

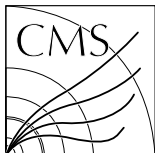
Fermilab

Measurement of the inclusive $t\bar{t}$ cross section in final states with at least one lepton and additional jets with 302 pb^{-1} of pp collisions at $\sqrt{s} = 5.0 \text{ TeV}$

FERMILAB-PUB-24-0797-CMS

arXiv:2410.21631

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.



Measurement of the inclusive $t\bar{t}$ cross section in final states with at least one lepton and additional jets with 302 pb^{-1} of pp collisions at $\sqrt{s} = 5.02 \text{ TeV}$

The CMS Collaboration*

Abstract

A measurement of the top quark pair ($t\bar{t}$) production cross section in proton-proton collisions at a centre-of-mass energy of 5.02 TeV is presented. The data were collected at the LHC in autumn 2017, in dedicated runs with low-energy and low-intensity conditions with respect to the default configuration, and correspond to an integrated luminosity of 302 pb^{-1} . The measurement is performed using events with one electron or muon, and multiple jets, at least one of them being identified as b quark (b tagged). Events are classified based on the number of all reconstructed jets and of b-tagged jets. Multivariate analysis techniques are used to enhance the separation between the signal and backgrounds. The measured cross section is $62.5 \pm 1.6 \text{ (stat)} \pm 2.6 \text{ (syst)} \pm 1.2 \text{ (lumi) pb}$. A combination with the result in the dilepton channel based on the same data set yields a value of $62.3 \pm 1.5 \text{ (stat)} \pm 2.4 \text{ (syst)} \pm 1.2 \text{ (lumi) pb}$, to be compared with the standard model prediction of $69.5^{+3.5}_{-3.7} \text{ pb}$ at next-to-next-to-leading order in perturbative quantum chromodynamics.

Submitted to the Journal of High Energy Physics

1 Introduction

The top quark is the heaviest fundamental particle discovered so far. It has a large mass and a large decay width corresponding to a very short lifetime of about 10^{-25} s, a time which is an order of magnitude shorter than the characteristic timescale on which bound state hadrons form. With its unique properties, the top quark potentially carries key information that may help to clarify many open questions in particle physics. The study of top quark pair production ($t\bar{t}$) is of crucial importance for precision tests of standard model (SM) predictions and a window to beyond-the-SM physics that may vary the production cross section.

First measurements of the $t\bar{t}$ production cross section in proton-antiproton collisions were made at the Tevatron at FNAL [1]. At the CERN LHC, the ATLAS, CMS, and LHCb Collaborations have performed further measurements in a variety of decay channels at various proton-proton (pp) collision energies [2–12], as well as in proton-nucleus [13] and nucleus-nucleus [14] collisions. Measurements at various centre-of-mass energies probe different fractions of the proton longitudinal momentum carried by the gluon [15] and thus can provide complementary information on the parton distribution functions (PDFs), in particular on that of the gluon. In addition, the contributions of the gluon-gluon and quark-antiquark diagram to the production cross section are expected to vary significantly at different centre-of-mass energies, thus making measurements at different \sqrt{s} values an important test of theoretical predictions [16].

The first measurement of the $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) in pp collisions at $\sqrt{s} = 5.02$ TeV, was performed by the CMS experiment combining the analyses of events with final states containing one or two leptons ($\ell = \text{electron or muon}$) and at least two jets, using a data sample collected in 2015 that corresponds to an integrated luminosity of 27.4 pb^{-1} [2]. A distinct feature of that data sample is the low number of additional interactions per bunch crossing (pileup) with respect to the standard operating conditions of the LHC. From the experimental side, this implies the important advantage of having a significantly cleaner detector environment, which leads to better detection and reconstruction of the events than in higher pileup scenarios. In 2017, the LHC performed a dedicated run of pp collisions at $\sqrt{s} = 5.02$ TeV and CMS collected a data sample corresponding to an integrated luminosity of 302 pb^{-1} . Using these data, CMS obtained an improved measurement of $\sigma_{t\bar{t}}$ by analyzing dilepton ($e^\pm\mu^\mp$) events [3]. The data collected during the same run with the ATLAS detector was used to measure $\sigma_{t\bar{t}}$ in both the lepton+jets (a single lepton and additional jets) and dilepton final states [4]. This paper presents a new CMS measurement of $\sigma_{t\bar{t}}$ using events with one lepton and multiple jets and its combination with the measurement in the dilepton final state contained in Ref. [3], resulting in an improved precision of the measured $\sigma_{t\bar{t}}$. The cross section is obtained by performing a maximum likelihood fit to several event categories. The fit is performed by simultaneously adjusting both the cross section and the nuisance parameters associated to the systematic uncertainties.

This paper is organized as follows. A brief description of the CMS detector is given in Section 2. Section 3 describes the data used for the measurement, as well as the Monte Carlo (MC) simulation samples, followed by the object reconstruction and event selection in Section 4. The background estimation methods are covered in Section 5, and the systematic uncertainties in Section 6. Results are discussed in Section 7, and the summary is given in Section 8. Tabulated results from this analysis are provided in the HEPData record [17].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [18, 19].

3 Data and simulated samples

The measurement is performed using pp collision data collected at $\sqrt{s} = 5.02$ TeV with the CMS detector during a low-energy and low-intensity LHC run in November 2017, corresponding to a total integrated luminosity of 302 pb^{-1} . The maximum instantaneous luminosity delivered by the LHC during this period was $\mathcal{L} = 1.37 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, and the mean pileup was 2, to be compared with the standard conditions in the 13 TeV run in 2017, where $\mathcal{L} = 2.07 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and the mean pileup was 33. Events of interest are selected using a two-tiered trigger system [20, 21]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of $4 \mu\text{s}$ [21]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 30 kHz before data storage. Events considered in this analysis are those in which the trigger detects at least one electron (muon) with transverse momentum $p_{\text{T}} > 20$ (17) GeV.

Signal and background contributions are simulated using several MC generators. These MC simulations are also used to evaluate efficiency and acceptance, and to predict background contributions. The propagation of the generated particles through the CMS detector and the modelling of the detector response in simulations are performed with the GEANT4 [22] package, using the alignment and calibration obtained from the experimental data.

Simulated $t\bar{t}$ events are generated at next-to-leading order (NLO) in perturbative quantum chromodynamics (pQCD) using POWHEG (v2) [23–26], assuming a top quark mass (m_t) of 172.5 GeV.

The NNPDF3.1 [27] next-to-next-to-leading order (NNLO) PDFs are used. The simulation of the single top quark production in the t channel and in association with a W boson (tW) is also performed with POWHEG, using the same setup.

The MADGRAPH5_aMC@NLO (v2.4.2) generator [28], is used to simulate Drell–Yan (DY) quark-antiquark annihilation into lepton-antilepton pairs through Z boson or virtual photon exchange, and W boson production with additional jets (W+jets). The simulation is performed at NLO in pQCD and includes up to two extra partons at the matrix element (ME) level. The FxFx matching scheme [29] is used to match jets from the ME calculations and the parton showering (PS). For all the processes, simulated events are interfaced with PYTHIA 8 (v230) [30] with the “CP5” tune [31] for PS, hadronization, and the underlying event description.

The SM prediction for $\sigma_{t\bar{t}}$ is calculated with the TOP++ program [32] at NNLO in pQCD including soft-gluon resummation at next-to-next-to-leading logarithmic (NNLL) accuracy [33]

for $m_t = 172.5$ GeV and a strong coupling at the Z boson mass, $\alpha_s(m_Z)$, of 0.118 ± 0.001 [34]. At 5.02 TeV, this prediction is $69.5_{-2.3}^{+2.0}$ (scale) ± 2.9 (PDF+ α_s) pb. The first uncertainty reflects variations in the factorization (μ_F) and renormalization (μ_R) scales. The second uncertainty is associated with possible choices of the PDFs and the α_s value, calculated using the PDF4LHC prescription [35], that encompasses the MSTW2008 68% CL NNLO [36, 37], CT10 NNLO [38, 39], and NNPDF2.3 5f FFN [40] PDF sets. The cross section predictions used for the normalization of t channel and tW events are calculated at NLO in both QCD and electroweak (EW) orders of approximation matched with PS resummation whereas for W +jets and DY events, the calculation is performed at NNLO in QCD and NLO in EW.

The signal and background MC samples used in the analysis are summarized in Table 1, as well as the cross section predictions used for the normalization of events.

Table 1: Summary of MC samples used to model the signal and background processes. The last column corresponds to the pQCD and EW order of approximation used to normalize the distributions provided by the generators. The predictions for $t\bar{t}$ and t channel and tW single top quark production are calculated with the PDF4LHC prescription [35]. Approximate NNLO refers to NLO calculation matched with PS resummation.

Process	Generator + Parton Shower	Cross section, σ_{norm} (pb)	Order of σ_{norm} approximation
$t\bar{t}$	POWHEG + PYTHIA 8	69.5 ± 3.6	NNLO + NNLL [32, 33]
t channel	POWHEG + PYTHIA 8	30.3 ± 0.6	Approximate NNLO [41]
tW	POWHEG + PYTHIA 8	6.54 ± 0.36	Approximate NNLO [42]
W +jets	MADGRAPH5_aMC@NLO + PYTHIA 8	$21\,160 \pm 330$	NNLO [QCD] + NLO [EW] [43]
DY	MADGRAPH5_aMC@NLO + PYTHIA 8	$3\,647 \pm 63$	NNLO [QCD] + NLO [EW] [43]

4 Object reconstruction and event selection

The particle-flow (PF) algorithm [44] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex (PV) as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Jets are clustered from the above-described reconstructed particles using the anti- k_T algorithm [45, 46] and a distance parameter of 0.4 is used. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. Particle-level jets are the result of adding PS and hadronization information to particles produced after the generation of the hard-scattering process. To determine any residual differences between the jet energy scale in data and in simulation, measurements of the momentum balance are used, leading to appropriate correction

factors [47]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [48]. Jets are identified as coming from the fragmentation of bottom quarks using the medium working point of the DeepCSV b tagging algorithm [49]. With this working point, we obtain for $t\bar{t}$ events a b tagging efficiency of 68% for b jets, and mistag rates of 12 and 1.1% for c and light jets with $p_T > 20$ GeV. Throughout the full text, we will be referring to jets in general as ‘j’, and to non-b-tagged jets as ‘u’.

A multivariate discriminator based on the shower shape and track quality of the electron candidates [50] is used to identify electrons. Electron candidates are required to satisfy $|\eta| < 2.4$ (except for the region $1.479 < |\eta| < 1.566$, which is excluded because that is the transition region between barrel and endcaps, where the electron reconstruction is suboptimal) and $p_T > 20$ GeV. A veto is applied on candidates that are matched to a secondary vertex consistent with a photon conversion, or have a missing hit in the inner layer of the tracker. Reconstructed muon candidates are required to have $|\eta| < 2.4$ and $p_T > 20$ GeV, and must fulfil criteria on the geometrical matching between the tracks reconstructed by the silicon tracker and the muon system, and on the quality of the global fit [51]. Both electron and muon energy scales and resolution are corrected according to measurements using Z boson events in simulation and low-pileup pp collision data at 5.02 TeV [50, 51].

Pileup collisions may cause events to contain multiple interaction vertices. The PV is taken to be the vertex corresponding to the hardest scattering in the event, which is evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [52].

Lepton candidates must be consistent with originating from the PV. This is guaranteed by requiring the longitudinal impact parameter to be smaller or equal to 0.10 cm and the transverse impact parameter smaller than 0.02 (0.05) cm for electrons (muons). Electrons and muons must also satisfy a requirement on their relative isolation (I_{rel}), defined as the scalar p_T sum of all the particles inside a cone around the lepton direction, excluding the lepton itself, divided by the lepton p_T . The cone size, defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where ϕ is the azimuthal angle, changes as a function of the lepton p_T as $\Delta R(p_T) = 10 \text{ GeV} / p_T$ if $50 < p_T < 200$ GeV, $\Delta R = 0.2$ if $p_T < 50$ GeV, and $\Delta R = 0.05$ if $p_T > 200$ GeV. Finally, electrons (muons) must satisfy the condition on isolation $I_{\text{rel}} < 0.085$ (0.325).

A gradient boosted decision tree (BDT) is used to distinguish leptons coming from hadron decays and misidentified leptons, collectively denoted “nonprompt” leptons, from those produced in the decays of weak bosons (“prompt”). The BDT is trained using MC simulations and exploits the properties of the jet which contains the lepton, as well as properties of the lepton itself, as input variables [53]. Leptons associated with a jet satisfying the loose working point of the DeepCSV b tagging algorithm [49] are rejected to further suppress nonprompt leptons originating from b quark decays. Using this working point with $t\bar{t}$ events, we obtain a b tagging efficiency of 84%, and mistag rates of 41 and 11% for c and light jets with $p_T > 20$ GeV.

The $t\bar{t}$ candidate events are required to contain a single selected electron or muon, and at least 3 jets. A veto on any second lepton of opposite flavour with respect to the selected one, with p_T as low as 10 GeV, is applied to ensure the orthogonality to the dilepton analysis [3]. Only jets with $p_T > 25$ GeV, $|\eta| < 2.4$, and containing no selected leptons are considered. Furthermore, events are required to ensure that the magnitude of the missing transverse momentum \vec{p}_T^{miss} , defined as the negative vector p_T sum of all identified physics objects [54], is greater than 30 GeV. This is done in order to reduce the background contamination from SM events composed uniquely of jets produced through the strong interaction, referred to as QCD multijets events. Events passing these selection requirements are classified into eight categories depending on the number of jets (N_{jets}) and b-tagged jets ($N_{\text{b-jets}}$) and on the flavour of the lep-

ton (electron or muon). Separate categories are defined for events with exactly 3 and ≥ 4 jets, which are further divided into categories of one b-tagged jet and ≥ 2 b-tagged jets. Throughout this document the jet multiplicity categories will be denoted as 3j1b, 4j1b, 3j2b, and 4j2b.

5 Background estimation

The event selection is designed to maximize the signal contribution over the expected background contamination. The background contributions come from the following processes: single top quark production in association with a W boson, W+jets production in the single-lepton final state, and QCD multijet events when a jet is misidentified as a lepton. In addition, DY events in three cases: when one of the two leptons in the final state is misidentified as a jet, if there is a lepton outside of the detector acceptance, or if a Z boson decays into two t leptons and there is a single leptonic t decay.

The estimation of these background contributions is based on MC simulation, except for the QCD multijet contribution, which is determined from control samples in data.

5.1 QCD background estimate

The QCD multijet background contribution is estimated from data using events with non-isolated leptons that are not selected by the lepton BDT described in Section 4. The evaluation of the QCD background follows the method used in Ref. [2]. A control region (CR) with events containing non-isolated leptons is defined by inverting both the isolation (I_{rel}) and the lepton BDT requirements. To estimate the amount of QCD background events ($N_{\text{QCD}}^{\text{SR}}$) in the signal region (SR), an extrapolation factor is calculated and applied to the QCD yield in the CR. To do so, the following formula is used:

$$N_{\text{QCD}}^{\text{SR}} = (N_{\text{obs}}^{\text{SR}} - N_{\text{MC}}^{\text{SR}}) \frac{N_{\text{obs, low } p_{\text{T}}^{\text{miss}}}^{\text{SR}} - N_{\text{MC, low } p_{\text{T}}^{\text{miss}}}^{\text{SR}}}{N_{\text{obs, low } p_{\text{T}}^{\text{miss}}}^{\text{CR}} - N_{\text{MC, low } p_{\text{T}}^{\text{miss}}}^{\text{CR}}}. \quad (1)$$

QCD multijet events in the CR are determined as the number of events in data ($N_{\text{obs}}^{\text{SR}}$) subtracted by the contribution, derived from the MC samples, of the signal and the other background sources considered ($N_{\text{MC}}^{\text{SR}}$). The factor is determined using events with $p_{\text{T}}^{\text{miss}} < 20$ GeV, where a large contribution of QCD background and low signal contamination is expected, as signal events contain genuine $\vec{p}_{\text{T}}^{\text{miss}}$ coming from a high- p_{T} neutrino.

To evaluate the normalization uncertainty in the QCD background contribution, the normalization factor is determined after varying the $p_{\text{T}}^{\text{miss}}$ requirement by ± 5 GeV in both the SR and CR. A flat normalization uncertainty of 30% is applied to the QCD contribution across all event categories since it covers most of the variations. It is worth noting that the QCD background contribution is quite small in this analysis, as can be seen in the distributions shown in Figs. 1–5.

5.2 W+jets background estimate

The final state with four quarks from the top quark decays leads to the expectation of at least four jets in signal events. Due to acceptance and selection efficiency effects, however, a relevant number of signal events has only three selected jets, thus contributing to the 3j1b category. In this category, a larger contribution from W+jets events is expected when compared to others. Since jets in this process come mainly from radiation, for higher jet multiplicity categories they are softer and more forward, thus not passing the selection criteria. Therefore, a multivariate-analysis (MVA) classifier based on random forests [55] is trained to separate the $t\bar{t}$ signal from

the W +jets background. The classifier is trained using the $t\bar{t}$ and the W +jets simulated samples, with 70% of events used for the training and the remaining events for testing. After an optimization procedure, the hyperparameters are fixed to 500 trees with a maximum depth of 6. The classifier is trained using the variables described in Table 2, where they are ordered according to their discriminating power.

Table 2: Summary of the variables used for the training of the MVA classifier in the 3j1b categories. The variables are ordered according to their discriminating power.

Variable	Definition
$\Delta R_{\text{med}}(j, j')$	Median ΔR between all possible combinations of two jets
$m(u, u')$	Invariant mass of the two non-b-tagged jets
$\Delta R(u, u')$	ΔR between the two non-b-tagged jets
$m_{\text{min}}(j, j')$	Minimum invariant mass of all possible combinations of two jets
$m(\ell, b)$	Invariant mass of the lepton and the b-tagged jet
H_T	Scalar p_T sum of all jets in the event
$\Delta R(\ell, b)$	ΔR between the lepton and the b-tagged jet
$p_T(j_0)$	p_T of the leading jet

Figure 1 shows the comparison of data and prediction for the two most discriminating input variables of the MVA, $\Delta R_{\text{med}}(j, j')$ and $m(u, u')$, used in the 3j1b category. Good agreement is observed across all variables.

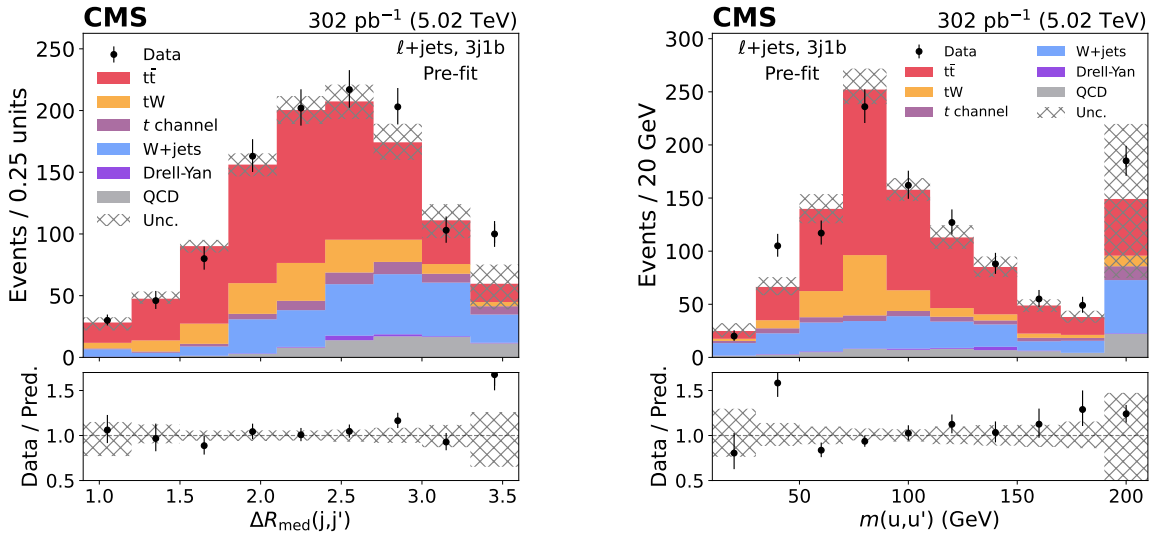


Figure 1: Distributions for data and expected signal and background contributions of the most discriminating input variables used for the random forest training, $\Delta R_{\text{med}}(j, j')$ (left) and $m(u, u')$ (right), in the 3j1b category, before the maximum likelihood fit. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the data-to-prediction ratio. The first and last bins in each distribution include underflow and overflow events, respectively. The normalizations are taken with respect to the SM predictions except for QCD, which is estimated from data.

The resulting MVA score distribution is shown in Fig. 2 for the e +jets and μ +jets final states, used then in the final fit for this category.

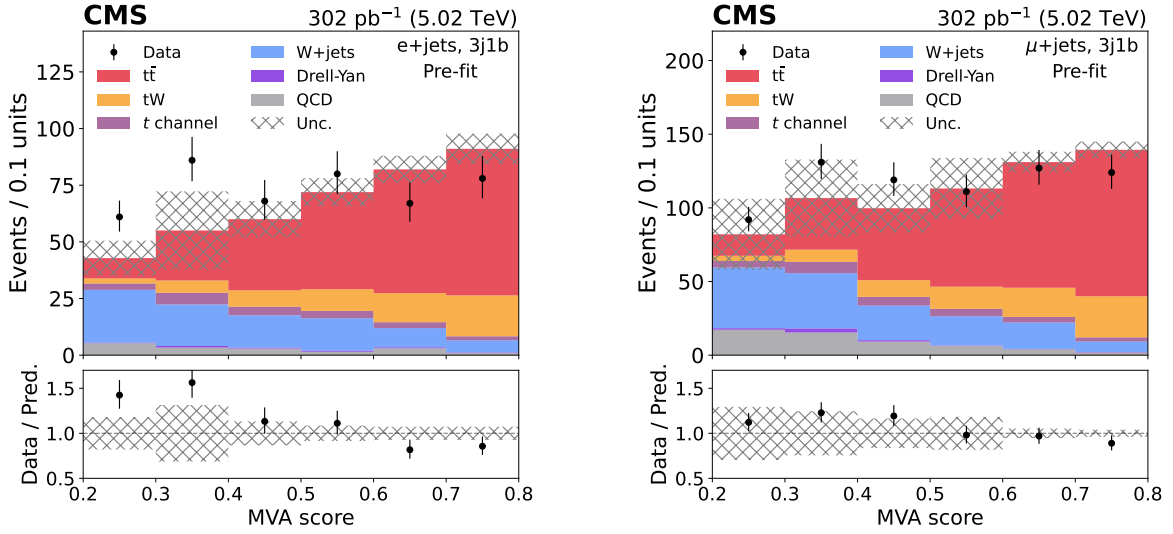


Figure 2: Distributions for data and expected signal and background contributions of the MVA score for the e +jets (left) and μ +jets (right) channels in the 3j1b category, before the maximum likelihood fit. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the data-to-prediction ratio. The first and last bins in each distribution include underflow and overflow events, respectively. The normalizations are taken with respect to the SM predictions except for QCD, which is estimated from data.

6 Systematic uncertainties

The measurement of $\sigma_{t\bar{t}}$ is affected by sources of systematic uncertainties related to detector effects, background normalization, running condition, and theoretical assumptions. The methods to estimate these uncertainties are the same as those in Ref. [3]. The experimental uncertainties mostly affect the efficiency, while modelling uncertainties affect both the acceptance and efficiency. The total uncertainty is calculated by combining the effects of all the individual systematic components, assuming they are independent. The sources of systematic uncertainties and the methods for their estimation are outlined below.

Lepton-related uncertainties: Lepton reconstruction and identification efficiencies are measured using Z boson events in simulation and low-pileup pp collision data at 5.02 TeV [50, 51]. Corrections are derived using the tag-and-probe method as a function of the lepton p_T and η , and are applied to the simulation to match the efficiencies in data. The uncertainty in these corrections is estimated through the variation of different parameters in the fitting templates of the method, as well as in the tag selection criteria, and is propagated to the $\sigma_{t\bar{t}}$ measurement as one single source per lepton flavour, including the statistical and systematic uncertainties.

The trigger efficiency is estimated using a cross-trigger technique. This consists in measuring it in data using an unbiased set of p_T^{miss} triggers. The related uncertainty is estimated by combining a statistical contribution, evaluated with the Clopper–Pearson binomial confidence intervals [56] and a systematic contribution, from MC to data efficiency ratios in several $p_T, |\eta|$ bins. It is found to be around 1–3% for electrons and 0.8–1.6% for muons.

Jet-related uncertainties: The contribution of the uncertainty in the jet energy scale (JES) is estimated from the change in the number of simulated events selected after changing the jet momenta by the JES uncertainties in bins of jet p_T and η , usually by no more than a few percent as described in [47]. 14 different sources of uncertainties are considered, and treated as independent nuisance parameters. The uncertainty due to the limited accuracy of the jet energy resolution (JER) is determined by changing the JER correction scale factor from its nominal value by ± 1 standard deviation, depending also on the p_T and η of the jet.

p_T^{miss} -related uncertainty: The uncertainty in p_T^{miss} from the contribution of unclustered energy (energy which is not aggregated into a specific cluster in the calorimeters) is evaluated based on the momentum resolution of the different PF candidates. Also, JER, JES, and lepton energy scale effects are propagated to p_T^{miss} .

b tagging uncertainties: In order to match the efficiency of the b tagging algorithm evaluated on MC samples to that observed in data, appropriate scale factors must be applied as a function of the p_T and $|\eta|$ of the jets. Values for these factors are determined separately for heavy- and light-flavour jets, considering as heavy flavour b and c jets, and as light the rest [49]. These scale factors are derived with an associated uncertainty, coming from different sources like JES, JER, scales. Their effect in the analysis is estimated by varying the scale factors by their uncertainties, and propagating the effect to all the categories in the analysis.

L1 inefficiency: During the data taking period corresponding to this measurement, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region $|\eta| > 2.0$ caused a trigger inefficiency [21]. Simulations are corrected to mimic this behaviour observed in data. This correction has an inherent uncertainty associated to the method used to calculate it, which is propagated to $\sigma_{t\bar{t}}$ by varying the correction by its associated uncertainty.

Renormalization and factorization scale choice: The uncertainty related to the missing higher-order diagrams in POWHEG is estimated by independently varying one or both the μ_F and μ_R choices independently by a factor 2 or 1/2, excluding combinations with variations in opposite directions, which do not have physical meaning. As uncertainty in the signal acceptance, the maximum difference of all variations from the nominal values is assigned.

PS scale: The effect of the choice of PS scale is studied by changing the scale used for the initial- and final-state radiation by a factor 2 and 1/2 with respect to its nominal value.

ME and PS matching (h_{damp}): The effect of the ME and PS matching is taken into account using the h_{damp} parameter of the POWHEG generator, with a nominal value of $(1.4_{-0.5}^{+0.9}) m_t$ [31]. The uncertainty is estimated by varying this parameter within the uncertainties quoted above, using dedicated signal $t\bar{t}$ samples. The variation with respect to the central value of the signal acceptance is taken as the uncertainty. Due to the limited size of the dedicated MC samples a normalization uncertainty is estimated in jet multiplicity bins.

Parton distribution functions: The uncertainty arising from the choice of the proton PDF is determined by reweighing the sample of simulated signal events according to 100 replicas from the NNPDF3.1 NNLO PDF set. The eigenvectors of the Hessian matrix are taken to obtain one nuisance parameter for each replica, and the differences of the resulting variations with respect to the central value are taken as individual uncertainties, leading to 100 independent nuisance parameters. An extra contribution from the variation of

$\alpha_S(m_Z)$ corresponding to its uncertainty is considered [35]. Since in this case there are two independent variations, two independent nuisance parameters are considered.

Underlying event tune: The parameters of PYTHIA related to the underlying event tune [31] are adjusted to match observations in data. We consider changes in these parameters as sources of uncertainties and we use dedicated simulated signal samples accounting for these changes. The variation with respect to the central value of the signal acceptance is taken as the uncertainty. Due to the limited size of the dedicated samples, a single uncertainty is estimated for all the bins and regions of the analysis.

Background normalization: The uncertainty in the tW production cross section is taken to be 5.6%, and 10% is used for the t -channel single top quark production, based on the theoretical uncertainties [41, 42]. A normalization uncertainty of 30% is applied to the QCD background, as discussed in Section 5, to account for the systematic uncertainties in its estimate. Normalization uncertainties of 20 and 30% are assigned in the W +jets and DY background estimates, respectively, following the prescription of previous analyses [2, 57], since the detector conditions and analysis strategy are very similar to the ones presented in this paper. In the case of W +jets, the normalization is considered as an uncorrelated parameter across the four $N_{\text{jets}}N_{\text{b-jets}}$ categories.

Pileup and integrated luminosity: Uncertainties related to pileup are not considered since the number of pileup events is small. The uncertainty in the measurement of the integrated luminosity is estimated to be 1.9% [58, 59]. This uncertainty is not included in the maximum likelihood fit, but treated as an external uncertainty and added in quadrature afterwards.

Most of these uncertainties, especially those coming from experimental effects, affect both the shape of the distributions and their normalization. Modelling uncertainties that are calculated with several weights, such as PDF and scale uncertainties, are estimated for each region of the analysis and applied as normalization uncertainties in each of the regions. Background normalization uncertainties and integrated luminosity uncertainty are treated as normalization uncertainties. Moreover, h_{damp} and underlying event tune uncertainties, both estimated with alternative samples, are also applied as normalization uncertainties because of the limited size of the dedicated samples. In the case of h_{damp} , this is done in bins of N_{jets} , while in the case of underlying event tune, a single normalization is used.

7 Results

After the event selection and categorization described above, the resulting observed number of events in data and the expected number of events for signal and background in each of the eight categories in the signal region are those shown in Fig. 3.

The cross section is obtained by performing a profiled maximum likelihood fit to the $\Delta R_{\text{med}}(j, j')$ distribution in the different jet/b-jet multiplicity and lepton flavour categories, except for the 3j1b category, where the MVA score distribution is used. The cross section value is fitted simultaneously with the nuisance parameters related to the systematic uncertainties. The choice of the $\Delta R_{\text{med}}(j, j')$ distribution is motivated by the fact that this observable is particularly sensitive to the kinematics of $t\bar{t}$ production: in fact, the signal peaks more sharply at intermediate $\Delta R_{\text{med}}(j, j')$ than the background. Using the MVA score distribution instead of $\Delta R_{\text{med}}(j, j')$ for the 3j1b category results in a relative reduction of 13% in the final uncertainty

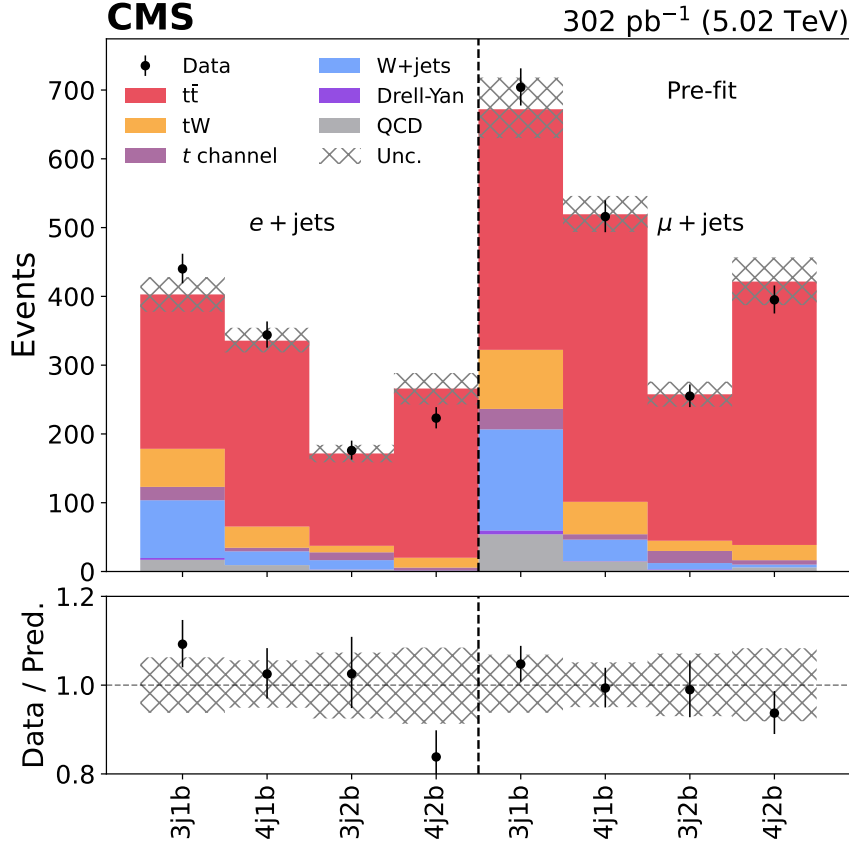


Figure 3: Observed and predicted number of events in each of the eight categories of the signal region, before the maximum likelihood fit. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the data-to-prediction ratio. The normalizations are taken with respect to the SM predictions except for QCD, which is estimated from data.

of the result. In the fit, seven bins are used for the $\Delta R_{\text{med}}(j, j')$ and six bins for the MVA score distributions, for a total of 54 bins (27 per lepton flavour). The most sensitive category is found to be the $\mu+3j1b$ one. The signal strength (r), i.e. the ratio of the observed to the predicted cross section is extracted and uncertainties are constrained. The statistical uncertainty coming from the limited size of the MC samples is incorporated into the maximum likelihood fit using the Barlow–Beeston “light” method [60]. The MVA score and $\Delta R_{\text{med}}(j, j')$ distributions for the e+jets and μ +jets final states before and after the fit are shown in Figs. 4 and 5.

The signal strength is extracted from a profile-likelihood fit using the CMS COMBINE tool [61] and a cross section of $\sigma_{t\bar{t}} = 62.5 \text{ pb}$ is measured. The systematic uncertainty amounts to $^{+4.2\%}_{-4.0\%}$, the statistical uncertainty to $\pm 2.6\%$, and the integrated luminosity uncertainty to $\pm 1.9\%$. The measurement is also done in e+jets ($\sigma_{t\bar{t}} = 61.8 \pm 4.6 \text{ pb}$) and μ +jets ($\sigma_{t\bar{t}} = 63.6 \pm 3.6 \text{ pb}$) separately, showing consistent cross section with the combined fit.

Figure 6 shows the impact of the different systematic uncertainties on the signal strength and the constraints on the nuisance parameters. The impact is defined as the shift $\Delta \hat{r}$ induced in r when the nuisance parameter θ is varied by ± 1 standard deviation (σ) around the value obtained for it after the fit. The leading uncertainties are those on the heavy-flavour b tagging

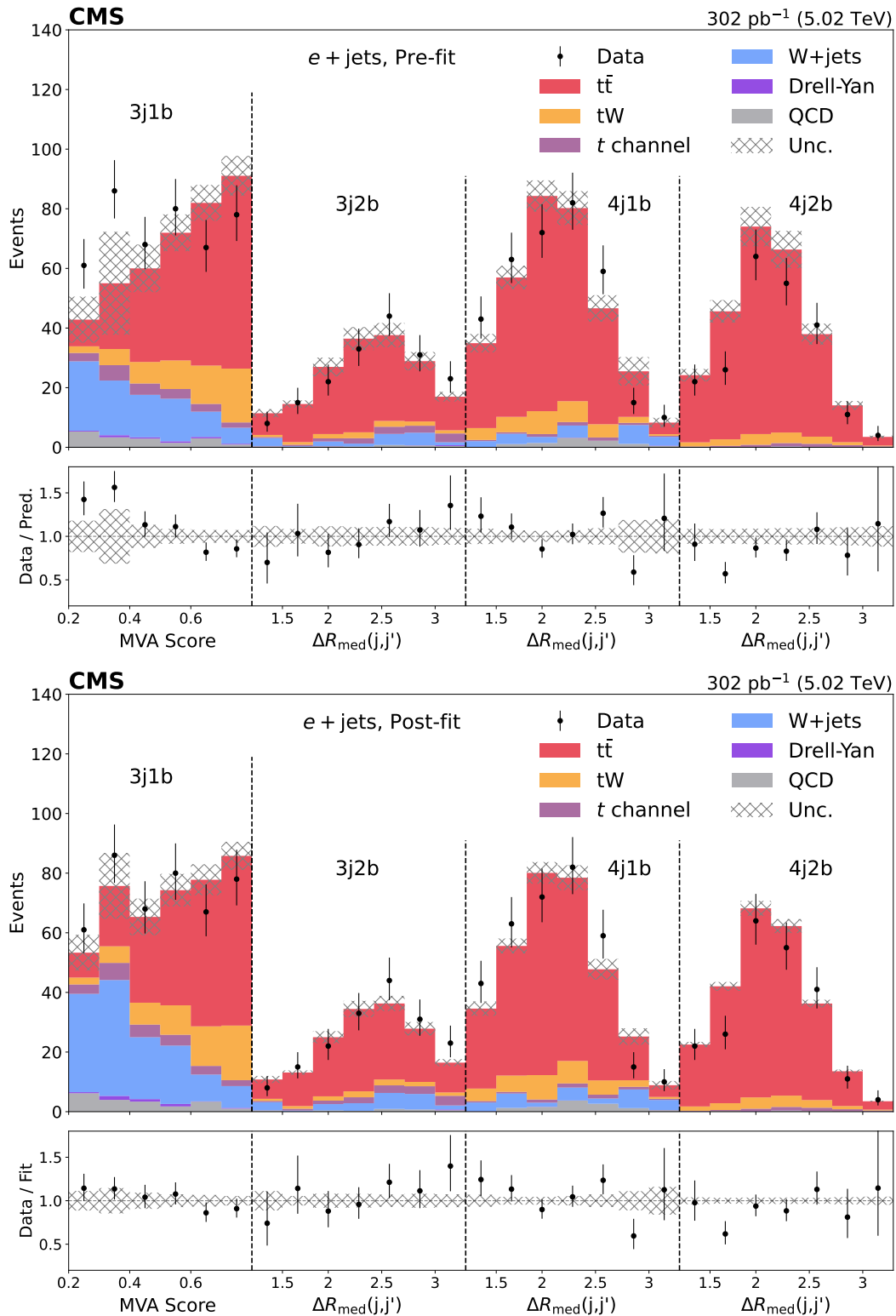


Figure 4: Distributions for the e+jets final state before (upper plot) and after (lower plot) the maximum likelihood fit: MVA score bins for the 3j1b category and $\Delta R_{\text{med}}(j, j')$ bins for the other categories. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty of the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the ratio of data to prediction or data to fit, respectively. The first and last bins in each distribution include underflow and overflow events, respectively.

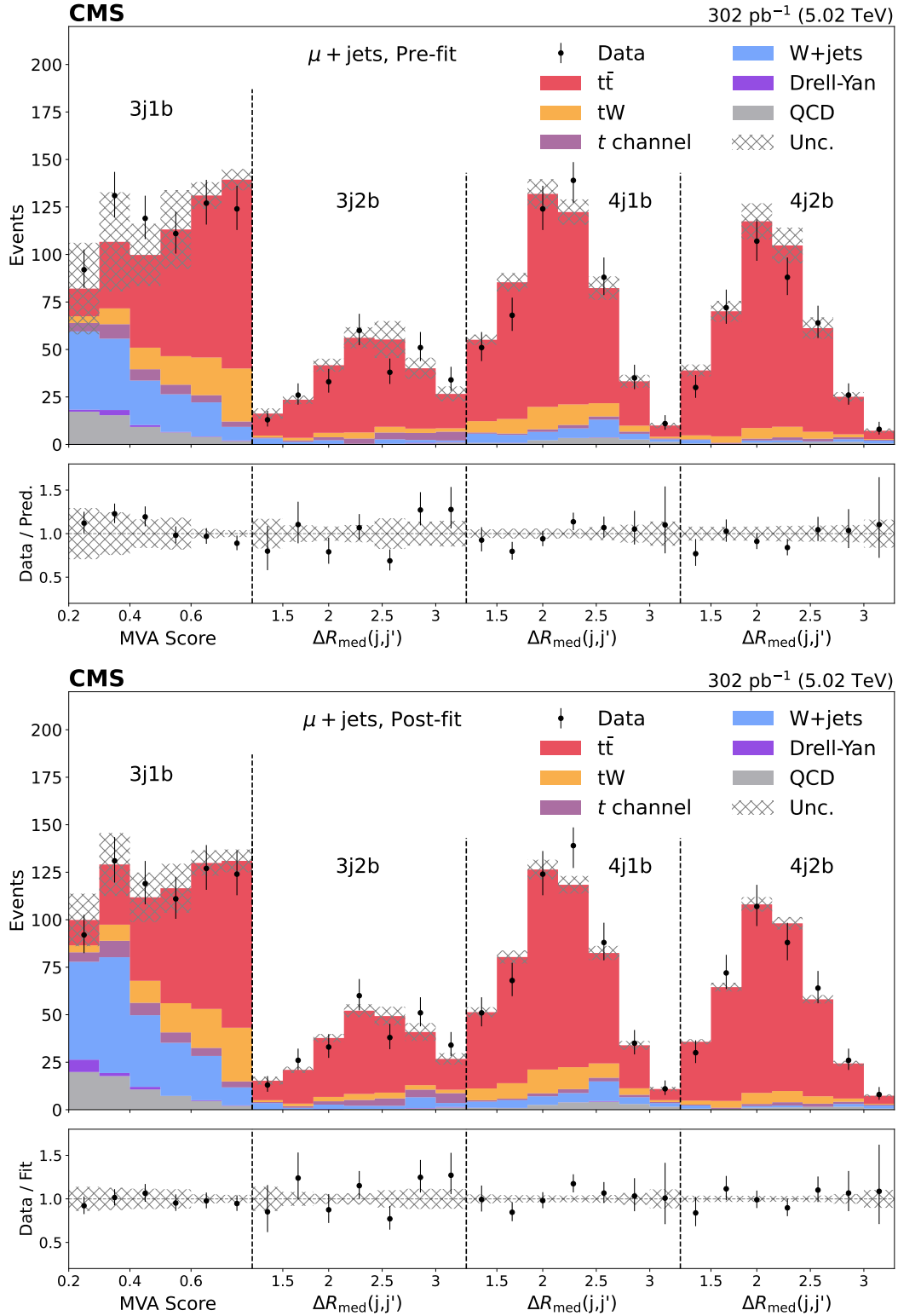


Figure 5: Distributions for the $\mu + \text{jets}$ final state before (upper plot) and after (lower plot) the maximum likelihood fit: MVA score bins for the 3j1b category and $\Delta R_{\text{med}}(j,j')$ bins for the other categories. The vertical error bars represent the statistical uncertainty in the data, and the shaded band the uncertainty of the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the ratio of data to prediction or data to fit, respectively. The first and last bins in each distribution include underflow and overflow events, respectively.

efficiency, the ME and PS matching, and the trigger efficiency. Figure 6 also shows the ratios $(\hat{\theta} - \theta_0)/\Delta\theta$, where $\hat{\theta}$ and θ_0 are the values of a given nuisance parameter after and before the fit, and $\Delta\theta$ the corresponding uncertainty before the fit. The uncertainties coming from the ME and PS matching, and heavy-flavour b tagging efficiencies appear as the dominant ones.

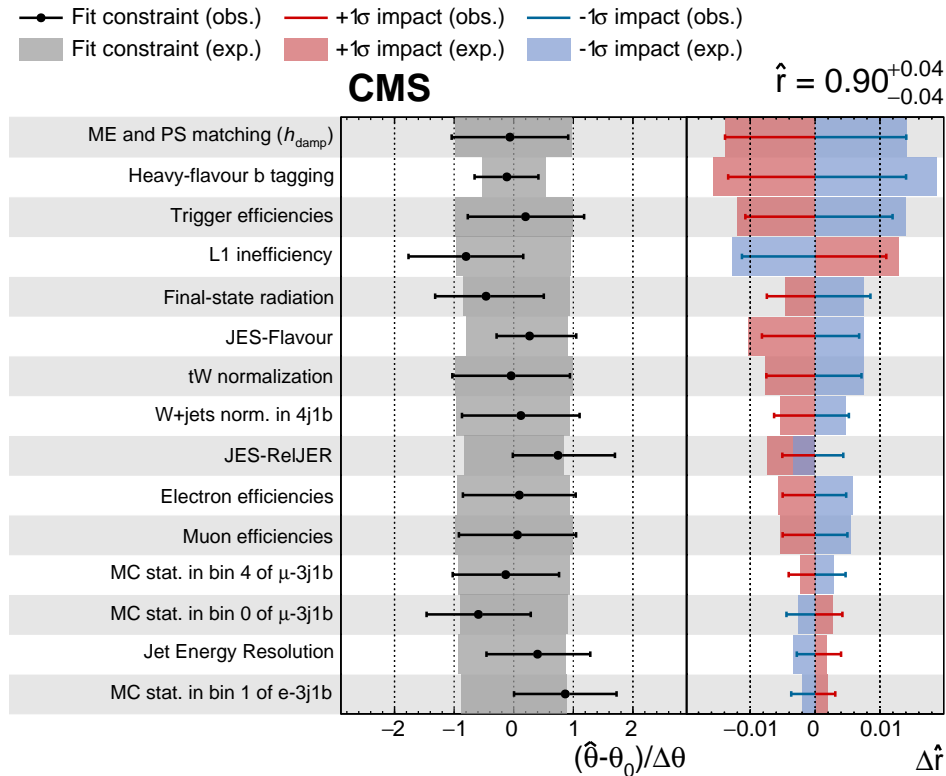


Figure 6: The largest impacts on the signal strength, $\Delta\hat{r}$ (right column) and ratios $(\hat{\theta} - \theta_0)/\Delta\theta$ (middle column) for the nuisance parameters listed in the left column from the maximum likelihood fit used to determine the $t\bar{t}$ cross section. The horizontal bars in the rightmost plot show the ratio of the uncertainties of the fit result to the pre-fit ones, effectively giving the constraint on the nuisance parameter. The JES uncertainties are divided into several sources, where “JES-Flavour” comes from the corrections applied to correct the different detector response to gluon and quark jets, and “JES-RelJER” accounts for the η dependence uncertainty from jet p_T resolution.

Alternative $t\bar{t}$ MC samples generated with $m_t = 166.5$ and 178.5 GeV are used to estimate, by linear interpolation, the variation in the $t\bar{t}$ cross section when m_t changes. The measured cross section varies by ∓ 0.11 pb when the top quark mass is varied from its nominal value of 172.5 GeV within its uncertainty of ± 0.33 GeV [62].

The result in the lepton+jets channel is combined with the result in the dilepton channel from Ref. [3]. The sources of systematic uncertainty are considered as fully correlated, with the exception of few uncertainties (such as JES, PDF, and $\alpha_S(m_Z)$) that are treated as uncorrelated. Namely, in the dilepton channel a single source per uncertainty is considered whereas in the lepton+jets, 14, 100, and 2 sources per uncertainty are considered, respectively. Moreover, there are other uncertainties which were not considered in the dilepton analysis, such as b tagging, unclustered energy, and QCD and t -channel single top quark production normalizations. As in the lepton+jets case, a profile likelihood fit is performed on the data and a cross section of $\sigma_{t\bar{t}} = 62.3$ pb is measured. The systematic uncertainty amounts to $\pm 3.9\%$, the statistical

uncertainty to $\pm 2.4\%$, and the integrated luminosity uncertainty to $\pm 1.9\%$. As expected, this result is dominated by the lepton+jets measurement, given its significantly smaller uncertainty.

Figure 7 shows the impact of the systematic uncertainties on the signal strength and the ratios $(\hat{\theta} - \theta_0)/\Delta\theta$ for the nuisance parameters as determined by the combined fit. In this case, the ME and PS matching, the heavy-flavour b tagging efficiency and the trigger efficiencies are still among the leading uncertainties. As in the lepton+jets analysis, the uncertainty coming from the heavy-flavour b tagging efficiency appears as one of the most constrained ones.

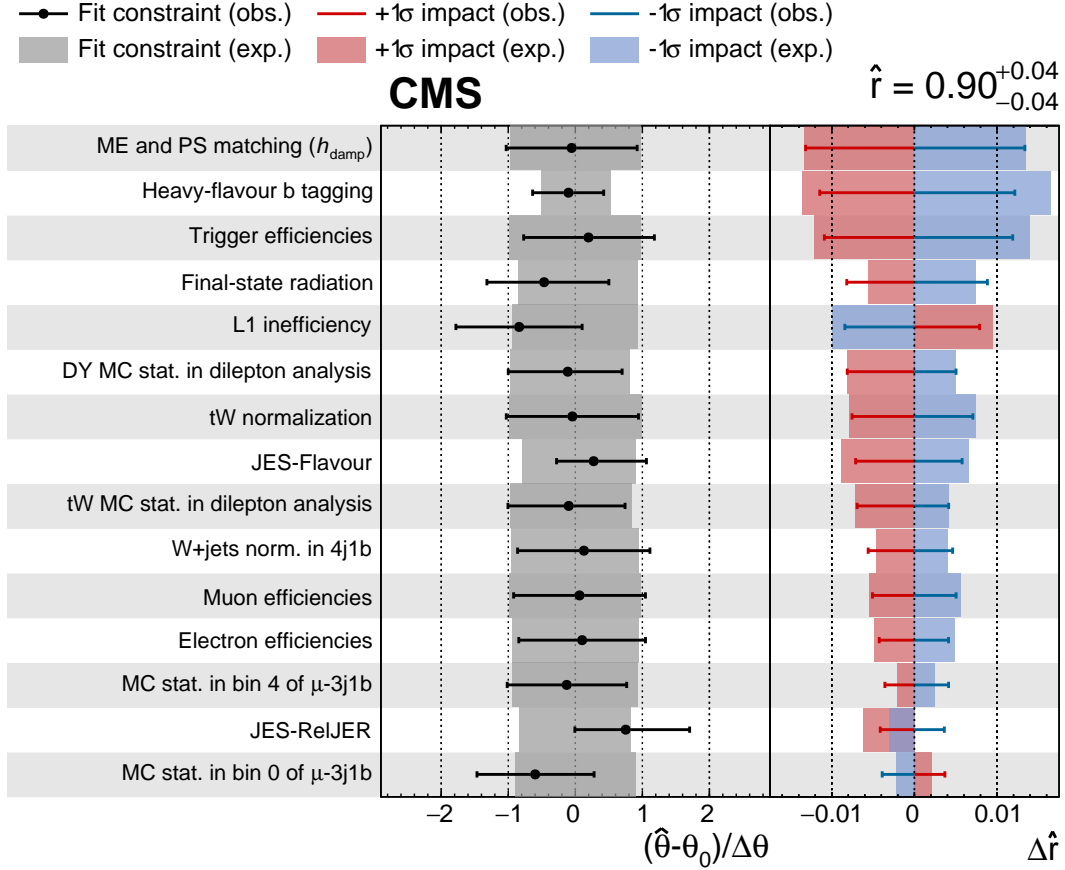


Figure 7: The largest impacts on the signal strength, $\Delta\hat{r}$ (right column) and ratios $(\hat{\theta} - \theta_0)/\Delta\theta$ (middle column) for the nuisance parameters listed in the left column from the maximum likelihood fit in the combination with the dilepton result, used to determine the $t\bar{t}$ cross section. The horizontal bars in the rightmost plot show the ratio of the uncertainties of the fit result to the pre-fit ones, effectively giving the constraint on the nuisance parameter. The JES uncertainties are divided into several sources, accounting for different effects, where “JES-Flavour” comes from the corrections applied to correct the different detector response to gluon and quark jets, and “JES-RelJER” accounts for the η dependence uncertainty from jet p_T resolution.

The results presented in this analysis are consistent within two standard deviations with the SM prediction. These results, together with previous CMS and ATLAS measurements, are shown in Fig. 8.

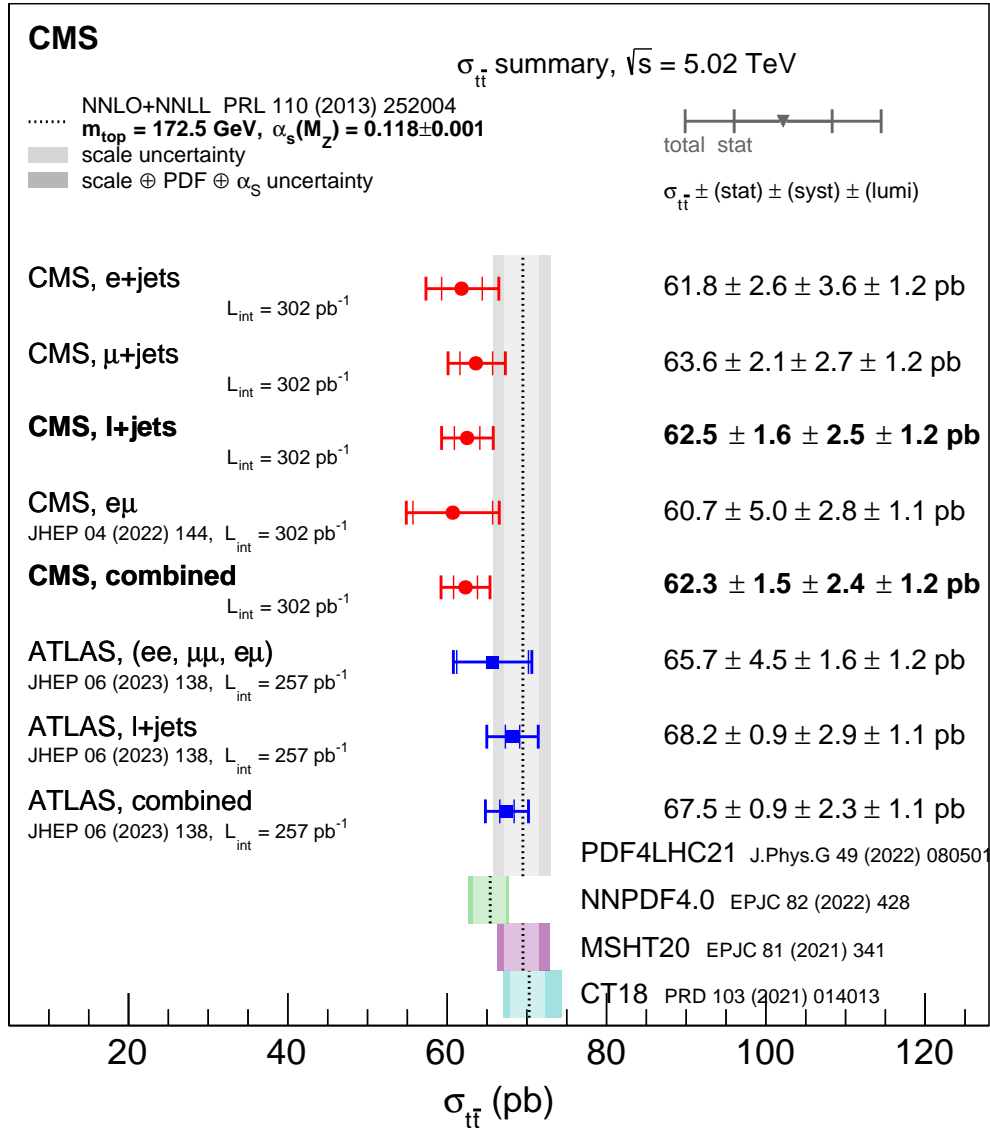


Figure 8: Summary of the most recent measurements from the ATLAS and CMS Collaborations using data collected at $\sqrt{s} = 5.02$ TeV. In the plot also several theoretical predictions are shown: the current prediction [63] (calculated with the PDF4LHC21 set) and other previous predictions using different PDF sets [64–66].

8 Summary

A measurement of the top quark pair production cross section in proton-proton collisions at a centre-of-mass energy of 5.02 TeV is performed for events with one electron or one muon and multiple jets using data collected by the CMS experiment in 2017 in conditions of low number of additional interactions per bunch crossing, corresponding to an integrated luminosity of 302 pb^{-1} . The dominant background sources in the analysis are W +jets and tW processes. In addition, the contribution from quantum chromodynamics multijet events is estimated from data. The cross section is measured using a maximum likelihood fit to eight event categories defined in terms of the number of jets, b -tagged jets and lepton flavour. The cross section is found to be 62.5 ± 1.6 (stat) $^{+2.6}_{-2.5}$ (syst) ± 1.2 (lumi) pb. This measurement is combined with

the result obtained in the dilepton channel, based on the same data set, resulting in a value of $62.3 \pm 1.5(\text{stat}) \pm 2.4(\text{syst}) \pm 1.2(\text{lumi}) \text{ pb}$. In both cases, the dominant uncertainties are those associated with the integrated luminosity and with the b tagging scale factors for heavy flavours. These values are consistent within two standard deviations with the standard model prediction and of previous measurements from CMS and ATLAS.

Acknowledgments

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 centres and personnel of the Worldwide LHC Computing Grid and other centres 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-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 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Centre for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369

and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] CDF and D0 Collaborations, “Combination of measurements of the top-quark pair production cross section from the Tevatron collider”, *Phys. Rev. D* **89** (2014) 072001, doi:10.1103/PhysRevD.89.072001, arXiv:1309.7570.
- [2] CMS Collaboration, “Measurement of the inclusive $t\bar{t}$ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV using final states with at least one charged lepton”, *JHEP* **03** (2018) 115, doi:10.1007/JHEP03(2018)115, arXiv:1711.03143.
- [3] CMS Collaboration, “Measurement of the inclusive $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s} = 5.02$ TeV”, *JHEP* **04** (2022) 144, doi:10.1007/JHEP04(2022)144, arXiv:2112.09114.
- [4] ATLAS Collaboration, “Measurement of the $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector”, *JHEP* **06** (2023) 138, doi:10.1007/JHEP06(2023)138, arXiv:2207.01354.
- [5] ATLAS and CMS Collaborations, “Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **07** (2023) 213, doi:10.1007/JHEP07(2023)213, arXiv:2205.13830.
- [6] ATLAS Collaboration, “Measurement of the $t\bar{t}$ production cross-section and lepton differential distributions in $e\mu$ dilepton events from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **80** (2020) 528, doi:10.1140/epjc/s10052-020-7907-9, arXiv:1910.08819.
- [7] CMS Collaboration, “Measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **116** (2016) 052002, doi:10.1103/PhysRevLett.116.052002, arXiv:1510.05302.
- [8] CMS Collaboration, “Measurement of the $t\bar{t}$ production cross section using events in the $e\mu$ final state in pp collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **77** (2017) 172, doi:10.1140/epjc/s10052-017-4718-8, arXiv:1611.04040.
- [9] CMS Collaboration, “Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **104** (2021) 092013, doi:10.1103/PhysRevD.104.092013, arXiv:2108.02803.

-
- [10] LHCb Collaboration, “Measurement of forward top pair production in the dilepton channel in pp collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **08** (2018) 174, doi:10.1007/JHEP08(2018)174, arXiv:1803.05188.
- [11] CMS Collaboration, “First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13.6$ TeV”, *JHEP* **08** (2023) 204, doi:10.1007/JHEP08(2023)204, arXiv:2303.10680.
- [12] ATLAS Collaboration, “Measurement of the $t\bar{t}$ cross section and its ratio to the Z production cross section using pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector”, *Phys. Lett. B* **848** (2024) 138376, doi:10.1016/j.physletb.2023.138376, arXiv:2308.09529.
- [13] CMS Collaboration, “Observation of top quark production in proton-nucleus collisions”, *Phys. Rev. Lett.* **119** (2017) 242001, doi:10.1103/PhysRevLett.119.242001, arXiv:1709.07411.
- [14] CMS Collaboration, “Evidence for top quark production in nucleus-nucleus collisions”, *Phys. Rev. Lett.* **125** (2020) 222001, doi:10.1103/PhysRevLett.125.222001, arXiv:2006.11110.
- [15] CMS Collaboration, “Measurement of double-differential cross sections for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV and impact on parton distribution functions”, *Eur. Phys. J. C* **77** (2017) 459, doi:10.1140/epjc/s10052-017-4984-5, arXiv:1703.01630.
- [16] S. Catani, M. L. Mangano, P. Nason, and L. Trentadue, “The top cross section in hadronic collisions”, *Phys. Lett. B* **378** (1996) 329, doi:10.1016/0370-2693(96)00387-5, arXiv:hep-ph/9602208.
- [17] HEPData record for this analysis, 2024. doi:10.17182/hepdata.150676.
- [18] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [19] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.
- [20] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [21] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [22] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [23] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.


- [24] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [25] S. Frixione, G. Ridolfi, and P. Nason, “A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction”, *JHEP* **09** (2007) 126, doi:10.1088/1126-6708/2007/09/126, arXiv:0707.3088.
- [26] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [27] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [28] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [29] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [30] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [31] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [32] M. Czakon and A. Mitov, “TOP++: a program for the calculation of the top-pair cross-section at hadron colliders”, *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.
- [33] M. Czakon, P. Fiedler, and A. Mitov, “Total top-quark pair-production cross section at hadron colliders through $\mathcal{O}(\alpha_s^4)$ ”, *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [34] Particle Data Group, R. L. Workman et al., “Review of particle physics”, *Prog. Theor. Exp. Phys.* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.
- [35] J. Butterworth et al., “PDF4LHC recommendations for LHC Run 2”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [36] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC”, *Eur. Phys. J. C* **63** (2009) 189, doi:10.1140/epjc/s10052-009-1072-5, arXiv:0901.0002.
- [37] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Uncertainties on α_s in global PDF analyses and implications for predicted hadronic cross sections”, *Eur. Phys. J. C* **64** (2009) 653, doi:10.1140/epjc/s10052-009-1164-2, arXiv:0905.3531.
- [38] H.-L. Lai et al., “New parton distributions for collider physics”, *Phys. Rev. D* **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024, arXiv:1007.2241.

-
- [39] J. Gao et al., “CT10 next-to-next-to-leading order global analysis of QCD”, *Phys. Rev. D* **89** (2014) 033009, doi:10.1103/PhysRevD.89.033009, arXiv:1302.6246.
- [40] NNPDF Collaboration, “Parton distributions with LHC data”, *Nucl. Phys. B* **867** (2013) 244, doi:10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
- [41] J. Campbell, T. Neumann, and Z. Sullivan, “Single-top-quark production in the t -channel at NNLO”, *JHEP* **02** (2021) 040, doi:10.1007/JHEP02(2021)040, arXiv:2012.01574.
- [42] N. Kidonakis and N. Yamanaka, “Higher-order corrections for tW production at high-energy hadron colliders”, *JHEP* **05** (2021) 278, doi:10.1007/JHEP05(2021)278, arXiv:2102.11300.
- [43] K. Melnikov and F. Petriello, “Electroweak gauge boson production at hadron colliders through $\mathcal{O}(\alpha_S^2)$ ”, *Phys. Rev. D* **74** (2006) 114017, doi:10.1103/PhysRevD.74.114017, arXiv:hep-ph/0609070.
- [44] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [45] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [46] M. Cacciari, G. P. Salam, and G. Soyez, “FASTJET user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [47] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [48] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.
- [49] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [50] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [51] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [52] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015. doi:10.17181/CERN.VU8I.D59J.
- [53] CMS Collaboration, “Muon identification using multivariate techniques in the CMS experiment in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **19** (2024) P02031, doi:10.1088/1748-0221/19/02/P02031, arXiv:2310.03844.


















- [54] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [55] A. Prinzie and D. Van den Poel, “Random multiclass classification: Generalizing random forests to random MNL and random NB”, in *Proc. 18th International Conference on Database and Expert Systems Applications (DEXA 2007): Regensburg, Germany, September 3–7, 2007*, p. 349. 2007. doi:10.1007/978-3-540-74469-6_35.
- [56] C. J. Clopper and E. S. Pearson, “The use of confidence or fiducial limits illustrated in the case of the binomial”, *Biometrika* **26** (1934) 404, doi:10.1093/biomet/26.4.404.
- [57] CMS Collaboration, “Measurement of the production cross section of a W boson in association with two b jets in pp collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C* **77** (2017) 92, doi:10.1140/epjc/s10052-016-4573-z, arXiv:1608.07561.
- [58] CMS Collaboration, “Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS”, CMS Physics Analysis Summary CMS-PAS-LUM-19-001, 2021.
- [59] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [60] J. S. Conway, “Incorporating nuisance parameters in likelihoods for multisource spectra”, in *Proc. 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding (PHYSTAT 2011): Geneva, Switzerland, January 17–20, 2011*. 2011. arXiv:1103.0354. doi:10.5170/CERN-2011-006.115.
- [61] CMS Collaboration, “The CMS statistical analysis and combination tool: COMBINE”, 2024. arXiv:2404.06614. Accepted by *Comput. Softw. Big Sci.*
- [62] ATLAS and CMS Collaborations, “Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at $\sqrt{s} = 7$ and 8 TeV”, *Phys. Rev. Lett.* **132** (2024) 261902, doi:10.1103/PhysRevLett.132.261902, arXiv:2402.08713.
- [63] PDF4LHC Working Group, R. D. Ball et al., “The PDF4LHC21 combination of global PDF fits for the LHC Run 3”, *J. Phys. G* **49** (2022) 080501, doi:10.1088/1361-6471/ac7216, arXiv:2203.05506.
- [64] NNPDF Collaboration, “The path to proton structure at 1% accuracy”, *Eur. Phys. J. C* **82** (2022) 428, doi:10.1140/epjc/s10052-022-10328-7, arXiv:2109.02653.
- [65] S. Bailey et al., “Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs”, *Eur. Phys. J. C* **81** (2021) 341, doi:10.1140/epjc/s10052-021-09057-0, arXiv:2012.04684.
- [66] T.-J. Hou et al., “New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC”, *Phys. Rev. D* **103** (2021) 014013, doi:10.1103/PhysRevD.103.014013, arXiv:1912.10053.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 












Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck² , R. Schöfbeck , D. Schwarz , M. Sonawane , W. Waltenberger , C.-E. Wulz² 

















Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , T. Van Laer, P. Van Mechelen 













Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat³ , G.P. Van Onsem , S. Van Putte , D. Vannerom















Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 











Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 

















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera⁴ , A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira⁴ 

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























W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, T. Laux Kuhn, M. Macedo , J. Martins⁷ , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maitto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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




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

University of Sofia, Sofia, BulgariaA. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka **Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**S. Keshri , D. Laroze , S. Thakur **Beihang University, Beijing, China**T. Cheng , T. Javaid , L. Yuan **Department of Physics, Tsinghua University, Beijing, China**Z. Hu , Z. Liang, J. Liu**Institute of High Energy Physics, Beijing, China**G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor⁹ , H. Liao , Z.-A. Liu¹⁰ , R. Sharma¹¹ , J.N. Song¹⁰, J. Tao , C. Wang⁸, J. Wang , Z. Wang⁸, H. Zhang , J. Zhao **State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou **Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**S. Yang **Sun Yat-Sen University, Guangzhou, China**Z. You **University of Science and Technology of China, Hefei, China**K. Jaffel , N. Lu **Nanjing Normal University, Nanjing, China**G. Bauer¹², B. Li, K. Yi^{13,14} , J. Zhang **Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**X. Gao¹⁵ , Y. Li**Zhejiang University, Hangzhou, Zhejiang, China**Z. Lin , C. Lu , M. Xiao **Universidad de Los Andes, Bogota, Colombia**C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega**Universidad de Antioquia, Medellin, Colombia**F. Ramirez , C. Rendón, M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac **University of Split, Faculty of Science, Split, Croatia**M. Kovac , A. Petkovic, T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov¹⁶ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 


Charles University, Prague, Czech Republic

M. Finger , M. Finger Jr. , A. Kveton 


Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 



Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 









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

A.A. Abdelalim^{17,18} , S. Elgammal¹⁹, A. Ellithi Kamel²⁰


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

A. Lotfy , M.A. Mahmoud 















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

Department of Physics, University of Helsinki, Helsinki, Finland

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 




























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow 


















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro²¹ , P. Simkina , M. Titov , M. Tornago 

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 







Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram²² , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 



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

A. Di Florio 

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen²³ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourd'huy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao








Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹⁶ , I. Lomidze , Z. Tsamalaidze¹⁶ 









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

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde




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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , C. Seth, A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo²⁴ , S. Wiedenbeck , S. Zaleski









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

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 





































Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman²⁵ , K. Borrás²⁶ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁵ , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁷ , W. Lohmann²⁸ , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham^{29,26} , S. Schnake²⁶ , P. Schütze , C. Schwanenberger²⁵ , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁶ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf










Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, U. Ellicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann³⁰ , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos³⁰, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsipolitis , A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strogas 

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu , D. Horvath^{31,32} , K. Márton, A.J. Rádl³³ , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkuti³⁴ , M.M.A. Gadallah³⁵ , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 




Faculty of Informatics, University of Debrecen, Debrecen, Hungary

B. Ujvari , G. Zilizi 













HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³⁴ , F. Nemes³⁴ , T. Novak 

Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁶ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J.B. Singh , A. Singla 

University of Delhi, Delhi, India









A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M.K. Saini, S. Saumya 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁷ , S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India










M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana 

P. Kalbhor , S. Kamble , J.R. Komaragiri³⁸ , D. Kumar³⁸ , T. Mishra , B. Parida , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay











Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, G.B. Mohanty , M. Shelake, P. Suryadevara











Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 




National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati³⁹ , C. Kar , D. Maity⁴⁰ , P. Mal , V.K. Muraleedharan Nair Bindhu⁴⁰ , K. Naskar⁴⁰ , A. Nayak⁴⁰ , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese⁴⁰ , D. Vats⁴⁰ 








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

S. Acharya⁴¹ , A. Alpana , S. Dube , B. Gomber⁴¹ , P. Hazarika , B. Kansal , A. Laha , B. Sahu⁴¹ , S. Sharma , K.Y. Vaish 



Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴² , A. Jafari⁴³ , M. Zeinali⁴⁴ 































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

S. Bashiri, S. Chenarani⁴⁵ , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie⁴⁶ , M. Mohammadi Najafabadi , S. Tizchang⁴⁷ 






























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} , A. Colaleo^{a,b} , D. Creanza^{a,c} , B. D'Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , W. Elmetenawee^{a,b,17} , L. Fiore^a , G. Iaselli^{a,c} , L. Longo^a , M. Louka^{a,b}, G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^a , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^{a,b} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,c} , Ü. Sözbilir^a , A. Stamerra^{a,b} , D. Troiano^{a,b} , R. Venditti^{a,b} , P. Verwilligen^a , A. Zaza^{a,b} 
















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


G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , P. Capiluppi^{a,b} , A. Castro^{+a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^a , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,48} , M. Lorusso^{a,b} , L. Lunerti^a , S. Marcellini^a , G. Masetti^a , F.L. Navarra^{a,b} , G. Paggi^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , S. Rossi Tisbeni^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,49} , A. Di Mattia^a , A. Lapertosa^a , R. Potenza^{a,b}, A. Tricomi^{a,b,49} , C. Tuve^{a,b} 

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

P. Assiouras^a , G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^a , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , T. Kello^a, G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^a , M. Meschini^a , S. Paoletti^a 

A. Papanastassiou^{a,b}, G. Sguazzoni^a , L. Viliani^a 










INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵⁰ , D. Piccolo 

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

P. Chatagnon^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 










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

A. Benaglia^a , F. Brivio^a , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^a , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , S. Palluotto^{a,b} , D. Pedrini^a , A. Perego^{a,b} , B.S. Pinolini^a, G. Pizzati^{a,b}, S. Ragazzi^{a,b} , T. Tabarelli de Fatis^{a,b}










INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,51} , P. Paolucci^{a,30} , B. Rossi^a 










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

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,52} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , A.C.M. Bulla^a , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , S. Giorgetti^a, M. Gulmini^{a,53} , E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b}










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

A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{a,b} , V. Re^a , 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

S. Ajmal^{a,b} , M.E. Ascioti^{a,b}, G.M. Bilei^a , C. Carrivale^{a,b}, D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,54} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b}









































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

C. Aimè^a , C.A. Alexe^{a,c} , P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , A.C. Marini^a , D. Matos Figueiredo^a , A. Messineo^{a,b} , S. Mishra^a , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , F. Vaselli^{a,c} , A. Venturi^a , P.G. Verdini^a








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

C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^{a,b} , M. Diemoz^a , F. Errico^{a,b} , E. Longo^{a,b} , L. Martikainen^{a,b} , J. Mijuskovic^{a,b} , 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

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

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , C. Borca^{a,b} , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , L. Finco^a , M. Grippo^{a,b} , B. Kiani^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , L. Markovic^{a,b} , S. Maselli^a , A. Mecca^{a,b} , L. Menzio^{a,b}, P. Meridiani^a , E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , D. Trocino^a , G. Umoret^{a,b} , R. White^{a,b} 


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

J. Babbar^{a,b} , S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a , G. Della Ricca^{a,b} 

Kyungpook National University, Daegu, Korea

S. Dogra , J. Hong , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon , Y.D. Oh , M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim 

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

G. Bak , P. Gwak , H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , J. Choi , D. Kim , T.J. Kim , J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Yoo 













Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 








Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee



Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh, I.J. Watson 

Yonsei University, Department of Physics, Seoul, Korea































S. Ha , H.D. Yoo 




Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 



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

T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, KuwaitF. Alazemi **Riga Technical University, Riga, Latvia**K. Dreimanis , A. Gaile , C. Munoz Diaz, D. Osite , G. Pikurs, A. Potrebko , M. Seidel ,
D. Sidiropoulos Kontos**University of Latvia (LU), Riga, Latvia**N.R. Strautnieks **Vilnius University, Vilnius, Lithuania**M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis **National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**I. Yusuff⁵⁵ , Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez,
M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-
De La Cruz⁵⁶ , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera,
A. Sánchez Hernández **Universidad Iberoamericana, Mexico City, Mexico**C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García **Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**I. Bautista , I. Pedraza , H.A. Salazar Ibarquen , C. Uribe Estrada **University of Montenegro, Podgorica, Montenegro**I. Bubanja , N. Raicevic **University of Canterbury, Christchurch, New Zealand**P.H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan **AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**V. Avati, L. Grzanka , M. Malawski **National Centre for Nuclear Research, Swierk, Poland**H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szleper , P. Zalewski **Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski ,
A. Muhammad **Warsaw University of Technology, Warsaw, Poland**K. Pozniak , W. Zabolotny **Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo ,
T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo 

G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff































Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , P. Milenovic 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

D. Devetak, M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic














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

J. Alcaraz Maestre , Cristina F. Bedoya , J.A. Brochero Cifuentes , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. Llorente Merino , E. Martin Viscasillas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 



















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 



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

B. Alvarez Gonzalez , J. Cuevas , J. Del Riego Badas, J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina , E. Palencia Cortezon , J. Prado Pico, C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 

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

S. Bhowmik , S. Blanco Fernández , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasiosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizán Garcia 














University of Colombo, Colombo, Sri Lanka

B. Kailasapathy⁵⁷ , D.D.C. Wickramarathna 

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













W.G.D. Dharmaratna⁵⁸ , K. Liyanage , N. Perera 

CERN, European Organization for Nuclear Research, Geneva, Switzerland



































D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Boronovi , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , J. Hegeman , J.K. Heikkilä , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban²⁸ , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabady , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁵⁹ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk⁶⁰ , J. Wang,

K.A. Wozniak⁶¹ , S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner




















Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua⁶² , L. Caminada⁶² , A. Ebrahimi , W. Erdmann , R. Horisberger ,
Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶² , L. Noehte⁶² ,
T. Rohe , A. Samalan




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

T.K. Aarrestad , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazzaniga , K. Datta ,
P. De Bryas Dexmiers D'archiac⁶⁰ , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà ,
F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte,
D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese ,
C. Martin Perez , A. Mascellani⁶⁰ , F. Nessi-Tedaldi , F. Pauss , V. Perovic ,
S. Pigazzini , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶⁰ , A. Tarabini ,
D. Valsecchi , R. Wallny 












Universität Zürich, Zurich, Switzerland

C. Amsler⁶³ , P. Bäertschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin ,
A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring ,
F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr,
F. Stäger , R. Tramontano 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁴, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁸ , S.S. Yu 




















National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao,
S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker ,
L.s. Tsai, D. Tsiou, H.y. Wu, E. Yazgan 

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu⁶⁵ , E. Eskut , Y. Guler⁶⁶ ,
E. Gurpınar Guler⁶⁶ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , Y. Komurcu ,
G. Onengut , K. Ozdemir⁶⁷ , A. Polatoz , B. Tali⁶⁸ , U.G. Tok , S. Turkcapar ,
E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac⁶⁹ 





Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷⁰ , O. Kaya⁷¹ , S. Tekten⁷² 





Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{65,73} , G.G. Dincer⁶⁵ , S. Sen⁷⁴ 

Istanbul University, Istanbul, Turkey

O. Aydılek⁷⁵ , B. Hacısahinoglu , I. Hos⁷⁶ , B. Kaynak , S. Ozkorucuklu , O. Potok ,
H. Sert , C. Simsek , C. Zorbilmez 

Yildiz Technical University, Istanbul, Turkey

S. Cerci , B. Isildak⁷⁷ , D. Sunar Cerci , T. Yetkin 


















Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

A. Boyaryntsev , B. Grynyov 

























National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 















































University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou⁷⁸ , K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball , K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 













Imperial College, London, United Kingdom

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller , V. Cacchio , C.A. Carrillo Montoya , G.S. Chahal⁸⁰ , D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , J. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard , G. Iles , C.R. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios , M. Mieskolainen , J. Nash⁸¹ , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage , T. Virdee³⁰ , M. Vojinovic , N. Wardle , D. Winterbottom 




Brunel University, Uxbridge, United Kingdom

J.E. Cole , A. Khan , P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish⁸² , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , A.E. Simsek 




















The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio⁸³ , E. Usai , R. Yi 

Boston University, Boston, Massachusetts, USA



















A. Akpinar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 

Brown University, Providence, Rhode Island, USA

G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell , S. Sagir⁸⁵ , X. Shen , F. Simpson , M. Stamenkovic , N. Venkatasubramanian 

X. Yan 

University of California, Davis, Davis, California, USA

S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo , F. Zhang 

























University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 















University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 





University of California, San Diego, La Jolla, California, USA

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang















California Institute of Technology, Pasadena, California, USA

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 






University of Colorado Boulder, Boulder, Colorado, USA

























J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 

Cornell University, Ithaca, New York, USA




















J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA













M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu 

C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi






University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 
























Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy⁸⁸ , M. Hohlmann , E. Yanes












University of Illinois Chicago, Chicago, Illinois, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , N. Singh, M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , D. Blend, K. Dilsiz⁸⁹ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁹⁰ , O. Neogi, H. Ogu⁹¹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹² 









Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 


















The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹³ , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 
























Kansas State University, Manhattan, Kansas, USA

B. Allmond , R. Guju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova⁹⁴ , A. Shevelev , L. Wang 













Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn, A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 












University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering , R. Rusack , R. Saradhy , N. Strobbe 



















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

State University of New York at Buffalo, Buffalo, New York, USA

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 



























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan, Y. Haddad , Y. Han , I. Israr , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , M. McGinnis , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco

















University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko¹⁶ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala 


The Ohio State University, Columbus, Ohio, USA

A. Basnet , M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 




















Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang , A. Wildridge , W. Xie , Y. Yao 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 





















Rice University, Houston, Texas, USA

D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , I. Krommydas , W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter , E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin⁹⁴ , R. Taus 
















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanunganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 












Texas A&M University, College Station, Texas, USA

D. Aebi , M. Ahmad , T. Akhter , K. Androsov⁶⁰ , O. Bouhali⁹⁵ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁶ , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 
























University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , H. Chung, B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu 







































Wayne State University, Detroit, Michigan, USA






































S. Bhattacharya , P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA


A. Aravind, S. Banerjee , K. Black , T. Bose , E. Chavez , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , L. Pétré , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin[†] , I. Gorbunov , V. Karjavine , V. Korenkov , A. Lanev , A. Malakhov , V. Matveev⁹⁷ , V. Palichik , V. Perelygin , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B.S. Yuldashev⁹⁸, A. Zarubin , I. Zhizhin , G. Gavrillov , V. Golovtsov , Y. Ivanov , V. Kim⁹⁷ , P. Levchenko⁹⁹ , V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov , A. Vorobyev[†], Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu , D. Kirpichnikov , M. Kirsanov 

N. Krasnikov , I. Tlisova , A. Toropin , T. Aushev , V. Gavrilov , N. Lychkovskaya , A. Nikitenko^{100,101} , V. Popov , A. Zhokin , R. Chistov⁹⁷ , M. Danilov⁹⁷ , S. Polikarpov⁹⁷ , V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov , E. Boos , V. Bunichev , M. Dubinin⁸⁶ , L. Dudko , A. Ershov , A. Gribushin , V. Klyukhin , S. Obraztsov , M. Perfilov, V. Savrin , P. Volkov , G. Vorotnikov , V. Blinov⁹⁷, T. Dimova⁹⁷ , A. Kozyrev⁹⁷ , O. Radchenko⁹⁷ , Y. Skovpen⁹⁷ , V. Kachanov , D. Konstantinov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin¹⁰² 

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

V. Chekhovsky, V. Makarenko 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Ghent University, Ghent, Belgium

⁴Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at China Center of Advanced Science and Technology, Beijing, China

¹⁰Also at University of Chinese Academy of Sciences, Beijing, China

¹¹Also at China Spallation Neutron Source, Guangdong, China

¹²Now at Henan Normal University, Xinxiang, China

¹³Also at Nanjing Normal University, Nanjing, China

¹⁴Now at The University of Iowa, Iowa City, Iowa, USA

¹⁵Also at Université Libre de Bruxelles, Bruxelles, Belgium

¹⁶Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁷Also at Helwan University, Cairo, Egypt

¹⁸Now at Zewail City of Science and Technology, Zewail, Egypt

¹⁹Now at British University in Egypt, Cairo, Egypt

²⁰Now at Cairo University, Cairo, Egypt

²¹Also at Purdue University, West Lafayette, Indiana, USA

²²Also at Université de Haute Alsace, Mulhouse, France

²³Also at Istinye University, Istanbul, Turkey

²⁴Also at The University of the State of Amazonas, Manaus, Brazil

²⁵Also at University of Hamburg, Hamburg, Germany

²⁶Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁷Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

²⁸Also at Brandenburg University of Technology, Cottbus, Germany

²⁹Also at Forschungszentrum Jülich, Juelich, Germany

³⁰Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

³¹Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

³²Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

³³Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

³⁴Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

³⁵Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

- ³⁶Also at Punjab Agricultural University, Ludhiana, India
- ³⁷Also at University of Visva-Bharati, Santiniketan, India
- ³⁸Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁹Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴⁰Also at Institute of Physics, Bhubaneswar, India
- ⁴¹Also at University of Hyderabad, Hyderabad, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁷Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵¹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵²Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵³Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁷Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁸Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁵⁹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶⁰Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶¹Also at University of Vienna, Vienna, Austria
- ⁶²Also at Universität Zürich, Zurich, Switzerland
- ⁶³Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁴Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁵Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁶Also at Konya Technical University, Konya, Turkey
- ⁶⁷Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁸Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁹Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷⁰Also at Marmara University, Istanbul, Turkey
- ⁷¹Also at Milli Savunma University, Istanbul, Turkey
- ⁷²Also at Kafkas University, Kars, Turkey
- ⁷³Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁴Also at Hacettepe University, Ankara, Turkey
- ⁷⁵Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United

Kingdom

⁸⁰Also at IPPP Durham University, Durham, United Kingdom

⁸¹Also at Monash University, Faculty of Science, Clayton, Australia

⁸²Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁸³Also at Università di Torino, Torino, Italy

⁸⁴Also at Bethel University, St. Paul, Minnesota, USA

⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁶Also at California Institute of Technology, Pasadena, California, USA

⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁸Also at Ain Shams University, Cairo, Egypt

⁸⁹Also at Bingol University, Bingol, Turkey

⁹⁰Also at Georgian Technical University, Tbilisi, Georgia

⁹¹Also at Sinop University, Sinop, Turkey

⁹²Also at Erciyes University, Kayseri, Turkey

⁹³Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

⁹⁴Now at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁵Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁶Also at Kyungpook National University, Daegu, Korea

⁹⁷Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁸Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

⁹⁹Also at Northeastern University, Boston, Massachusetts, USA

¹⁰⁰Also at Imperial College, London, United Kingdom

¹⁰¹Now at Yerevan Physics Institute, Yerevan, Armenia

¹⁰²Also at Universiteit Antwerpen, Antwerpen, Belgium