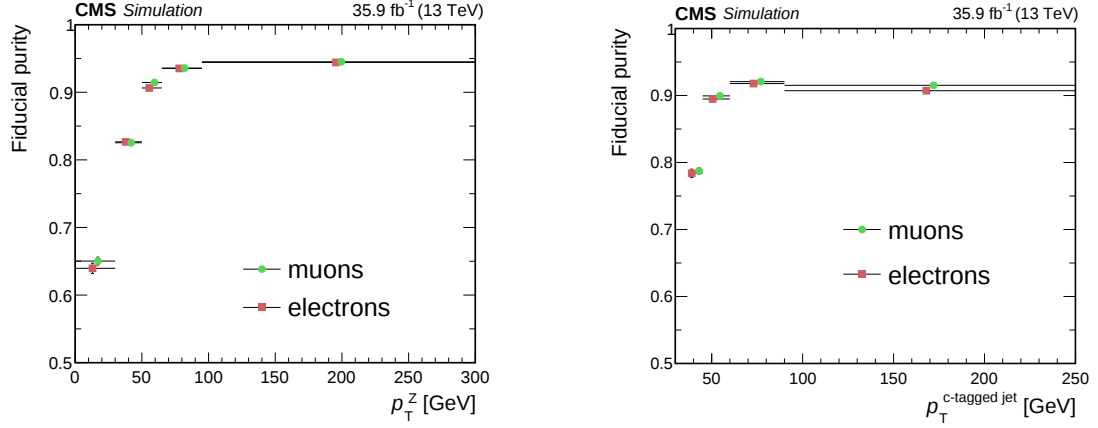


Figure 5: Fraction of selected Z+c jet events originating within the fiducial phase space as a function of p_T . The plots show distributions for electron and muons channels as a function of p_T^Z (left) and $p_T^{c\text{-tagged jet}}$ (right).

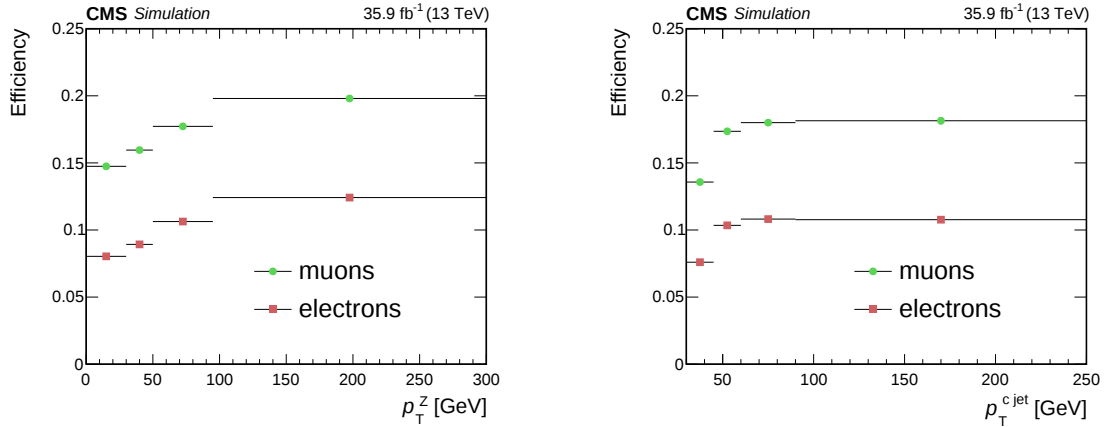


Figure 6: Efficiency as a function of p_T . The plots show distributions for the electron and muon channels, as a function of p_T^Z (left) and $p_T^{c \text{ jet}}$ (right).

than 2%.

- *Top pair production cross section:* The uncertainty because of the cross section used for the modeling of top quark pair production is estimated by varying the normalization of the top pair component of the background by $\pm 10\%$ [42].
- *Luminosity:* The uncertainty is obtained by changing the luminosity value used to normalize the unfolded distributions by $\pm 2.5\%$ [43].
- *Statistical uncertainties in m_{SV} templates:* The uncertainty is obtained by taking into account statistical fluctuations in each bin of the simulated m_{SV} distributions, used in the fit of SF_l , SF_c and SF_b .

The uncertainties in the integral fiducial cross section from the considered sources are listed in Table 5.

Table 5: Summary of the systematic uncertainties in the integral fiducial cross section arising from the various sources for electron (ee) and muon ($\mu\mu$) channels, calculated by integrating over $p_T^{c\text{ jet}}$ or p_T^Z .

Channel	QCD (%)	PDF (%)	c tag/mistag (%)	JER (%)	JES (%)	Pileup (%)	Top Pair (%)	ID\Iso (%)	$\mathcal{L}$ (%)	MC stat. (%)
$\mu\mu, p_T^{c\text{ jet}}$	5.5	0.5	4.2	3.9	4.8	1.5	0.6	1.0	2.5	4.2
$\mu\mu, p_T^Z$	1.9	0.5	4.2	1.1	3.9	1.6	0.8	1.0	2.5	3.1
ee, $p_T^{c\text{ jet}}$	6.4	0.6	4.2	3.1	6.4	3.0	0.7	2.6	2.5	6.3
ee, p_T^Z	2.6	0.5	4.1	1.1	4.8	1.8	0.6	2.6	2.5	3.8

7 Results

The total fiducial cross section is measured as

$$\sigma_{\text{fid}} = \frac{N_{\text{charm}} P_{\text{fid}}}{\epsilon \mathcal{L} \mathcal{B}(Z \rightarrow \ell\ell)}, \quad (1)$$

where N_{charm} is the integral number of measured charm events, P_{fid} is the integral fiducial purity, ϵ is the integral fiducial selection efficiency, $\mathcal{L}$ is the integrated luminosity, and $\mathcal{B}(Z \rightarrow \ell\ell) = 3.36\%$ is the branching fraction of the Z boson to $\ell\ell$ with $\ell = e$ or μ .

The fiducial differential cross sections are obtained from the unfolded distributions as

$$\frac{d\sigma}{dp_T} = \frac{N_i}{\mathcal{L} \Delta_i \mathcal{B}(Z \rightarrow \ell\ell)}, \quad (2)$$

where N_i is the number of events in p_T bin i of the unfolded distribution and Δ_i is the width of the bin.

The results of the measurement of total and differential fiducial cross sections from the electron and muon channels are combined by a fit using the CONVINO tool [44], which includes statistical and systematic uncertainties. The uncertainties related to the c tag and mistag rates, JER, JES, pileup, luminosity, and top quark pair cross section are assumed fully correlated between the channels, whereas uncertainties from other sources are assumed to be uncorrelated. The experimental systematic uncertainties are those related to c tag and mistag rates, JER, JES, identification and isolation, pileup, and luminosity. The rest are designated as theoretical systematic uncertainties.

The total fiducial cross section value for Z boson $p_T < 300 \text{ GeV}$ equals $405.4 \pm 5.6 (\text{stat}) \pm 24.3 (\text{exp}) \pm 3.7 (\text{theo}) \text{ pb}$, where (exp) and (theo) denote experimental and theoretical systematic uncertainties, respectively. This value is significantly lower than the MG5_aMC (NLO) predicted value of $524.9 \pm 11.7 (\text{theo}) \text{ pb}$. The theoretical systematic uncertainty includes uncertainties in QCD scale and PDF.

The values of the cross sections as a function of p_T of the Z boson and c jet after combining are shown in Fig. 7. This also shows a comparison of the measured fiducial cross sections with predictions from the generators MG5_aMC (NLO), MG5_aMC (LO), and SHERPA. The prediction from MG5_aMC at leading order shows good agreement with data, while both MG5_aMC and SHERPA at next-to-leading order tend to overestimate the cross section.

The values of the measured differential cross sections are presented in Tables 6 and 7.

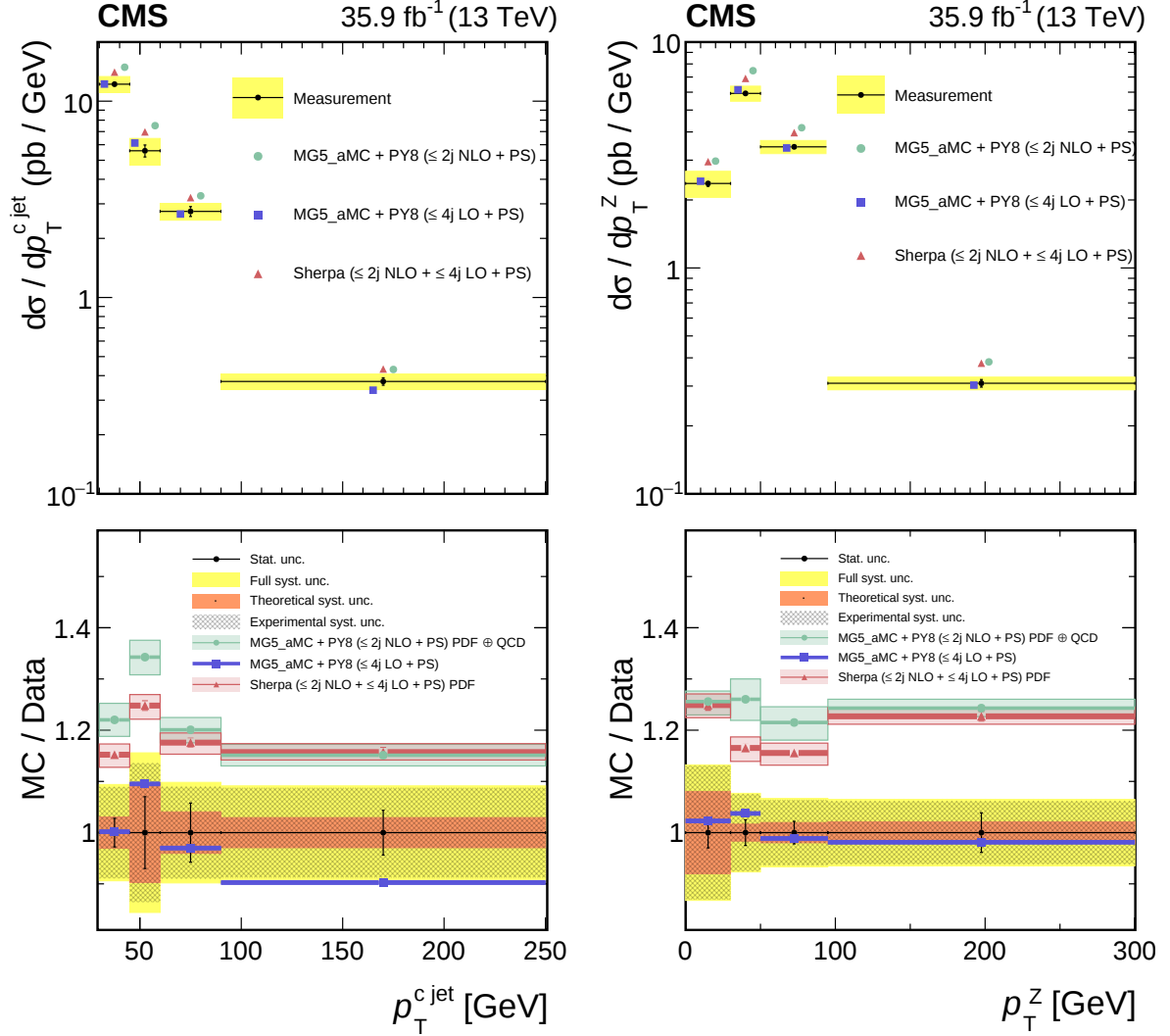


Figure 7: Measured fiducial differential cross sections for inclusive $Z+c$ jet production, $d\sigma/dp_T^{c\text{jet}}$ (left) and $d\sigma/dp_T^Z$ (right). Yellow band shows total systematic uncertainties. Predictions from MG5.aMC (LO) are shown with statistical uncertainties only. The vertical bars on the data points represent statistical uncertainties.

8 Summary

The first differential cross sections for inclusive $Z+c$ jet production as functions of transverse momenta p_T of the Z boson and of the associated c jet are presented for collisions at $\sqrt{s} = 13$ TeV using 35.9 fb^{-1} of data collected by the CMS experiment at the CERN LHC. The measurements pertain to a fiducial space defined as containing a c jet with $p_T > 30 \text{ GeV}$ and pseudorapidity $|\eta| < 2.4$, and a pair of leptons with each lepton having $p_T > 10 \text{ GeV}$, $|\eta| < 2.4$, and at least one with $p_T > 26 \text{ GeV}$, and a dilepton mass between 71 and 111 GeV. The main background sources correspond to Z +light jet, Z + b jet, top quark pair, and diboson (ZZ , ZW , or WW) production. To provide a direct comparison with predictions from Monte Carlo (MC) event generators, we unfold detector effects from our measurements.

Table 6: Measured differential cross section as a function of $p_T^{c\text{jet}}$ for electron and muon channels and combined value. The first and second uncertainty values correspond to the statistical and systematic contributions, respectively.

$p_T^{c\text{jet}}$ (GeV)	electrons (pb/GeV)	muons (pb/GeV)	combined (pb/GeV)
30–45	$11.91 \pm 0.54 \pm 1.50$	$12.34 \pm 0.44 \pm 1.05$	$12.20 \pm 0.34 \pm 1.15$
45–60	$5.30 \pm 0.63 \pm 0.92$	$5.73 \pm 0.49 \pm 0.66$	$5.59 \pm 0.39 \pm 0.87$
60–90	$3.10 \pm 0.25 \pm 0.51$	$2.66 \pm 0.19 \pm 0.41$	$2.74 \pm 0.16 \pm 0.27$
90–250	$0.43 \pm 0.03 \pm 0.06$	$0.34 \pm 0.02 \pm 0.03$	$0.37 \pm 0.02 \pm 0.03$

Table 7: Measured differential cross section as a function of p_T^Z for electron and muon channels and combined value. The first and second uncertainty values correspond to the statistical and systematic contributions, respectively.

p_T^Z (GeV)	electrons (pb/GeV)	muons (pb/GeV)	combined (pb/GeV)
0–30	$2.28 \pm 0.13 \pm 0.28$	$2.40 \pm 0.08 \pm 0.24$	$2.37 \pm 0.07 \pm 0.31$
30–50	$5.91 \pm 0.23 \pm 0.54$	$5.90 \pm 0.19 \pm 0.46$	$5.93 \pm 0.15 \pm 0.45$
50–95	$3.69 \pm 0.13 \pm 0.27$	$3.32 \pm 0.09 \pm 0.22$	$3.44 \pm 0.08 \pm 0.23$
95–300	$0.32 \pm 0.02 \pm 0.03$	$0.30 \pm 0.02 \pm 0.02$	$0.31 \pm 0.01 \pm 0.02$

The total fiducial cross section for the Z boson with $p_T < 300$ GeV is measured to be $405.4 \pm 5.6(\text{stat}) \pm 24.3(\text{exp}) \pm 3.7(\text{theo})$ pb, while the MADGRAPH5_aMC@NLO generator at next-to-leading order predicts $524.9 \pm 11.7(\text{theo})$ pb for the same fiducial region. The theoretical uncertainties include QCD scale variation and parton distribution function uncertainties. The predictions from MC event generators were compared with measurements, which are in good agreement with MADGRAPH5_aMC@NLO at leading order, while both MADGRAPH5_aMC@NLO and SHERPA at next-to-leading order tend to overestimate the cross section. Predictions from all three generators were normalized to the cross section calculated with FEWZ at next-to-next-to-leading order. The prediction of inclusive Z+jets production at next-to-leading order is in better agreement with data than that at leading order [45]. This could be an indication that the parton distribution functions overestimate the charm content. These results can be used to improve existing constraints on the charm quark content in the proton.

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References

- [1] S. J. Brodsky et al., "A review of the intrinsic heavy quark content of the nucleon", *Adv. High Energy Phys.* **2015** (2015) 231547, doi:10.1155/2015/231547, arXiv:1504.06287.
- [2] T.-J. Hou et al., "CT14 intrinsic charm parton distribution functions from CTEQ-TEA global analysis", *JHEP* **02** (2018) 059, doi:10.1007/JHEP02(2018)059, arXiv:1707.00657.
- [3] NNPDF Collaboration, "A determination of the charm content of the proton", *Eur. Phys. J. C* **76** (2016) 647, doi:10.1140/epjc/s10052-016-4469-y, arXiv:1605.06515.
- [4] CMS Collaboration, "Search for the pair production of third-generation squarks with two-body decays to a bottom or charm quark and a neutralino in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **778** (2018) 263, doi:10.1016/j.physletb.2018.01.012, arXiv:1707.07274.

-
- [5] CMS Collaboration, “Measurement of associated Z + charm production in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C* **78** (2018) 287, doi:10.1140/epjc/s10052-018-5752-x, arXiv:1711.02143.
- [6] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [7] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [8] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [9] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [10] T. Gleisberg, S. Hoeche, F. Krauss, M. Schoenherr, S. Schumann, F. Siegert, and J. Winter, “Event generation with SHERPA 1.1”, *JHEP* **07** (2008) 0902, doi:10.1088/1126-6708/2009/02/007, arXiv:0811.4622.
- [11] F. Buccioni, J. Lang, J. M. Lindert, P. Maierhofer, S. Pozzorini, H. Zhang, and M. F. Zoller, “OpenLoops 2”, *Eur. Phys. J. C* **79** (2019) 866, doi:10.1140/epjc/s10052-019-7306-2, arXiv:1907.13071.
- [12] Y. Li and F. Petriello, “Combining QCD and electroweak corrections to dilepton production in the framework of the FEWZ simulation code”, *Phys. Rev. D* **86** (2012) 094034, doi:10.1103/PhysRevD.86.094034, arXiv:1208.5967.
- [13] NNPDF Collaboration, “Parton distributions for the LHC run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [14] CMS Collaboration, “Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **09** (2017) 051, doi:10.1007/JHEP09(2017)051, arXiv:1701.06228.
- [15] CMS Collaboration, “Measurement of the $t\bar{t}$ production cross section using events in the $e\mu$ final state in pp collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **77** (2017) 172, doi:10.1140/epjc/s10052-017-4718-8, arXiv:1611.04040.
- [16] N. Kidonakis, “Differential and total cross sections for top pair and single top production”, in *Proceedings of the XX International Workshop on Deep-Inelastic Scattering and Related Subjects*. Bonn, Germany, 2012. arXiv:1205.3453. doi:10.3204/DESY-PROC-2012-02/251.
- [17] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO single-top production matched with shower in POWHEG: s- and t-channel contributions”, *JHEP* **09** (2009) 111, doi:10.1088/1126-6708/2009/09/111, arXiv:0907.4076. [Erratum: doi:10.1007/JHEP02(2010)011].
- [18] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

- [19] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [20] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [21] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [22] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [23] CMS Collaboration, “Investigations of the impact of the parton shower tuning in PYTHIA 8 in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and 13 TeV”, CMS Physics Analysis Summary CMS-PAS-TOP-16-021, 2016.
- [24] R. D. Ball et al., “Parton distributions with LHC data”, *Nucl. Phys. B* **867** (2013) 244, doi:10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
- [25] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [26] J. Alwall, S. de Visscher, and F. Maltoni, “QCD radiation in the production of heavy colored particles at the LHC”, *JHEP* **02** (2009) 017, doi:10.1088/1126-6708/2009/02/017, arXiv:0810.5350.
- [27] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [28] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [29] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [30] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [31] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [32] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [33] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

-
- [34] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [35] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [36] CMS Collaboration, “Performance of missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [37] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.
- [38] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the CMS experiment”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [39] CMS Collaboration, “Measurement of $B\bar{B}$ angular correlations based on secondary vertex reconstruction at $\sqrt{s} = 7$ TeV”, *JHEP* **03** (2011) 136, doi:10.1007/JHEP03(2011)136, arXiv:1102.3194.
- [40] S. Schmitt, “TUnfold: an algorithm for correcting migration effects in high energy physics”, *JINST* **7** (2012) T10003, doi:10.1088/1748-0221/7/10/T10003, arXiv:1205.6201.
- [41] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [42] M. Czakon, P. Fiedler, and A. Mitov, “Total top quark pair production cross section at hadron colliders through $O(\alpha_s^4)$ ”, *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [43] CMS Collaboration, “CMS Luminosity Measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.
- [44] J. Kieseler, “A method and tool for combining differential or inclusive measurements obtained with simultaneously constrained uncertainties”, *Eur. Phys. J. C* **77** (2017) 792, doi:10.1140/epjc/s10052-017-5345-0, arXiv:1706.01681.
- [45] CMS Collaboration, “Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **78** (2018) 965, doi:10.1140/epjc/s10052-018-6373-0, arXiv:1804.05252.

A Post-fit secondary vertex mass distributions

Figures A.1 and A.2 show post-fit secondary vertex mass distributions for electron and muon channels. The normalization scale factors from the fit of m_{SV} were applied as a function of Z or c-tagged central jet p_T .

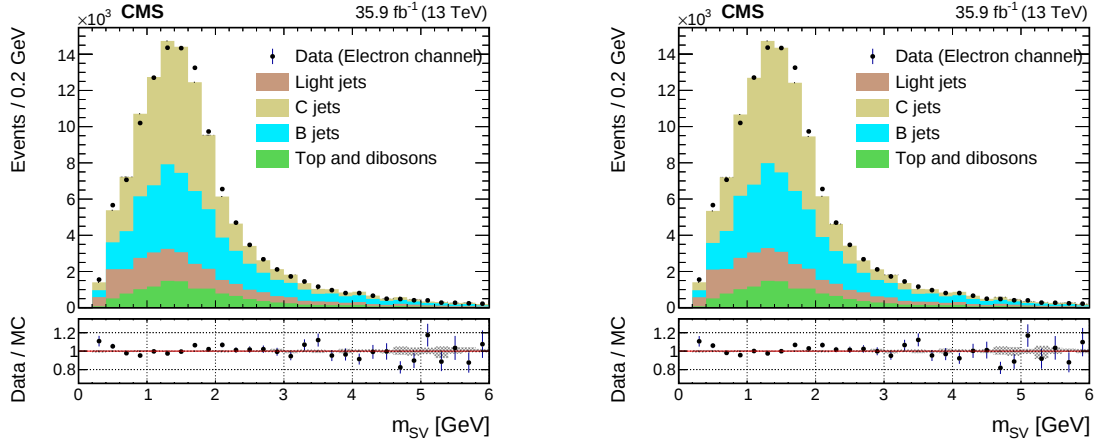


Figure A.1: Distribution of the secondary vertex mass m_{SV} of the highest- p_T c-tagged central jet, for electron channel. The observed data is compared to the different signal and background components in simulation, after normalization scale factors as function of Z p_T (left) and c-tagged central jet p_T (right) are applied. Bottom panels on each plot represent the data to MC ratio.

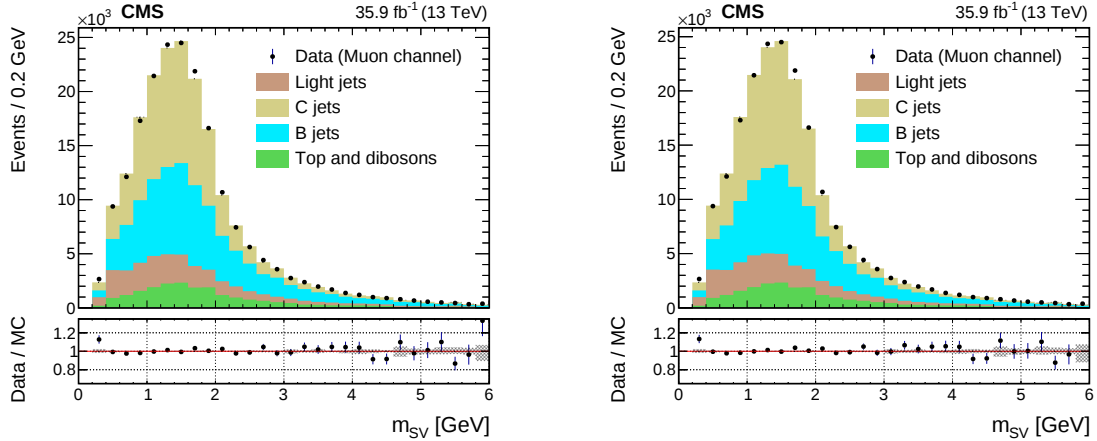


Figure A.2: Distribution of the secondary vertex mass m_{SV} of the highest- p_T c-tagged central jet, for muon channel. The observed data is compared to the different signal and background components in simulation, after normalization scale factors as function of Z p_T (left) and c-tagged central jet p_T (right) are applied. Bottom panels on each plot represent the data to MC ratio.

B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov⁴, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, 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, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato⁵, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁶, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins⁷, D. Matos Figueiredo, M. Medina Jaime⁸, C. Mora Herrera, 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

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

Beihang University, Beijing, China

W. Fang³, Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China

E. Chapon, G.M. Chen⁹, H.S. Chen⁹, M. Chen, T. Javaid⁹, A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang⁹, 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

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. Starodumov¹⁰, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, 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, D. Tsiakkouri

Charles University, Prague, Czech Republic

M. Finger¹¹, M. Finger Jr.¹¹, A. Kveton, J. Tomsa

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

H. Abdalla¹², A.A. Abdelalim^{13,14}, S. Elgammal¹⁵

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, 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, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, 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, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, 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, France

J.-L. Agram¹⁷, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine¹⁷, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, 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, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

I. Bagaturia¹⁸, Z. Tsamalaidze¹¹

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

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, 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, Germany

C. Dziwok, G. Flügge, W. Haj Ahmad¹⁹, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl²⁰, 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. Borras²¹, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo²², A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari²³, N.Z. Jomhari, H. Jung, A. Kasem²¹, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁴, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otari, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, 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, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, 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, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, 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, A. Gottmann, F. Hartmann²⁰, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov²⁵, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniowski

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, 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, 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. Gianneios, P. Katsoulis, P. Kokkas, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas

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

Budapest, Hungary

M. Bartók²⁶, M. Csanad, M.M.A. Gadallah²⁷, S. Lökös²⁸, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²⁹, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁶, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

T. Csorgo, F. Nemes, 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, India

S. Bahinipati³⁰, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak³¹, D.K. Sahoo³⁰, N. Sur, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³², R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, 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, India

M. Bharti³³, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber³⁴, M. Maity³⁵, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh³³, S. Thakur³³

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, India

D. Dutta, V. Kumar, K. Naskar³⁶, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, 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, Iran

H. Bakhshiansohi³⁷, M. Zeinali³⁸

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

S. Chenarani³⁹, 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, Italy

M. Abbrescia^{a,b}, R. Aly^{a,b,40}, 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. 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. Borghoni^a, S. Braibant-Giacomelli^{a,b}, 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, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,41}, 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,42}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,42}, 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, 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, A. Beschi^{a,b}, F. Brivio^{a,b}, F. Cetorelli^{a,b}, V. Ciriolo^{a,b,20}, 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, 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,20}, 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, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,20}, P. Paolucci^{a,20}, B. Rossi^a, C. Sciacca^{a,b}, E. Voevodina^{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,43}, 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. Aime^{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

M. Biasini^{a,b}, 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

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, M.R. Di Domenico^{a,d}, S. Donato^a, L. Giannini^{a,c}, 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,b}, R. Tramontano^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, C. Biino^a, 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. Ruspà^{a,c}, R. Salvatico^{a,b}, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, 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}, 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

B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, S. Ha, 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, K. Lee, S. Lee, K. Nam, 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

H.D. Yoo

Sungkyunkwan University, Suwon, Korea

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

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

Y. Maghrbi

Riga Technical University, Riga, Latvia

V. Veckalns⁴⁴

Vilnius University, Vilnius, Lithuania

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

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

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 Cruz⁴⁵, 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

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

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

A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic⁴, 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, A. Byszuk⁴⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, 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, K. Shchelina, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, I. Kashunin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{47,48}, V.V. Mitsyn, V. Palichik, V. Perehygin, M. Savina, S. Shmatov, S. Shulha, O. Teryaev, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim⁴⁹, E. Kuznetsova⁵⁰, 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. Tliso[†], A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko⁵¹, 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
R. Chistov⁵², M. Danilov⁵³, A. Oskin, P. Parygin, S. Polikarpov⁵²

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, M. Dubinin⁵⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov⁵⁵, T. Dimova⁵⁵, L. Kardapoltsev⁵⁵, I. Ov[†], 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, A. Iuzhakov, 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, P. Cirkovic, M. Dordevic, P. Milenovic, J. 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, J.A. Brochero Cifuentes, 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, A. García Alonso, 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, A. Triossi, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, 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. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan 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, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Bossini, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, 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. Guilbaud, D. Gulhan, 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, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo²⁰, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, 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. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

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

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, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, 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, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. Amsler⁶¹, C. Botta, D. Brzhechko, M.F. Canelli, 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, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶², C.M. Kuo, W. Lin, A. Roy, T. Sarkar³⁵, 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

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

B. Asavapibhop, C. Asawatangkuldee, N. Srimanobhas

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

F. Boran, S. Damarsecin⁶³, Z.S. Demiroglu, F. Dolek, C. Dozen⁶⁴, I. Dumanoglu⁶⁵, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar 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

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, 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, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸⁰, 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, A. Bundock, V. Cepaitis, G.S. Chahal⁸¹, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash⁸², V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee²⁰, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

S. Abdullin, A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, 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, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

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

Brown University, Providence, USA

G. Benelli, B. Burkle, X. Coubez²¹, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁸³, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁸⁴, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, 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, M.I. Paneva, 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, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, 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, B. Marsh, H. Mei, A. Ovcharova, H. Qu, 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, J. Pata, 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, M. Sun, I. Vorobiev

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, 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, A. Datta, A. Frankenthal, K. McDermott, J. Monroy, J.R. Patterson, D. Quach, 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, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, 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, W.J. Spalding, 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, S. Wang, 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. Elkafrawy⁸⁵, M. Hohlmann, 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

The University of Iowa, Iowa City, USA

M. Alhusseini, K. Dilsiz⁸⁶, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁸⁷, A. Moeller, J. Nachtman, H. Ogul⁸⁸, Y. Onel, F. Ozok⁸⁹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi⁹⁰

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, 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, A. Mohammadi

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, G.Y. Jeng, 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, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. 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, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, 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, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

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. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko⁴⁷, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos,

G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, A. Purohit, H. Qiu, J.F. Schulte, M. Stojanovic¹⁶, N. Trevisani, F. Wang, A. Wildridge, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, 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. Karacheban²⁴, 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. Bouhali⁹¹, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹², H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, 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, R. Janjam, 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, Y. Wang, E. Wolfe, F. Xia

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, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudan Sreekala, A. Mallampalli, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, J. Steggemann, 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, Alexandria, Egypt
- 3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 5: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 7: Also at UFMS, Nova Andradina, Brazil
- 8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 9: Also at University of Chinese Academy of Sciences, Beijing, China
- 10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
- 11: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 12: Also at Cairo University, Cairo, Egypt
- 13: Also at Helwan University, Cairo, Egypt
- 14: Now at Zewail City of Science and Technology, Zewail, Egypt
- 15: Now 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 Ilia State University, Tbilisi, Georgia
- 19: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 20: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 21: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 22: Also at University of Hamburg, Hamburg, Germany
- 23: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
- 24: Also at Brandenburg University of Technology, Cottbus, Germany
- 25: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 26: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 28: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 29: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 30: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 31: Also at Institute of Physics, Bhubaneswar, India
- 32: Also at G.H.G. Khalsa College, Punjab, India
- 33: Also at Shoolini University, Solan, India
- 34: Also at University of Hyderabad, Hyderabad, India
- 35: Also at University of Visva-Bharati, Santiniketan, India
- 36: Also at Indian Institute of Technology (IIT), Mumbai, India
- 37: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 38: Also at Sharif University of Technology, Tehran, Iran
- 39: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 40: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy
- 41: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic

Development, Bologna, Italy

42: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy

43: Also at Università di Napoli 'Federico II', NAPOLI, Italy

44: Also at Riga Technical University, Riga, Latvia, Riga, Latvia

45: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico

46: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

47: Also at Institute for Nuclear Research, Moscow, Russia

48: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

49: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

50: Also at University of Florida, Gainesville, USA

51: Also at Imperial College, London, United Kingdom

52: Also at P.N. Lebedev Physical Institute, Moscow, Russia

53: Also at Moscow Institute of Physics and Technology, Moscow, Russia, 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, Pavia, Italy

59: Also at National and Kapodistrian University of Athens, Athens, Greece

60: Also at Universität Zürich, Zurich, Switzerland

61: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria

62: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

63: Also at Şırnak University, Sirnak, Turkey

64: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China

65: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey

66: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey

67: Also at Istanbul Aydın University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), 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 Universitetsi Rektörlüğü, Yozgat, Turkey, 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 School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

81: Also at IPPP Durham University, Durham, United Kingdom

82: Also at Monash University, Faculty of Science, Clayton, Australia

83: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA

84: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

- 85: Also at Ain Shams University, Cairo, Egypt
- 86: Also at Bingol University, Bingol, Turkey
- 87: Also at Georgian Technical University, Tbilisi, Georgia
- 88: Also at Sinop University, Sinop, Turkey
- 89: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 90: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 91: Also at Texas A&M University at Qatar, Doha, Qatar
- 92: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea