Eur. Phys. J. C (2020) 80:718
https://doi.org/10.1140/epjc/s10052-020-8166-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Study of central exclusive $\pi^+\pi^-$ production in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 5 March 2020 / Accepted: 17 June 2020

Abstract Central exclusive and semiexclusive production of $\pi^+\pi^-$ pairs is measured with the CMS detector in proton-proton collisions at the LHC at center-of-mass energies of 5.02 and 13 TeV. The theoretical description of these non-perturbative processes, which have not yet been measured in detail at the LHC, poses a significant challenge to models. The two pions are measured and identified in the CMS silicon tracker based on specific energy loss, whereas the absence of other particles is ensured by calorimeter information. The total and differential cross sections of exclusive and semiexclusive central $\pi^+\pi^-$ production are measured as functions of invariant mass, transverse momentum, and rapidity of the $\pi^+\pi^-$ system in the fiducial region defined as transverse momentum $p_T(\pi) > 0.2$ GeV and pseudorapidity $|\eta(\pi)| < 2.4$. The production cross sections for the four resonant channels $f_0(500)$, $\rho^0(770)$, $f_0(980)$, and $f_2(1270)$ are extracted using a simple model. These results represent the first measurement of this process at the LHC collision energies of 5.02 and 13 TeV.

1 Introduction

The central exclusive production (CEP) process has been studied for a long time from both theoretical [1–7] and experimental [8–18] perspectives. In this process, both protons remain intact in the collision and a central system is produced. The process is referred to as exclusive when no particles other than the central system are produced. If one or both protons dissociate into a forward diffractive system, the process is called semiexclusive production. Various central systems can be produced in this process, like $\pi^+\pi^-$, K^+K^-, and 4π. In this paper, the $\pi^+\pi^-$ central system is measured. At the CERN LHC energies, the two dominant mechanisms of $\pi^+\pi^-$ production via CEP are *double pomeron exchange* (DPE) and *vector meson photoproduction* (VMP), which are illustrated by the diagrams shown in Fig. 1. The pomeron ($\mathbb{P}$) is a color singlet object introduced to explain the rise of the inelastic cross section at high collision energies [19,20]. The quantum numbers of the pomeron constrain the possible central systems in DPE processes, whereas the photon exchange restricts the central system in VMP processes. By functioning as a quantum number filter, the CEP process is suitable to study low-mass resonances, which would be difficult to study otherwise. Furthermore, DPE processes are also suitable to search for glueballs (bound states of gluons without valence quarks), because they provide a gluon-rich environment [21,22]. Another process that could contribute to the same final state is the two-photon fusion $\gamma\gamma \to \pi^+\pi^-$, which is expected to have a much smaller cross section than DPE and VMP processes and gives a negligible contribution [23].

The DPE process of pion pair production has two subcategories: continuum and resonant production. In the case of continuum production, the pion pair is directly produced; thus the pairs have a nonresonant invariant mass spectrum. Resonant production means that an intermediate meson resonance is produced centrally, which manifests itself as a peak in the invariant mass distribution of the pion pair. Since the pomeron is a Regge trajectory running over states with quantum numbers $J^{PC} = \{0^{++}, 1^{++}, 2^{++}, \ldots\}$ and $I^G = 0^+$, the resonance is restricted to have $J^{PC} = \{0^{++}, 2^{++}, 4^{++}, \ldots\}$ and $I^G = 0^+$, where J is the total angular momentum, I is the isospin, P is the parity, C is the charge parity, and $G = C\,(-1)^I$. The known particles [24] satisfying these criteria are the f_0, f_2, χ_{c0}, χ_{c2}, χ_{b0}, and χ_{b2} resonances. The cross section for DPE ($\sigma^{\text{DPE}}_{\pi^+\pi^-}$) can be calculated from the amplitude of continuum ($A^{\text{DPE,C}}_{\pi^+\pi^-}$) and resonant ($A^{\text{DPE,R}}_{\pi^+\pi^-}$) production as

$$\sigma^{\text{DPE}}_{\pi^+\pi^-} \propto |A^{\text{DPE,C}}_{\pi^+\pi^-} + A^{\text{DPE,R}}_{\pi^+\pi^-}|^2. \quad (1)$$

Interference terms between the continuum and resonant production channels must be included to describe the observed spectra and to measure the cross sections for resonances.

* e-mail: cms-publication-committee-chair@cern.ch

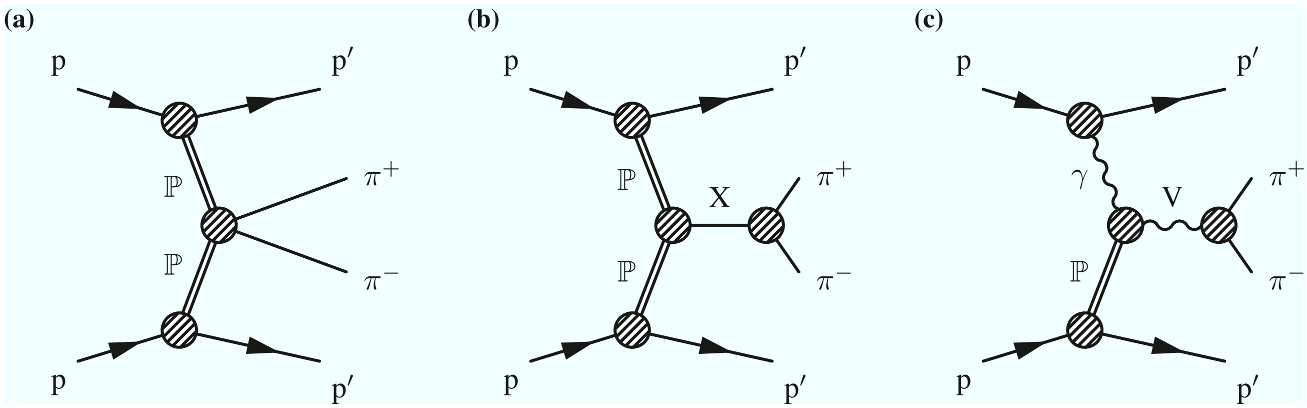

Fig. 1 Diagrams of the dominant mechanisms for $\pi^+\pi^-$ production via CEP in proton-proton collisions: **a** continuum; **b** resonant double pomeron exchange; and **c** vector meson photoproduction

In VMP, one of the protons emits a virtual photon, which fluctuates into a quark-antiquark bound state and scatters from the proton via the pomeron exchange. The quantum numbers of the possible resonances are constrained by the quantum numbers of the pomeron and the photon ($J^{PC} = 1^{--}$), leading to mesons with odd spin and the following quantum numbers $J^{PC} = \{1^{--}, 3^{--}, \ldots\}$. Resonances satisfying these conditions are ρ^0, ω, ϕ, J/ψ, $\psi(2S)$, and Υ, but only the $\rho^0 \to \pi^+\pi^-$ decay has a significant branching fraction, since decays in this channel are strongly suppressed in the case of ϕ, J/ψ, $\psi(2S)$, and Υ according to the Okubo–Zweig–Iizuka rule [25–27] and in the case of ω because of G-parity conservation [28].

This paper presents measurements of exclusive and semiexclusive $\pi^+\pi^-$ total and differential cross sections as functions of invariant mass $m(\pi^+\pi^-)$, transverse momentum $p_T(\pi^+\pi^-)$, and rapidity $y(\pi^+\pi^-)$ of the pion pair, in a fiducial region defined by single pion transverse momentum $p_T(\pi) > 0.2$ GeV and single pion pseudorapidity $|\eta(\pi)| < 2.4$. Because the outgoing protons are not tagged in this measurement, there is a residual contribution from semiexclusive production with all dissociation products outside the $|\eta| > 4.9$ range. In the following, the exclusive and the residual semiexclusive contribution together will be referred to as central exclusive production. The data were recorded by CMS with beam conditions ensuring a small probability of multiple pp collisions in the same bunch crossing (pileup) in August 2015 at a center-of-mass energy of 13 TeV with luminosity $258\mu b^{-1}$ and in November 2015 at 5.02 TeV with a luminosity of $522\mu b^{-1}$. The average number of pp collisions in a bunch crossing was around 0.3–0.5 for the 5.02 TeV and around 0.5 for the 13 TeV data sets.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections, covering the $|\eta| < 3.0$ region. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T solenoid field. Three pixel barrel layers (PXB) are situated at radii of 4.4, 7.3, and 10.2 cm; PXB also has two pixel endcap disks (PXF). The strip tracker consists of the innermost tracker inner barrel (TIB) and the tracker inner disks (TID), which are surrounded by the tracker outer barrel (TOB). It is completed by endcaps (TEC) on both sides. The barrel part of the strip tracker has a total of 10 layers at radii from 25 to 110 cm, whereas the endcap of the strip tracker consists of 12 layers. For charged particles with $p_T < 1$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1–2% in p_T , and 90–300 and 100–350 μ for the transverse and longitudinal impact parameters, respectively [29]. The tracker provides an opportunity to identify charged particles with $0.3 < p < 2$ GeV based on their specific ionization in the silicon detector elements [30].

The ECAL consists of 75 848 lead tungstate crystals, which provide coverage in $|\eta| < 1.479$ in the barrel region and $1.479 < |\eta| < 3.0$ in the two endcap regions.

The barrel and endcap sections of the HCAL consist of 36 wedges each and cover the $|\eta| < 3.0$ region. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and

0.087 radians in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 ECAL crystal arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of $|\eta|$, the towers are larger and the matching ECAL arrays contain fewer crystals.

The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located at 11.2 m from the interaction region, one at each end. Together they provide coverage in the range $3.0 < |\eta| < 5.2$. Each HF calorimeter consists of 432 readout towers, containing long and short quartz fibers running parallel to the beam. The long fibers run the entire depth of the HF calorimeter (165 cm, or approximately 10 interaction lengths), whereas the short fibers start at a depth of 22 cm from the front of the detector. By reading out the two sets of fibers separately, it is possible to distinguish showers generated by electrons or photons, which deposit a large fraction of their energy in the long-fiber calorimeter segment, from those generated by hadrons, which typically produce, on average, nearly equal signals in both calorimeter segments.

The triggers used in this analysis are based on signals from the Beam Pick-up and Timing for eXperiments (BPTX) detectors [31]. The BPTX devices have a time resolution of less than 0.2 ns. They are located around the beam pipe at a distance of ±175 m from the nominal interaction point, and are designed to provide precise information on the bunch structure and timing of the proton beams.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [32].

3 Monte Carlo simulations

Two kinds of Monte Carlo (MC) event generators are used in this analysis: inclusive and exclusive generators. The inclusive generators model the inclusive diffractive dissociation [33] and nondiffractive interactions, and are used to estimate the tracking efficiency, multiple reconstruction and misreconstruction rates. The exclusive generators are used to generate CEP events and to calculate the vertex correction factors. There are no available MC event generators that produce exclusive scalar and tensor resonances via DPE, such as the production of $f_0(500)$, $f_0(980)$, and $f_2(1270)$ mesons.

Event samples are generated with various tunes for diffraction and the underlying event:

- PYTHIA 8.205 [34] with CUETP8M1 tune [35] and MBR model [36]: PYTHIA 8 is an inclusive generator based on the Schuler and Sjöstrand model. It is capable of modeling a wide variety of physical processes, such as single diffractive (SD), double diffractive (DD), and central diffractive (CD) dissociation, as well as nondiffractive (ND) production [33]. The SD, DD, and ND events are generated with the CUETP8M1 tune. The Minimum Bias Rockefeller (MBR) model of PYTHIA is based on the renormalized pomeron flux model and it is capable of generating SD, DD, ND and CD events.
- EPOS [37] with its LHC tune [38]: This inclusive generator is based on the Regge–Gribov phenomenology [39], and it models SD, DD, CD, and ND processes.
- STARLIGHT [40]: This event generator models photon-photon and photon-pomeron interactions in pp and heavy ion collisions. The production of ρ^0 mesons and their successive decay into two pions through the VMP process is simulated by STARLIGHT. For background studies, ω mesons are also generated with STARLIGHT and their decay simulated by PYTHIA to the $\pi^+\pi^-\pi^0$ final state.
- DIME MC 1.06 [5]: The DIME MC software describes continuum $\pi^+\pi^-$ production through DPE. The generator uses a phenomenological model based on Regge theory. Events are generated with the Orear-type off-shell meson form factors with parameters $a_{or} = 0.71\,\text{GeV}^{-1}$ and $b_{or} = 0.91\,\text{GeV}^{-1}$ [5]. Furthermore, two additional MC samples are generated with an exponential form factor with $b_{exp} = 0.45$ [5] and $1\,\text{GeV}^{-2}$ [1] to study the systematic uncertainty in the measured resonance cross sections arising from uncertainties in the DIME MC parametrization.

All of the generated events are processed by a detailed GEANT4 simulation [41] of the CMS detector.

4 Event selection

The following triggers were employed:

- Zero bias: zero-bias events are selected by using either the BPTX detectors (13 TeV data) or the LHC clock signal and the known LHC bunch structure (5.02 TeV data). Both methods provided zero-bias events.
- BPTX XOR: Here XOR stands for the exclusive OR logic, where only one BPTX is fired, corresponding to an incoming proton bunch from only one direction. This trigger was used in both 5.02 and 13 TeV data sets.
- No-BPTX: There is no signal in the BPTX detectors, which means there are no incoming proton bunches. This trigger was used in both 5.02 and 13 TeV data sets.

The present analysis uses events acquired with the zero bias trigger. The BPTX XOR and No-BPTX triggers select events with no interacting bunches, which are used to estimate the electronic noise of calorimeters and possible col-

Table 1 The value of calorimeter thresholds for different calorimeter constituents, used in the selection of exclusive events

Calorimeter	Threshold [GeV]	η coverage
ECAL barrel	0.6	$\|\eta\| < 1.5$
ECAL endcap	3.3	$1.5 < \|\eta\| < 3.0$
HCAL barrel	2.0	$\|\eta\| < 1.3$
HCAL endcap	3.8	$1.3 < \|\eta\| < 3.0$
HF	4.0	$3.15 < \|\eta\| < 5.2$

lisions between beam particles and residual gas molecules in the CMS beampipe (beam-gas background). The contribution from beam-gas collisions is negligible because there is no difference in the measured calorimeter tower energy distributions for the BPTX XOR and No-BPTX triggered events.

In the offline selections, it is required that the event has exactly two tracks, both of which satisfy $\chi^2/\text{ndf} < 2$ (where the χ^2 value is calculated based on the fitted trajectory and the measured tracker hits, and ndf is the number of degrees of freedom), $p_T > 0.2$ GeV, and $|\eta| < 2.4$ to ensure high track reconstruction efficiency. Only events with oppositely charged (opposite-sign, OS) tracks are selected for analysis, whereas events with same-sign (SS) tracks are used in the background estimation.

Events with a single collision are selected by requiring the two tracks form a single reconstructed vertex subject to the constraint that

$$|z_1 - z_2| < 3\sqrt{\sigma_1^2 + \sigma_2^2}, \tag{2}$$

where z_1 and z_2 are the z coordinates of the closest approach of the reconstructed tracks to the beamline, and σ_1 and σ_2 are their corresponding uncertainties.

To select exclusive events, all calorimeter towers not matching the trajectories of the two tracks must have energy deposits below a threshold, which is defined in Table 1. A tower is matched to a track if the intersection of the extrapolated trajectory with the calorimeter surface is within three standard deviations in η and ϕ from the center of the tower. The threshold values are chosen to have a maximum 1% rejection of signal events resulting from the electronic noise of the calorimeters. Non-exclusive events might be also selected because of the lack of coverage in the eta gap between the HF and central calorimeters; these events are also taken into account in the background estimation presented later in this paper.

Using all of the above listed event selection criteria, a total of 48 961 events were selected from the 5.02 TeV and 20 980 from the 13 TeV dataset.

5 Data analysis

5.1 Particle identification

Particle identification is used to select pion pairs by the mean energy loss ($\mathrm{d}E/\mathrm{d}x$) of particles in the silicon tracking detectors. The $\mathrm{d}E/\mathrm{d}x$ values shown in the left panel of Fig. 2 are calculated by a second-order harmonic mean using only the strip detectors [42]:

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \left(\frac{1}{N} \sum_{i=1}^{N} (\Delta E/\Delta x)_i^{-2} \right)^{-\frac{1}{2}}, \tag{3}$$

where N is the number of energy loss measurements, $\Delta E/\Delta x$ is a single energy loss measurement per path length in one tracker module, and the sum runs over the strip detectors carrying energy loss measurements. The -2 exponent in this formula suppresses high $\Delta E/\Delta x$ values arising from the highly asymmetric $\Delta E/\Delta x$ Landau distribution, thus avoiding a bias in the estimate of the average $\mathrm{d}E/\mathrm{d}x$ of the track.

The track classification is achieved by fitting the mean energy loss distributions of tracks from low multiplicity ($N_{\text{track}} \leq 4$) events with a sum of three Gaussian functions corresponding to pions, kaons, and protons. An example for such a fit is shown in the right panel of Fig. 2. In the 0.3–2 GeV momentum range pions are selected from the ± 3 standard deviation region of the corresponding Gaussian peak. This region is shown in the left panel of Fig. 2. Tracks that have $p < 0.3$ or $p > 2$ GeV are assumed to be pions. The contamination from kaons and protons is estimated using the data-driven approach described in Sect. 5.3.

5.2 Corrections

Each event is weighted by several correction factors to compensate for the detector and reconstruction effects. The multiplying factor is the product of four independent corrections: tracking, multiple reconstruction, vertex, and pileup correction.

A tracking correction is used to correct for track reconstruction inefficiencies:

$$C_{\text{tr}} = \frac{1}{\varepsilon_{\text{tr},1}} \frac{1}{\varepsilon_{\text{tr},2}}, \tag{4}$$

where $\varepsilon_{\text{tr},1}$ ($\varepsilon_{\text{tr},2}$) is the tracking efficiency in the region where the first (second) particle is reconstructed. A single charged particle may lead to two reconstructed tracks, such as spiralling tracks near $\eta \approx 0$ or split tracks in the overlap region of the tracker barrel and endcap. This effect is corrected using

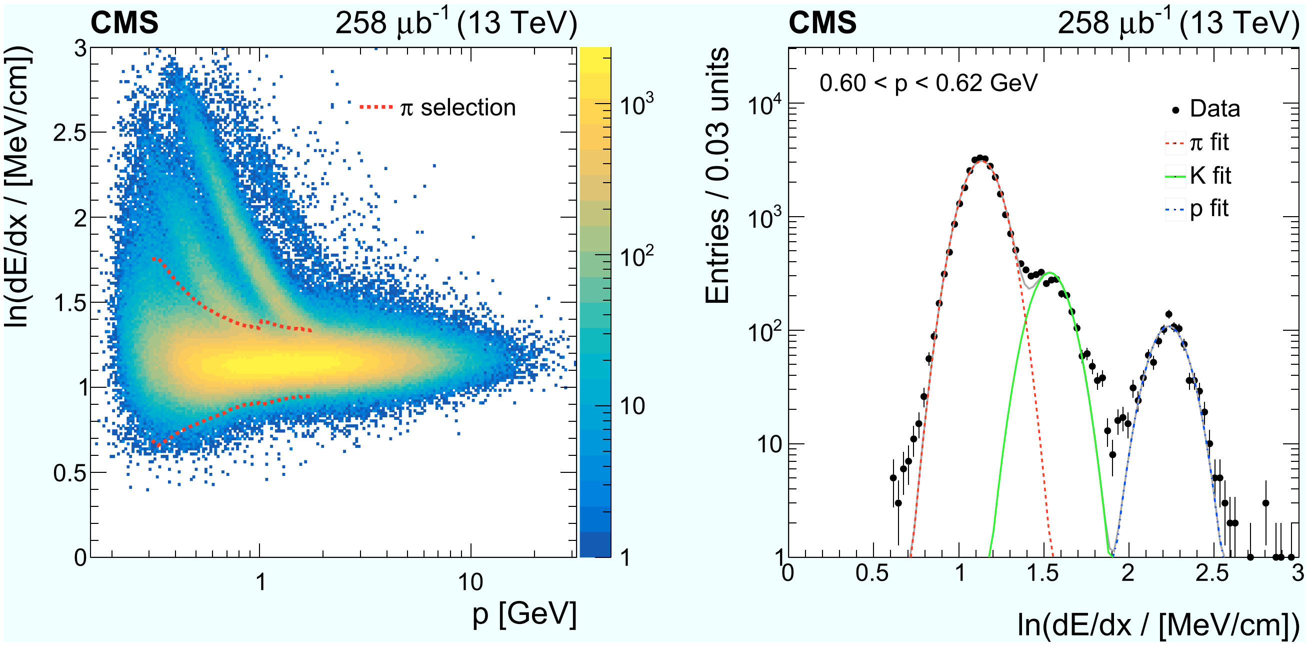

Fig. 2 Left: The distribution of the logarithm of the mean energy loss and absolute value of the momentum of tracks from low-multiplicity ($N_{\text{track}} \leq 4$) events collected at $\sqrt{s} = 13$ TeV. The π-selection region is shown in the 0.3–2 GeV range. All tracks outside this momentum range are identified as pions. Right: The fit of energy loss distributions in a given momentum bin with the sum of three Gaussian curves. Plots are similar for the 5.02 TeV data

$\varepsilon_{\text{mrec}}$, which is the probability for this situation to occur. In this case the correction factor takes the form

$$C_{\text{mrec}} = \frac{1}{1-\varepsilon_{\text{mrec},1}} \frac{1}{1-\varepsilon_{\text{mrec},2}}. \quad (5)$$

The values of ε_{tr} and $\varepsilon_{\text{mrec}}$ are estimated as a function of η and p_{T} using MC simulations. Their dependence on the track ϕ and the vertex position z-coordinate is integrated over. The simulated events are weighted such that the vertex z-coordinate distribution agrees with collision data.

The vertex correction C_{vert} accounts for events with an unreconstructed vertex. It is the reciprocal of the vertex efficiency, which is calculated using samples produced by the DIME MC and STARLIGHT generators. The vertex efficiency has a slight dependence on the invariant mass of the track pair that is included when applying the vertex correction.

Some real CEP events are rejected because of pileup. To account for these lost events, a correction factor C_{pu} for the number of selected events can be computed. The CEP events are selected from bunch crossings with a single collision, so by assuming that the number of collisions follows a Poisson distribution, one can derive C_{pu}:

$$C_{\text{pu}} = \frac{N\mu}{N\,\mu\exp(-\mu)} = \exp(\mu). \quad (6)$$

Table 2 Correction factors

Type	Range
Tracking	1.05–1.50
Multiple reconstruction	1.005–1.040
Vertex	1.05–1.33
Pileup	1.3–2.1

Here, μ is the average number of visible inelastic collisions, in a given bunch crossing, N is the total number of analyzed events. The value of μ depends on the instantaneous luminosity associated with individual bunch crossings, $\mathcal{L}_{\text{bunch}}$, according to the following expression:

$$\mu = \frac{\sigma_{\text{inel,vis}}\mathcal{L}_{\text{bunch}}}{f}, \quad (7)$$

where $\sigma_{\text{inel,vis}}$ is the visible inelastic pp cross section, f is the revolution frequency of protons, and $\mathcal{L}_{\text{bunch}}$ is the average instantaneous luminosity at the given bunch crossing position for time periods of 23.3 s. The ratio of $\sigma_{\text{inel,vis}}$ to f is obtained by fitting the fraction of events with no observed collisions as a function of $\mathcal{L}_{\text{bunch}}$ with the functional form $A\exp(-b\,\mathcal{L}_{\text{bunch}})$, where A and b are free parameters of the fit.

The range of correction factors is summarized in Table 2.

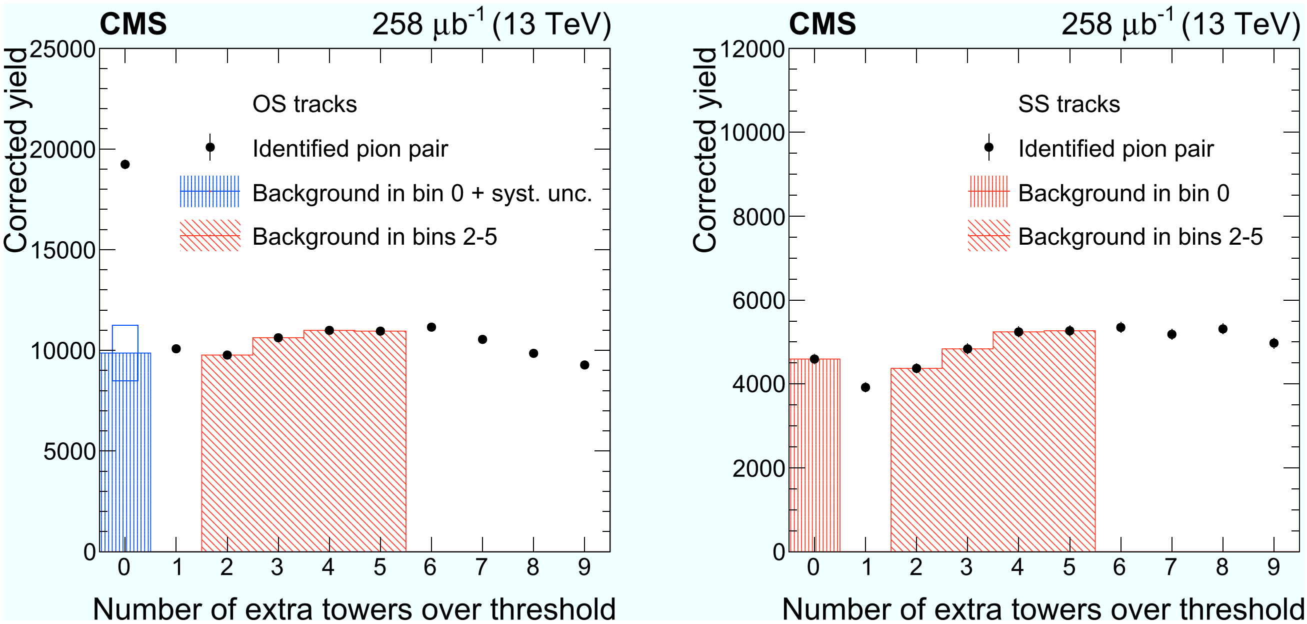

Fig. 3 The number of extra calorimeter towers over threshold in events containing an identified pion pair with opposite (left) and same (right) charge. The known contributions, denoted with the red hatched areas, are used to estimate the background in the zero bin of the opposite-sign distribution, which is denoted by the blue hatched area. The error bars correspond to statistical uncertainties, whereas the error rectangle on the background denotes the 14% systematic uncertainty in the background normalization. Plots are similar for 5.02 TeV data

5.3 Background estimation

The main background contributions to $\pi^+\pi^-$ CEP are the multiparticle background and the exclusive $K^+K^-/p\bar{p}$ production. The multiparticle background in the selected exclusive sample consists of events with more than two particles created in the interaction, of which only two are observed because the additional particles yield energy deposits below the thresholds, or outside the acceptance. The SD, DD, ND, and CD processes with more than two centrally produced particles belong to this contribution. A method based on control regions is used to estimate this multiparticle background. Control regions are selected in which events have at least two calorimeter towers above threshold, not matched to the two selected pions, with all the other selection criteria satisfied. The distribution of the number of events selected in this way as a function of the number of extra towers with energy above threshold is shown in Fig. 3. The counts in the bins with 2, 3, 4, and 5 towers are used to estimate the background. The normalization factor is calculated using the following assumption:

$$\frac{N_{\text{mpart,SS}}(0\text{ extra towers})}{N_{\text{mpart,SS}}(2\text{–}5\text{ extra towers})} = \frac{N_{\text{mpart,OS}}(0\text{ extra towers})}{N_{\text{mpart,OS}}(2\text{–}5\text{ extra towers})}, \quad (8)$$

where $N_{\text{mpart,OS/SS}}$ is the number of multiparticle events with two OS or SS tracks. The validity of this assumption is checked by comparing the true and predicted number of background events in inclusive MC samples (Table 3). The observed discrepancy reflects the differences between OS and SS events and is included as a systematic uncertainty in the estimate of the total number of multiparticle background events, as discussed in Sect. 5.4. With this formula and the fact that all SS events are multiparticle events because of charge conservation, it is possible to calculate the value of $N_{\text{mhad,OS}}(0\text{ towers})$, which is the number of multiparticle background events. The expected distribution of the multiparticle background is obtained using OS events with 2–5 extra calorimeter towers.

This method does not take into account the background contribution from $\omega \to \pi^+\pi^-\pi^0$, because this decay cannot be observed in the SS events. This latter contribution is negligible (0.5%) based on MC simulation results.

Table 3 Checking the validity of Eq. (8) by comparing the true and predicted number of background events in inclusive MC samples

Event generator	Difference in normalization
EPOS	$(+11 \pm 4)\%$
PYTHIA 8 CUETP8M1	$(-5.5 \pm 3)\%$
PYTHIA 8 MBR	$(+10 \pm 4)\%$

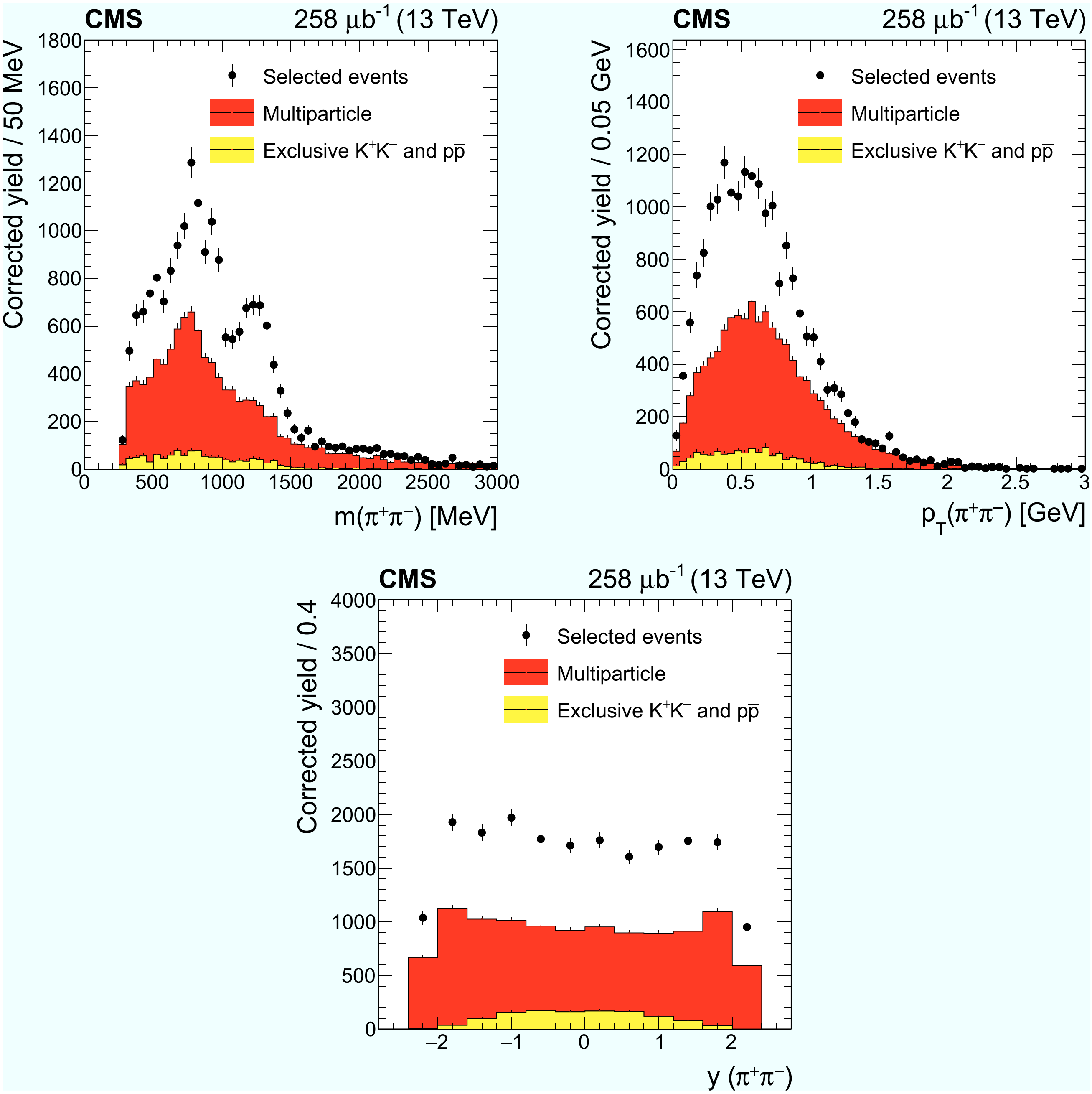

Fig. 4 Background distributions as functions of kinematic variables estimated by data-driven methods. The proton dissociation background is not shown here, since it is included via scaling of the final cross section values. The error bars correspond to statistical uncertainties. The results for the 5.02 TeV data set are similar

Genuine exclusive K^+K^- and $p\bar{p}$ events, where both particles are misidentified as pions, are included in the previous multiparticle background estimate. To correct for this contribution, the K/π ratios are calculated in the exclusive events using tracks with $p < 1$ GeV. Similarly, the p/π ratio is calculated in the same sample in the range $1 < p < 2$ GeV. The K/π and p/π ratios are assumed to be $0.3^{+0.1}_{-0.05}$ in the region $p > 1$ and $p > 2$ GeV, respectively [43]. Using this assumption and the measured ratios, the average K/π and p/π ratios are then calculated over the entire momentum range of the exclusive sample. These average ratios can then be used to compute the number of K^+K^- and $p\bar{p}$ events under two extreme scenarios. The first scenario assumes that the production of a K or a p is always accompanied by the production of its antiparticle, whereas in the second scenario it is assumed that the production of an individual K^+, K^-, p, or $\overline{\mathrm{p}}$ is a totally independent process. The final estimate of the exclusive $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{p}\overline{\mathrm{p}}$ background normalization is calculated as the average of the estimates obtained from assuming these two scenarios. According to these calculations, there is an 11% residual contribution of exclusive $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{p}\overline{\mathrm{p}}$ events in the sample after the multiparticle background subtraction. The background distributions of this contribution are calculated by using two-track OS exclusive events with at least one identified $\mathrm{K}^\pm$ (Fig. 4).

The estimated multiparticle and exclusive $\mathrm{K}^+\mathrm{K}^-/\mathrm{p}\overline{\mathrm{p}}$ background distributions, as functions of the main kinematic variables, are shown in Fig. 4. These two background contributions are subtracted from the measured distributions. The background subtracted spectra are divided by the integrated luminosity to obtain the differential cross sections.

5.4 Systematic uncertainties

Systematic uncertainties in the measured cross sections originate from various sources. These include reconstruction effects, particle identification, correction factors, background estimation, and the luminosity estimation. The uncertainty assigned to the tracking efficiency in the case of a single track is 3.9% [29], which corresponds to 7.8% uncertainty for two tracks. Furthermore, the uncertainty in the multiple reconstruction rate for a single track is also 3.9%, which propagates to a maximum of 0.4% uncertainty in the cross section for two tracks, which is neglected in the analysis. Misreconstructed tracks bias the sample in two ways: either a CEP event is rejected if a third misreconstructed track is found, or an event is identified as CEP with a misreconstructed and a genuine track. This source of systematic uncertainty is estimated to be 1% for a single track, which is the maximal misreconstruction rate calculated using inclusive MC samples in the kinematic region ($p_{\mathrm{T}}(\pi) > 0.2$ GeV and $|\eta(\pi)| < 2.4$) of the analysis. Since the probability to have two or more misreconstructed tracks in these low-multiplicity events is negligible, the final uncertainty remains 1%. From the comparison of the DIME MC and STARLIGHT simulations, the uncertainty of the vertex correction is estimated to be 1%.

The systematic uncertainty in the pileup correction factor for a single event is calculated from only the systematic uncertainties in the luminosity measurement that do not affect its overall normalization. Indeed, the normalization-related systematic uncertainties are compensated in the exponential fit described in Sect. 5.2. The uncertainties that do not affect the normalization are estimated to be 1.6% and 1.5% for 5.02 [44] and 13 TeV [45] data, respectively. These values propagate to a 1% uncertainty in the pileup correction factor for a single event. After adding up all the selected events, the pileup uncertainty becomes smaller than 0.1%, which is neglected in the following.

The measured signal yield is affected by the uncertainty arising from the two effects associated with calorimeter noise and veto inefficiency caused by the adopted energy thresholds. A genuine CEP event can be erroneously discarded if the calorimeter noise appears above the energy thresholds used in the veto. Conversely a nonCEP event can pass the final selection if the extra particles pass the veto requirements. In the HF, these uncertainties are estimated by varying the calorimeter energy thresholds by ±10% [46]. The resulting uncertainty is estimated to be 3% for both the 5.02 and 13 TeV data sets. Similarly, the ECAL and HCAL thresholds are varied by ±5% [47,48], which results in a 1% uncertainty in the corrected yields at both energies.

The systematic uncertainty estimation of the multiparticle background is done by varying the control region used in the background estimation procedure: 1–2, 2–9, and 5–9 extra towers. The estimate of the systematic uncertainty in the multiparticle background normalization is 10%. Additionally, a 10% uncertainty is added to this value quadratically, taking into account the deviations shown in Table 3; thus the final uncertainty in the multiparticle background normalization is 14%. After subtracting this contribution, this propagates to systematic uncertainties depending on the invariant mass, transverse momentum and rapidity of the pion pair. The multiparticle background estimation uncertainty varies between 10–20% below 1500 MeV. Over 1500 MeV the uncertainty varies between 20–60%, because the signal versus background ratio is much smaller. The average uncertainty, used as the systematic uncertainty of the total cross section, is 15%.

The exclusive $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{p}\overline{\mathrm{p}}$ background uncertainty comes from three sources: (1) multiparticle contamination in the $\mathrm{d}E/\mathrm{d}x$ vs. momentum distribution that modifies the K/π and p/π ratios, (2) the uncertainty in the K/π ratio above 1 GeV, and (3) the uncertainty in the p/π ratio above 2 GeV. The multiparticle contamination is estimated by checking the difference between two extreme cases: all particle types are produced independently, or the sample is purely exclusive. The results correspond to an uncertainty of 70% in the normalization of this background contribution at both energies. To account for the uncertainty of K/π above 1 GeV and p/π over 2 GeV, the exclusive background normalization is calculated assuming different values (0.25, 0.30, and 0.40 [43]) for the K/π and p/π ratios in these regions. The uncertainties assigned to these effects are 16 and 4%, respectively. Thus the total systematic uncertainty of the exclusive $\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{p}\overline{\mathrm{p}}$ background normalization is 72%. After subtracting this background contribution, this propagates to systematic uncertainties, which depend on the invariant mass, transverse momentum, and rapidity of the pion pair. The typical range of this systematic uncertainty contribution is 5–20%. For the total cross section, this source contributes to an average uncertainty of 6%.

Table 4 The sources and average values of systematic uncertainties, used as the systematic uncertainty of the total cross section

Source	Average value
Tracking efficiency	7.8%
Misreconstructed tracks	1%
Vertex	1%
HF energy scale	3%
ECAL and HCAL energy scale	1%
Multiparticle background	15%
Exclusive K^+K^- and $p\bar{p}$ background	6%
Total w/o int. luminosity	18.3%
+ Integrated luminosity	2.3%

All of the systematic uncertainties listed above are the same for the 5.02 and 13 TeV data sets. Additionally, the systematic uncertainty in the integrated luminosity is 2.3% [44,45]. The average values of the systematic uncertainties are summarized in Table 4. The total systematic uncertainty is obtained by adding the individual contributions in quadrature. All systematic uncertainty contributions are considered fully correlated across invariant mass bins.

6 Results

The differential cross sections are calculated from the selected events as functions of the invariant mass, transverse momentum, and rapidity of the pion pair. These are shown in Fig. 5 with the generator-level predictions from the STARLIGHT and DIME MC generators, normalized to their cross sections. The MC generators provide an incomplete description of the available data, since they do not model the $f_0(500)$, $f_0(980)$, and $f_2(1270)$ resonances as mentioned in Sect. 3.

There is a peak at 800 MeV, which corresponds to the $\rho^0(770)$ resonance. Since its quantum numbers $I^G(J^{PC}) = 1^+(1^{--})$ are forbidden in DPE processes, the ρ^0 mesons must be produced in VMP processes. The sharp drop visible around 1000 MeV is expected from previous measurements [11,16] and can be attributed to the quantum mechanical interference of $f_0(980)$ with the continuum contribution. There is a prominent peak at 1200–1300 MeV, which corresponds to the $f_2(1270)$ resonance with $I^G(J^{PC}) = 0^+(2^{++})$ quantum numbers. This resonance is produced via a DPE process.

Both DIME MC and STARLIGHT underestimate the measured spectrum as these MC event generators do not model the forward dissociation of protons.

The total cross section of the CEP process with two pions in the final state in the kinematic region $p_T(\pi) > 0.2$ GeV and $|\eta(\pi)| < 2.4$ is obtained by integrating the observed spectra in this region:

$$\sigma_{pp\to p'p'\pi^+\pi^-}(\sqrt{s} = 5.02\,\text{TeV}) = 32.6 \pm 0.7\,(\text{stat}) \pm 6.0\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\mu\text{b}, \tag{9}$$

$$\sigma_{pp\to p'p'\pi^+\pi^-}(\sqrt{s} = 13\,\text{TeV}) = 33.7 \pm 1.0\,(\text{stat}) \pm 6.2\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\mu\text{b}. \tag{10}$$

Below, it is demonstrated that the measured invariant $\pi^+\pi^-$ mass spectrum is well-described by the sum of the continuum distributions obtained from the DIME MC model and four dominant resonances, modeled here by Breit-Wigner functions. In the fitting procedure the quantum mechanical interference effect and the detector resolution are also included.

The following fit function is used:

$$f(m) = \int G(m - m'; \sigma)\Big[|A^{\rho^0}_{\text{RBW}}(m')|^2 + |A^{f_0(500)}_{\text{RBW}}(m')e^{i\phi^{f_0(500)}m'} + A^{f_0(980)}_{\text{RBW}}(m')e^{i\phi^{f_0(980)}m'} + A^{f_2}_{\text{RBW}}(m')e^{i\phi^{f_2}m'} + b\,B^{\text{DIME}}(m')|^2\Big]\text{d}m'. \tag{11}$$

Here $G(m;\sigma)$ is a Gaussian distribution with variance σ and zero mean, $B^{\text{DIME}}(m)$ is the nonresonant background estimated from the DIME MC using the Orear-type form factor, and b is a scale factor for the continuum contribution, and $\phi^{f_0(500)}$, $\phi^{f_0(980)}$, and ϕ^{f_2} are phases that characterize interference effects. The $A^i_{\text{RBW}}(m)$ is the relativistic Breit–Wigner amplitude, which can be written as [49]:

$$A^{i,J}_{\text{RBW}}(m) = A_i \frac{\sqrt{mM_i\Gamma(m)}}{m^2 - M_i^2 + iM_i\Gamma(m)}, \tag{12}$$

$$\Gamma(m) = \Gamma_i \frac{M_i}{m}\left[\frac{m^2 - 4m_\pi^2}{M_i^2 - 4m_\pi^2}\right]^{\frac{2J+1}{2}}, \tag{13}$$

where A_i, M_i, and Γ_i are the yield, mass, and width of the resonance, respectively, m_π is the mass of charged pions, and J is the total angular momentum of the resonance. According to Ref. [2], the magnitude of the interference between the DPE and VMP processes is around 1%, therefore no interference term is used between ρ^0 and DPE resonances. The convolution with the Gaussian distribution models the mass resolution of the detector.

The mass resolution (σ) is calculated by fitting the distribution of the difference between generator-level and reconstructed mass from the STARLIGHT and DIME MC simulations. Based on these calculations, the mass resolution is found to vary from 9 to 14 MeV in the mass range 500–2000 MeV. In the final fit, an effective mass resolution of 11 MeV is used and the systematic uncertainty associated with this value is

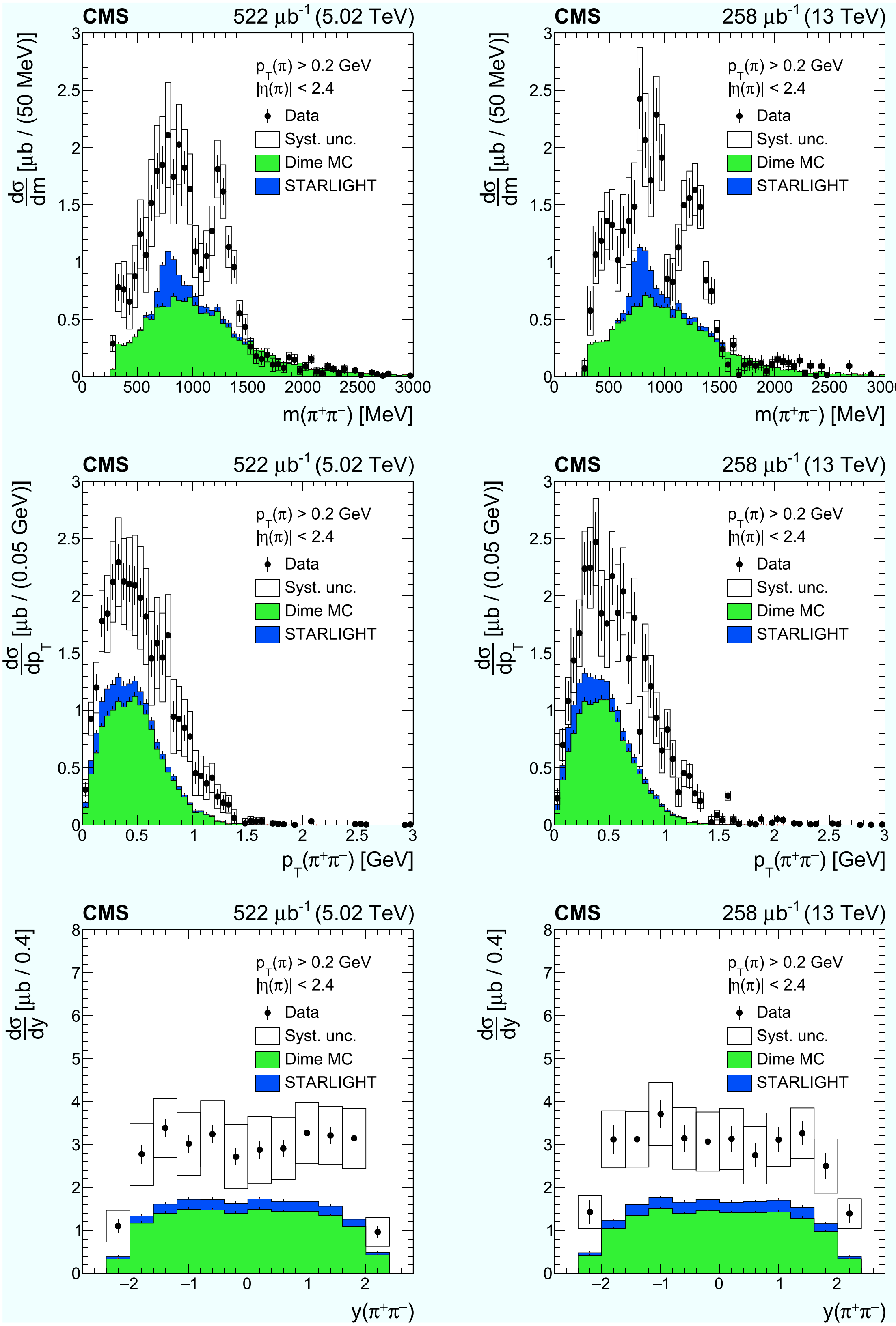

Fig. 5 Differential cross sections as functions of mass (upper row), transverse momentum (middle row), and rapidity (bottom row), compared with generator-level simulations for the 5.02 (left) and 13 TeV (right) data sets. The error bars correspond to statistical, whereas the open boxes to systematic uncertainties

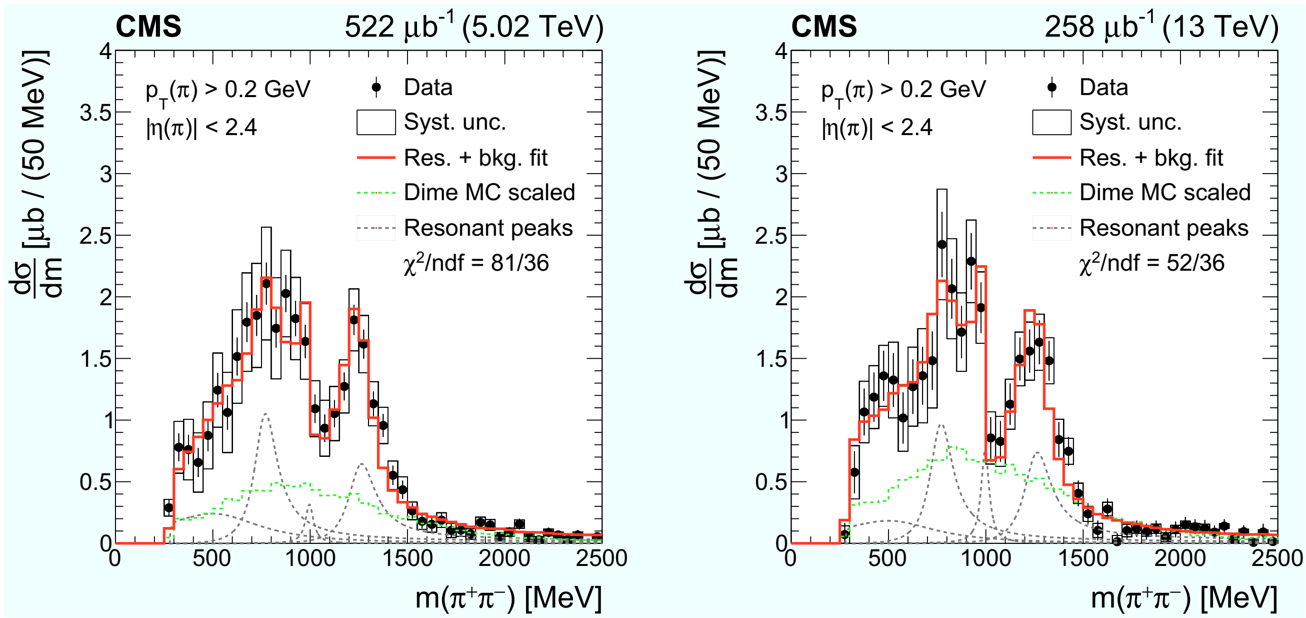

Fig. 6 Fit to the measured cross section with the sum of four interfering relativistic Breit–Wigner functions convolved with a normal distribution (to account for the the experimental resolution of the detector) for the 5.02 (left) and 13 TeV (right) data sets. The error bars correspond to statistical, whereas the open boxes correspond to systematic uncertainties

Table 5 Cross sections of the resonant processes in the $p_{\mathrm{T}}(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$ fiducial region, extracted from the simple model fit using the sum of the continuum distribution obtained from the DIME MC model and four dominant resonances. The luminosity-related uncertainties are included in the systematic uncertainties. The STARLIGHT predictions for $\mathrm{pp} \rightarrow \mathrm{p'p'}\rho^0 \rightarrow \mathrm{p'p'}\pi^+\pi^-$ processes are 2.3 and 3.0 μb for 5.02 and 13 TeV, respectively, which is compatible with the fit results

Resonance	$\sigma_{\mathrm{pp}\rightarrow\mathrm{p'p'}X\rightarrow\mathrm{p'p'}\pi^+\pi^-}$ [μb]	
	$\sqrt{s} = 5.02$ TeV	$\sqrt{s} = 13$ TeV
$f_0(500)$	$2.8 \pm 1.4\,(\mathrm{stat}) \pm 2.2\,(\mathrm{syst})$	$2.2 \pm 0.8\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})$
$\rho^0(770)$	$4.7 \pm 0.9\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})$	$4.3 \pm 1.3\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})$
$f_0(980)$	$0.5 \pm 0.1\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst})$	$1.1 \pm 0.4\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})$
$f_2(1270)$	$3.6 \pm 0.6\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst})$	$4.2 \pm 0.9\,(\mathrm{stat}) \pm 0.8\,(\mathrm{syst})$

taken into account by repeating the fit with a mass resolution varying from 9 to 14 MeV. The resulting systematic uncertainty is 7–8% for the yield of $f_0(980)$ and around 1–2% for the yields of the $f_0(500)$, $\rho^0(770)$, and $f_2(1270)$ resonances. The impact of the uncertainty in the multiparticle (exclusive K^+K^- and $p\bar{p}$) background yield is included by varying the background normalization in the fit by ±14% (±72%).

The masses and widths of $\rho^0(770)$ and $f_2(1270)$ resonances are fixed to the values of Ref. [24]. The mass and width of $f_0(500)$ and $f_0(980)$ are fixed according to the results from the most advanced calculations using dispersion relations [50].

The fits are also performed with the mass and width of $f_0(500)$ and $f_0(980)$ varied according to their uncertainties [24] and the resulting variation in the cross section of the resonances is added in quadrature to the other systematic uncertainty contributions. Furthermore the fit is repeated with the two other DIME MC settings and the variation in the cross section is taken as an additional systematic uncertainty and added in quadrature to the other uncertainties.

The above simple model fit also provides values for the cross sections of the resonances; these are obtained by integrating the fitted squared amplitudes from the dipion threshold ($2m_\pi$) to $M_i + 5\Gamma_i$:

$$\sigma_i^{\mathrm{res}} = \int_{2m_\pi}^{M_i+5\Gamma_i} |A^2_{\mathrm{RBW},i}(m)|\mathrm{d}m. \tag{14}$$

The fits are shown in Fig. 6 and the cross sections are summarized in Table 5.

The model of interfering Breit–Wigner resonances with a continuum gives a good description of the data in the region of resonant peaks (below 1500 MeV). The cross sections for $\rho^0(770)$ production calculated from the fits are slightly larger than the predicted values from STARLIGHT, which are 2.3 and 3.0μbfor 5.02 and 13 TeV, respectively. The differences can be attributed to the additional semiexclusive contribution that is not modeled by STARLIGHT. The values of the scale parameter b are 0.7 ± 0.2 for 5.02 TeV and 1.1 ± 0.3 for 13 TeV, and therefore they are consistent within uncertainties for the two energies.

7 Summary

The cross sections for central exclusive pion pair production have been measured in pp collisions at 5.02 and 13 TeV center-of-mass energies. Exclusive events are selected by vetoing additional energy deposits in the calorimeters and by requiring two oppositely charged pions identified via their mean energy loss in the tracker detectors. These events are used together with correction factors to obtain invariant mass, transverse momentum, and rapidity distributions of the $\pi^+\pi^-$ system. The measured total exclusive $\pi^+\pi^-$ production cross section is $32.6 \pm 0.7\,(\text{stat}) \pm 6.0\,(\text{syst}) \pm 0.8\,(\text{lumi})$ and $33.7 \pm 1.0\,(\text{stat}) \pm 6.2\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\mu\text{b}$ for 5.02 and 13 TeV, respectively. The observed mass spectrum exhibits resonant structures, which can be fitted with a simple model containing four interfering Breit-Wigner functions, corresponding to the $f_0(500)$, $\rho^0(770)$, $f_0(980)$, and $f_2(1270)$ resonances, and a continuum contribution modeled by the DIME MC. The exclusive production cross sections are extracted from this fit. The obtained cross sections of $\rho^0(770)$ production are higher than the STARLIGHT model prediction, which can be explained by the presence of semiexclusive production which is not modeled by the STARLIGHT generator.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 14.W03.31.0026 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program and "Nauka" Project FSWW-2020-0008 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as written in its document "CMS data preservation, re-use and open access policy" (https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=6032&filename=CMSDataPolicyV1.2.pdf&version=2).]

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Funded by SCOAP^3.

References

1. P. Lebiedowicz, A. Szczurek, Exclusive $pp \to pp\pi^+\pi^-$ reaction: From the threshold to LHC. Phy. Rev. D **81**, 036003 (2010). https://doi.org/10.1103/PhysRevD.81.036003. arXiv:0912.0190

2. P. Lebiedowicz, O. Nachtmann, A. Szczurek, Central exclusive diffractive production of $\pi^+\pi^-$ continuum, scalar and tensor resonances in pp and p$\bar{\text{p}}$ scattering within tensor pomeron approach. Phys. Rev. D **93**, 054015 (2016). https://doi.org/10.1103/PhysRevD.93.054015. arXiv:1601.04537
3. P. Lebiedowicz, O. Nachtmann, A. Szczurek, ρ^0 and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies. Phys. Rev. D **91**, 074023 (2015). https://doi.org/10.1103/PhysRevD.91.074023. arXiv:1412.3677
4. A. Bolz et al., Photoproduction of $\pi^+\pi^-$ pairs in a model with tensor-pomeron and vector-odderon exchange. JHEP **01**, 151 (2015). https://doi.org/10.1007/JHEP01(2015)151. arXiv:1409.8483
5. L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, Modelling exclusive meson pair production at hadron colliders. Eur. Phys. J. C **74**, 2848 (2014). https://doi.org/10.1140/epjc/s10052-014-2848-9. arXiv:1312.4553
6. L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Probing the perturbative dynamics of exclusive meson pair production. Phys. Lett. B **725**, 316 (2013). https://doi.org/10.1016/j.physletb.2013.07.022. arXiv:1304.4262
7. R.A. Ryutin, Central exclusive diffractive production of two-pion continuum at hadron colliders. Eur. Phys. J. C **79**, 981 (2019). https://doi.org/10.1140/epjc/s10052-019-7497-6. arXiv:1910.06683
8. E690 Collaboration, Partial wave analysis of the centrally produced K_S K_S system at 800 GeV/c. Phys. Rev. Lett. **81**, 4079 (1998). https://doi.org/10.1103/PhysRevLett.81.4079
9. WA102 Collaboration, A partial wave analysis of the centrally produced K^+K^- and $K^0_SK^0_S$ systems in pp interactions at 450GeV/c and new information on the spin of the $f_J(1710)$. Phys. Lett. B **453**, 305 (1999). https://doi.org/10.1016/S0370-2693(99)00365-2, arXiv:hep-ex/9903042
10. WA102 Collaboration, A partial wave analysis of the centrally produced $\pi^0\pi^0$ system in pp interactions at 450GeV/c. Phys. Lett. B **453**, 325 (1999). https://doi.org/10.1016/S0370-2693(99)00367-6, arXiv:hep-ex/9903044
11. WA102 Collaboration, A partial wave analysis of the centrally produced $\pi^+\pi^-$ system in pp interactions at 450GeV/c. Phys. Lett. B **453**, 316 (1999). https://doi.org/10.1016/S0370-2693(99)00366-4, arXiv:hep-ex/9903043
12. ABCDHW Collaboration, Production of the f_0 meson in the double pomeron exchange reaction pp $\to$ pp$\pi^+\pi^-$ at $\sqrt{s} = 62$ GeV. Z. Phys. C **31**, 185 (1986). https://doi.org/10.1007/BF01479525
13. ABCDHW Collaboration, The reaction pomeron-pomeron $\to$ $\pi^+\pi^-$ and an unusual production mechanism for the $f_2(1270)$. Z. Phys. C **48**, 569 (1990). https://doi.org/10.1007/BF01614690
14. ABCDHW Collaboration, Evidence for $f_2(1720)$ production in the reaction pomeron-pomeron $\to \pi^+\pi^-\pi^+\pi^-$. Z. Phys. C **58**, 251 (1993). https://doi.org/10.1007/BF01560342
15. Axial-Field Spectrometer Collaboration, A search for glueballs and a study of double pomeron exchange at the CERN Intersecting Storage Rings. Nucl. Phys. B **264**, 154 (1985). https://doi.org/10.1016/0550-3213(86)90477-3
16. CDF Collaboration, Measurement of central exclusive $\pi^+\pi^-$ production in p$\bar{\text{p}}$ collisions at $\sqrt{s} = 0.9$ and 1.96 TeV at CDF. Phys. Rev. D **91**, 091101 (2015). https://doi.org/10.1103/PhysRevD.91.091101, arXiv:1502.01391
17. H1 Collaboration, Elastic photoproduction of J/ψ and Υ mesons at HERA. Phys. Lett. B **483**, 23 (2000). https://doi.org/10.1016/S0370-2693(00)00530-X. arXiv:hep-ex/0003020
18. Z.E.U.S. Collaboration, Exclusive photoproduction of Υ mesons at HERA. Phys. Lett. B **680**, 4 (2009). https://doi.org/10.1016/j.physletb.2009.07.066. arXiv:0903.4205
19. J.R. Forshaw, D.A. Ross, *Quantum Chromodynamics and the Pomeron* (Cambridge University Press, Cambridge, 1997). https://doi.org/10.1017/CBO9780511524387. (ISBN 9780511524387)
20. S. Donnachie, G. Dosch, P. Landshoff, O. Nachtmann, Cambridge University Press. Pomeron Physics and QCD (2002). https://doi.org/10.1017/CBO9780511534935. (ISBN 9780511534935)
21. W. Ochs, The status of glueballs. J. Phys. G **40**, 043001 (2013). https://doi.org/10.1088/0954-3899/40/4/043001. arXiv:1301.5183
22. A.A. Godizov, High-energy central exclusive production of the lightest vacuum resonance related to the soft pomeron. Phys. Lett. B **787**, 188 (2018). https://doi.org/10.1016/j.physletb.2018.10.061. arXiv:1810.01824
23. A.J. Baltz, Y. Gorbunov, S.R. Klein, J. Nystrand, Two-Photon Interactions with Nuclear Breakup in Relativistic Heavy Ion Collisions. Phys. Rev. C **80**, 044902 (2009). https://doi.org/10.1103/PhysRevC.80.044902. arXiv:0907.1214
24. Particle Data Group, M. Tanabashi et al., Review of particle physics. Phys. Rev. D **98**, 030001 (2018). https://doi.org/10.1103/PhysRevD.98.030001
25. S. Okubo, ϕ-meson and unitary symmetry model. Phys. Lett. **5**, 165 (1963). https://doi.org/10.1016/S0375-9601(63)92548-9
26. G. Zweig, An SU(3) model for strong interaction symmetry and its breaking. version 2, in *Developments in the quark theory of hadrons. vol 1. 1964–1978*, D. Lichtenberg and S. P. Rosen, eds., p. 22, 1964
27. J. Iizuka, Systematics and phenomenology of meson family. Prog. Theor. Phys. Suppl. **37**, 21 (1966). https://doi.org/10.1143/PTPS.37.21
28. H.B. O'Connell, B.C. Pearce, A.W. Thomas, A.G. Williams, ρ-ω mixing, vector meson dominance and the pion form-factor. Prog. Part. Nucl. Phys. **39**, 201 (1997). https://doi.org/10.1016/S0146-6410(97)00044-6. arXiv:hep-ph/9501251
29. C.M.S. Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker. JINST **9**, P10009 (2014). https://doi.org/10.1088/1748-0221/9/10/P10009. arXiv:1405.6569
30. C.M.S. Collaboration, CMS Tracking Performance Results from Early LHC Operation. Eur. Phys. J. C **70**, 1165 (2010). https://doi.org/10.1140/epjc/s10052-010-1491-3. arXiv:1007.1988
31. C.M.S. Collaboration, The CMS trigger system. JINST **12**, P01020 (2017). https://doi.org/10.1088/1748-0221/12/01/P01020. arXiv:1609.02366
32. C.M.S. Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004
33. C.M.S. Collaboration, Measurement of diffraction dissociation cross sections in pp collisions at $\sqrt{s} = 7$ TeV. Phys. Rev. D **92**, 012003 (2015). https://doi.org/10.1103/PhysRevD.92.012003. arXiv:1503.08689
34. T. Sjöstrand et al., An Introduction to PYTHIA 8.2. Comput. Phys. Commun. **191**, 159 (2015). https://doi.org/10.1016/j.cpc.2015.01.024. arXiv:1410.3012
35. C.M.S. Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements. Eur. Phys. J. C **76**, 155 (2016). https://doi.org/10.1140/epjc/s10052-016-3988-x. arXiv:1512.00815
36. R. Ciesielski, K. Goulianos, MBR Monte Carlo Simulation in PYTHIA8. PoS ICHEP2012 **2013**, 301 (2013). https://doi.org/10.22323/1.174.0301, arXiv:1205.1446
37. K. Werner, F.-M. Liu, T. Pierog, Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at RHIC. Phys. Rev. C **74**, 044902 (2006). https://doi.org/10.1103/PhysRevC.74.044902. arXiv:hep-ph/0506232
38. T. Pierog et al., EPOS LHC: test of collective hadronization with data measured at the CERN Large Hadron Collider. Phys. Rev. C

39. H.J. Drescher et al., Parton based Gribov-Regge theory. Phys. Rept. **350**, 93 (2001). https://doi.org/10.1016/S0370-1573(00)00122-8. arXiv:hep-ph/0007198
40. S.R. Klein, J. Nystrand, Photoproduction of quarkonium in proton-proton and nucleus-nucleus collisions. Phys. Rev. Lett. **92**, 142003 (2004). https://doi.org/10.1103/PhysRevLett.92.142003. arXiv:hep-ph/0311164
41. GEANT4 Collaboration, GEANT4–a simulation toolkit. Nucl. Instrum. Meth. A **506**, 250 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8
42. L. Quertenmont, Particle identification with ionization energy loss in the CMS silicon strip tracker. Nucl. Phys. Proc. Suppl. **215**, 95 (2011). https://doi.org/10.1016/j.nuclphysbps.2011.03.145
43. CMS Collaboration, Study of the inclusive production of charged pions, kaons, and protons in pp collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV. Eur. Phys. J. C **72**, 2164 (2012). https://doi.org/10.1140/epjc/s10052-012-2164-1, arXiv:1207.4724
44. CMS Collaboration, CMS luminosity calibration for the pp reference run at $\sqrt{s} = 5.02$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-16-001 (2016)
45. CMS Collaboration, CMS luminosity measurement for the 2015 data-taking period, CMS Physics Analysis Summary CMS-PAS-LUM-15-001 (2017)
46. CMS Collaboration, Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV. JHEP **11**, 148 (2011). https://doi.org/10.1007/JHEP11(2011)148, arXiv:1110.0211. [Erratum: https://doi.org/10.1007/JHEP02(2012)055]
47. C.M.S. Collaboration, Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV. JINST **8**, P09009 (2013). https://doi.org/10.1088/1748-0221/8/09/P09009. arXiv:1306.2016
48. C.M.S. Collaboration, Calibration of the CMS hadron calorimeters using proton-proton collision data at $\sqrt{s} = 13$ TeV. J. Instrum. **15**, P05002 (2019). arXiv:1910.00079
49. J.D. Jackson, Remarks on the phenomenological analysis of resonances. Il Nuovo Cim. **34**, 1644 (1964). https://doi.org/10.1007/BF02750563
50. R. Garcia-Martin, R. Kaminski, J.R. Pelaez, J. Ruiz de Elvira, Precise determination of the $f_0(600)$ and $f_0(980)$ pole parameters from a dispersive data analysis. Phys. Rev. Lett. **107**, 072001 (2011). https://doi.org/10.1103/PhysRevLett.107.072001. arXiv:1107.1635

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M. R. Darwish, E. A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, 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, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A. K. Kalsi, J. Luetic, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, I. Khvastunov[2], C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrzkowski, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F. L. Alves, G. A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E. M. Da Costa, G. G. Da Silveira[4],

D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, J. Martins[5], D. Matos Figueiredo, M. Medina Jaime[6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, L. J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E. J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista[a], Universidade Federal do ABC[b], São Paulo, Brazil
S. Ahuja[a], C. A. Bernardes[a], L. Calligaris[a], T. R. Fernandez Perez Tomei[a], E. M. Gregores[b], D. S. Lemos, P. G. Mercadante[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, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[7], X. Gao[7], L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
M. Ahmad, G. M. Chen, H. S. Chen, M. Chen, C. H. Jiang, D. Leggat, H. Liao, Z. Liu, S. M. Shaheen[8], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S. J. Qian, D. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, C. F. González Hernández, M. A. Segura Delgado

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

Faculty of Science, University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

University of Cyprus, Nicosia, Cyprus
M. W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[10], M. Finger Jr.[10], 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
M. A. Mahmoud[11,12], Y. Mohammed[11]

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, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, J. Havukainen, J. K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Ö. Sahin, A. Savoy-Navarro[13], M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris, France
C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, R. Granier de Cassagnac, 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. Agram[14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E. C. Chabert, C. Collard, E. Conte[14], J.-C. Fontaine[14], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I. B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[15]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M. P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, A. Schmidt, S. C. Schuler, A. Sharma, S. Thüer, S. Wiedenbeck

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, W. Haj Ahmad[16], O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[17]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, C. Asawatangtrakuldee, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A. A. Bin Anuar, K. Borras[18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M. M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[19], A. Geiser, J. M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, N. Z. Jomhari, H. Jung, A. Kasem[18], M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann[20], R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S. K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer,

P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G. P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, D. Marconi, J. Multhaup, M. Niedziela, C. E. N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M. A. Harrendorf, F. Hartmann[17], U. Husemann, S. Kudella, S. Mitra, M. U. Mozer, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H. J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

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

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioannina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F. A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[21], M. Csanad, P. Major, K. Mandal, A. Mehta, M. I. Nagy, G. Pasztor, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[22], F. Sikler, T. Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z. L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. F. Csorgo, W. J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J. R. Komaragiri, P. C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[24], C. Kar, G. Kole, P. Mal, V. K. Muraleedharan Nair Bindhu, A. Nayak[25], S. Roy Chowdhury, D. K. Sahoo[24], S. K. Swain

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J. B. Singh, A. K. Virdi, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B. C. Choudhary, R. B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[26], M. Bharti[26], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[26], D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity[27], K. Mondal, S. Nandan, A. Purohit, P. K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar[27], M. Sharan, B. Singh[26], S. Thakur[26]

Indian Institute of Technology Madras, Madras, India
P. K. Behera, P. Kalbhor, A. Muhammad, P. R. Pujahari, A. Sharma, A. K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D. K. Mishra, P. K. Netrakanti, L. M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M. A. Bhat, S. Dugad, G. B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[27], E. Eskandari Tadavani, S. M. Etesami[27], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F. R. Cavallo[a], S. C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G. M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi, P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,29], 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,30], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,30], C. Tuve[a,b,30]

INFN Sezione di Firenze[a], Università di Firenze[b], Florence, Italy
G. Barbagli[a], R. Ceccarelli[a,b], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,31], G. Sguazzoni[a], D. Strom[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], Genoa, 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], Milan, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], S. Di Guida[a,b,17], M. E. Dinardo[a,b], P. Dini[a], S. Fiorendi[a,b], 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], G. Ortona[a,b], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata[c], Potenza, Italy, Università G. Marconi[d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A. O. M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,17], P. Paolucci[a,17], 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], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Y. Hoh, P. Lujan, M. Margoni[a,b], A. T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], 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,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
M. Biasini[a,b], G. M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M. A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], F. Fiori[a,c], 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], A. Rizzi[a,b], G. Rolandi[32], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a], 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,b], M. Diemoz[a], E. Longo[a,b], B. Marzocchi[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]

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], 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], 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], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G. L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], R. Salvatico[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

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], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
B. Kim, D. H. Kim, G. N. Kim, M. S. Kim, J. Lee, S. W. Lee, C. S. Moon, Y. D. Oh, S. I. Pak, S. Sekmen, D. C. Son, Y. C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D. H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, T. J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, K. Lee, K. S. Lee, J. Lim, J. Park, S. K. Park, Y. Roh

Department of Physics, Kyung Hee University, Gwangju-si, South Korea
J. Goh

Sejong University, Seoul, Korea
H. S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. H. Bhyun, J. Choi, S. Jeon, J. Kim, J. S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, S. B. Oh, B. C. Radburn-Smith, S. h. Seo, U. K. Yang, H. D. Yoo, I. Yoon, G. B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park, I. Watson

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[33]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z. A. Ibrahim, F. Mohamad Idris[34], 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
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], R. Lopez-Fernandez, 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
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. Ahmad, Q. Hassan, 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, Kraków, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov,

V. Matveev[37,38], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, Russia
L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim[39], E. Kuznetsova[40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[41], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[42], D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin[38], M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, A. Ershov, A. Gribushin, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[43], V. Blinov[43], T. Dimova[43], L. Kardapoltsev[43], Y. Skovpen[43]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

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. Adzic[44], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J. A. Brochero Cifuentes, C. A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M. S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J. F. de Trocóniz

Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

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, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, J. M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
D. U. J. Sonnadara

Department of Physics, University of Ruhuna, Matara, Sri Lanka
W. G. D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[45], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, A. Jafari, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F. M. Pitters, M. Quinto, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[46], J. Steggemann, V. R. Tavolaro, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[47], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R. A. Manzoni, M. Marionneau, M. T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D. A. Sanz Becerra, M. Schönenberger, L. Shchutska, M. L. Vesterbacka Olsson, R. Wallny, D. H. Zhu

Universität Zürich, Zurich, Switzerland
T. K. Aarrestad, C. Amsler[48], D. Brzhechko, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, B. Kilminster, S. Leontsinis, V. M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan
T. H. Doan, C. M. Kuo, W. Lin, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan
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

Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Physics Department, Science and Art Faculty, Çukurova University, Adana, Turkey
M. N. Bakirci[49], A. Bat, F. Boran, S. Damarseckin[50], Z. S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, EmineGurpinar Guler[51], Y. Guler, I. Hos[52], C. Isik, E. E. Kangal[53], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[55], A. E. Simsek, D. Sunar Cerci[55], U. G. Tok, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey
B. Isildak[56], G. Karapinar[57], M. Yalvac

Bogazici University, Istanbul, Turkey
I. O. Atakisi, E. Gülmez, M. Kaya[58], O. Kaya[59], B. Kaynak, Ö. Özçelik, S. Ozkorucuklu[60], S. Tekten, E. A. Yetkin[61]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[62]

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, UK
F. Ball, E. Bhal, S. Bologna, J. J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, D. Smith, V. J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, UK
K. W. Bell, A. Belyaev[63], C. Brew, R. M. Brown, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, 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, W. J. Womersley

Imperial College, London, UK
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL[64], D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[65], V. Palladino, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[17], N. Wardle, D. Winterbottom, J. Wright, A. G. Zecchinelli, S. C. Zenz

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

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, D.C., USA
R. Bartek, A. Dominguez, R. Uniyal

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S. I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J. M. Hogan[66], K. H. M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir[67], R. Syarif, E. Usai, D. Yu

University of California, 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. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O. R. Long, M. Olmedo Negrete, M. I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates, Y. Zhang

University of California, San Diego, La Jolla, USA
J. G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

Department of Physics, University of California, Santa Barbara, Santa Barbara, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J. M. Lawhorn, N. Lu, H. B. Newman, T. Q. Nguyen, J. Pata, M. Spiropulu, J. R. Vlimant, S. Xie, Z. Zhang, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M. B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J. P. Cumalat, W. T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K. A. Ulmer, S. R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, N. Mirman, J. R. Patterson, D. Quach, A. Rinkevicius[68], A. Ryd, S. M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V. D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, AllisonReinsvold Hall, J. Hanlon, R. M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M. J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J. M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R. D. Field, S. V. Gleyzer, B. M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K. H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y. R. Joshi

Florida State University, Tallahassee, USA
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K. F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M. M. Baarmand, V. Bhopatkar, S. Butalla, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C. E. Gerber, D. A. Hangal, D. J. Hofman, K. Jung, C. Mills, T. Roy, M. B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[51], W. Clarida, K. Dilsiz[69], S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, O. K. Köseyan, J.-P. Merlo, A. Mestvirishvili[70], A. Moeller, J. Nachtman, H. Ogul[71], Y. Onel, F. Ozok[72], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, W. T. Hung, P. Maksimovic, J. Roskes, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J. D. Tapia Takaki, Q. Wang, J. Williams

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D. R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S. C. Eno, Y. Feng, N. J. Hadley, S. Jabeen, G. Y. Jeng, R. G. Kellogg, J. Kunkle, A. C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y. H. Shin, A. Skuja, S. C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I. A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, 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, B. Wyslouch

University of Minnesota, Minneapolis, USA
A. C. Benvenuti[†], R. M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M. A. Wadud

University of Mississippi, Oxford, USA
J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, D. R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. E. Siado, G. R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D. M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, T. Gunter, K. A. Hahn, N. Odell, M. H. Schmitt, K. Sung, M. Trovato, 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, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T. Y. Ling, B. L. Winer

Princeton University, Princeton, USA
S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M. T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V. E. Barnes, S. Das, L. Gutay, M. Jones, A. W. Jung, A. Khatiwada, B. Mahakud, D. H. Miller, G. Negro, N. Neumeister, C. C. Peng, S. Piperov, H. Qiu, J. F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
K. M. Ecklund, S. Freed, F. J. M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A. G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, J. L. Dulemba, C. Fallon, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

The Rockefeller University, New York, USA
R. Ciesielski

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, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA
H. Acharya, A. G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[73], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[74], S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, 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
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M. W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P. E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin-Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber, M. Herndon[75], A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W. H. Smith, D. Teague, S. Trembath-reichert, N. Woods

[†] **Deceased**

1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS, Nova Andradina, Brazil

6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics, named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Fayoum University, El-Fayoum, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Also at Purdue University, West Lafayette, USA
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at Shoolini University, Solan, India
27: Also at University of Visva-Bharati, Santiniketan, India
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
30: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University ’Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, USA
41: Also at Imperial College, London, UK
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
49: Also at Gaziosmanpasa University, Tokat, Turkey
50: Also at Şırnak University, Sirnak, Turkey
51: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
52: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
53: Also at Mersin University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Adiyaman University, Adiyaman, Turkey

56: Also at Ozyegin University, Istanbul, Turkey
57: Also at Izmir Institute of Technology, Izmir, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul University, Istanbul, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
64: Also at IPPP Durham University, Durham, UK
65: Also at Monash University, Faculty of Science, Clayton, Australia
66: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
68: Also at Vilnius University, Vilnius, Lithuania
69: Also at Bingol University, Bingol, Turkey
70: Also at Georgian Technical University, Tbilisi, Georgia
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
75: Also at University of Hyderabad, Hyderabad, India