

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

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 12 November 2016 / Accepted: 24 February 2017

© CERN for the benefit of the CMS collaboration 2017. This article is an open access publication

Abstract The cross section of top quark–antiquark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV is measured by the CMS experiment at the LHC, using data corresponding to an integrated luminosity of 2.2 fb^{-1} . The measurement is performed by analyzing events in which the final state includes one electron, one muon, and two or more jets, at least one of which is identified as originating from hadronization of a b quark. The measured cross section is 815 ± 9 (stat) ± 38 (syst) ± 19 (lumi) pb, in agreement with the expectation from the standard model.

1 Introduction

The measurement of the top quark–antiquark pair ($t\bar{t}$) cross section provides a test of the hadroproduction of top quark pairs as predicted by quantum chromodynamics (QCD). At the CERN LHC, measurements have been performed in many different decay channels and at three different proton–proton collision energies [1–24]. Precision measurements of these cross sections allow for a test of their energy dependence as predicted by QCD; they can also place constraints on the parton distribution functions (PDFs) [25]. In combination with some theory, they also provide unambiguous measurements of interesting quantities, such as the top quark pole mass [13, 21], which is difficult to determine by other means. A detailed understanding of the production cross section is also required in searches for evidence of new physics beyond the standard model, as $t\bar{t}$ production is often the dominant background process. This is especially important if the signature for the new physics is similar to that of $t\bar{t}$ production [13, 26]. This paper presents a measurement of the $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) in the $e^\pm\mu^\mp$ decay channel using an event-counting method, based on observed yields. The analysis follows closely [12], and uses the full data set recorded by CMS at 13 TeV during 2015, which corresponds

to an integrated luminosity of 2.2 fb^{-1} . This represents a factor of 50 increase in the amount of data over the original analysis and allows for more detailed studies of the experimental and theory uncertainties.

2 The CMS detector and Monte Carlo simulation

The CMS detector [27] has a superconducting solenoid in its central region that provides an axial magnetic field of 3.8 T. The silicon pixel and strip trackers cover $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. The lead tungstate crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter are located inside the solenoid. These are used to identify electrons, photons and jets. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, providing reliable measurement of the momentum imbalance in the plane transverse to the beams. A two-level trigger system selects the most interesting pp collisions for offline analysis. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [27].

Different Monte Carlo (MC) event generators are used to simulate signal and background events. The next-to-leading-order (NLO) POWHEG (v2) [28, 29] generator is used for $t\bar{t}$ events, with the top quark mass (m_t) set to 172.5 GeV. The NNPDF3.0 NLO [30] PDFs are used. For the reference $t\bar{t}$ sample, the events are interfaced with PYTHIA (v8.205) [31, 32] with the CUETP8M1 tune [33, 34] to simulate parton showering, hadronization, and the underlying event. Additional samples are produced by showering the events in the reference sample with HERWIG++ (v2.7.1) [35] or by generating events using MG5_aMC@NLO (v5_2.2.2) [36] interfaced with MADSPIN [37] to account for spin correlations in the decays of the top quarks, and using PYTHIA for parton showering and hadronization.

The MG5_aMC@NLO generator is also used to simulate W +jets events and Drell–Yan (DY) quark–antiquark anni-

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

hilation into lepton-antilepton pairs through a virtual photon or a Z boson exchange; for these backgrounds the event yields are estimated from data. Single top quark events are simulated using POWHEG (v1) [38,39] and PYTHIA, and the event yields are normalized to the approximate next-to-next-to-leading order (NNLO) cross sections from Ref. [40]. The diagram removal approach [41] is used to handle the interference between the $t\bar{t}$ and tW final states starting at NLO. The contributions from WW, WZ, and ZZ (referred to as “VV”) processes are simulated with PYTHIA, and the event rates are normalized to the NLO cross sections from Ref. [42]. Other contributions from W and Z boson production in association with $t\bar{t}$ events (referred to as “ $t\bar{t}V$ ”) are simulated using MG5_AMC@NLO and PYTHIA. The simulated samples include additional interactions per bunch crossing (pileup), with the distribution matching that observed in data, with an average of about 11 collisions per bunch crossing.

The SM prediction for $\sigma_{t\bar{t}}$ at 13 TeV is 832_{-29}^{+20} (scales) ± 35 (PDF+ α_s) pb for $m_t = 172.5$ GeV, as calculated with the TOP++ program [43] at NNLO in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log order [44]. The first uncertainty reflects uncertainties in the factorization (μ_F) and renormalization (μ_R) scales. The second one is associated with possible choices of PDFs and the value of the strong coupling constant, following the PDF4LHC prescriptions [45,46], using the MSTW2008 68% confidence level NNLO [47,48], CT10 NNLO [49,50], and NNPDF2.3 5f FFN [51] PDF sets. The expected event yields for signal in all figures and tables are normalized to this cross section.

3 Event selection

In the SM, top quarks in pp collisions are mostly produced as $t\bar{t}$ pairs, where each top quark decays predominantly to a W boson and a bottom quark. In $t\bar{t}$ events where both W bosons decay leptonically, the final state contains two leptons of opposite electric charge and at least two jets coming from the hadronization of the bottom quarks.

At the trigger level, a combination of the single lepton and dilepton triggers is used. Events are required to contain either one electron with transverse momentum $p_T > 12$ GeV and one muon with $p_T > 17$ GeV or one electron with $p_T > 17$ GeV and one muon with $p_T > 8$ GeV. In addition, single-lepton triggers with one electron (muon) with $p_T > 23$ GeV (20) are used in order to increase the efficiency. The efficiency for the combination of the single lepton and dilepton triggers is measured in data using triggers based on p_T imbalance in the event. The trigger efficiency is measured to be 0.99 ± 0.01 (combined statistical and systematic uncertainties) when the selection on the leptons described below is applied. The trigger in simulation is corrected using

a multiplicative data-to-simulation scale factor (SF), given by the trigger efficiency measured in data with independent monitoring triggers.

The particle-flow (PF) event algorithm [52,53] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. Selected dilepton events are required to contain one isolated electron [54] and one isolated muon [55] with opposite electric charge and $p_T > 20$ GeV and $|\eta| < 2.4$. Isolation requirements are based on the ratio of the scalar sum of the transverse momenta of all PF candidates, reconstructed inside a cone centered on the lepton, excluding the contribution from the lepton candidate. This isolation variable is required to be smaller than 7% (15%) of the electron (muon) p_T .

In events with more than one pair of leptons passing the selection, the two opposite-sign different-flavour leptons with the largest p_T are selected for further study. Events with W bosons decaying into τ leptons contribute to the measurement only if the τ leptons decay into electrons or muons that satisfy the selection requirements.

The efficiency of the lepton selection is measured using a “tag-and-probe” [56] method in a sample of same-flavour dilepton events, which is enriched in Z boson candidates. The measured p_T - and η -dependent values for the combined identification and isolation efficiencies average to about 80% for electrons and 90% for muons. To account for the difference in efficiencies determined using data and simulation, the event yield in simulation is corrected using p_T - and η -dependent SFs based on a comparison of lepton selection efficiencies in data and simulation. These have an average of 0.99 for electrons and 0.98 for muons.

In order to suppress backgrounds from DY production of τ lepton pairs with low invariant dilepton mass, $t\bar{t}$ candidate events are further required to have a dilepton pair of invariant mass $m_{e\mu} > 20$ GeV.

Jets are reconstructed from the PF particle candidates using the anti- k_r clustering algorithm [57,58] with a distance parameter of 0.4. The jet momentum is determined from the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole p_T spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from additional proton–proton interactions within the same or nearby bunch crossings. Jet energy corrections are derived from simulation, confirmed with in situ measurements of the energy balance in dijet and photon + jet events, and are applied as a function of the jet p_T and η [59] to both data and simulated events. The $t\bar{t}$ candidate events are required to have at least two reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.4$.

Since $t\bar{t}$ events decay into final states containing a bottom quark–antiquark pair, requiring the presence of jets identified

as originating from b quarks (“b jets”) reduces backgrounds from DY and W+jets production. Jets are identified as b jets using the combined secondary vertex algorithm [60,61], with an operating point which yields an identification efficiency of 67% and a misidentification (mistag) probability of about 1% and 15% [61] for light-flavour jets (u, d, s, and gluons) and c jets, respectively. The selection requires the presence of at least one b jet in the event.

4 Background determination

Background events arise primarily from single top quark, DY, and VV events in which at least two prompt leptons are produced by Z or W boson decays. The single top quark and VV contributions are estimated from simulation.

The DY event yield is estimated from data using the “ $R_{\text{out/in}}$ ” method [1,2,6], where events with same-flavour leptons are used to normalize the yield of $e^\pm\mu^\mp$ pairs from DY production of τ lepton pairs. A data-to-simulation normalization factor is estimated from the number of events in data within a 15 GeV window around the Z boson mass and extrapolated to the number of events outside the Z mass window with corrections applied using control regions enriched in DY events in data. The SF is found to be 0.95 ± 0.05 (statistical uncertainty) after applying the final event selection.

Other background sources, such as $t\bar{t}$ or W+jets events in the lepton+jets final state, can contaminate the signal sample if a jet is incorrectly reconstructed as a lepton, or the lepton is incorrectly identified as being isolated. This is more important for electrons. For muons, the dominant contribution comes from the semileptonic decay of bottom or charm quarks. These events are grouped into the nonprompt leptons category (“non-W/Z leptons”) since prompt leptons are defined as originating from decays of W or Z boson, together with contributions that can arise, for example, from decays of mesons or photon conversions.

The contribution of non-W/Z lepton events is estimated from a control region of same-sign (SS) events and propagated in the opposite-sign (OS) signal region. The SS control region is defined using the same criteria as the nominal signal region, except for requiring $e\mu$ pairs with the same electric charge. The SS dilepton events are predominantly events containing misidentified leptons. Other SM processes produce prompt SS or charge-misidentified dilepton events with significantly smaller rates; these are estimated using simulation and subtracted from the observed number of events in data.

The scaling from the SS control region in data to the signal region is performed through the ratio of the numbers of OS to SS events with misidentified leptons in simulation. This ratio is calculated using simulated $t\bar{t}$ and W+jets samples, which are rich in nonprompt dilepton events, and is measured to be

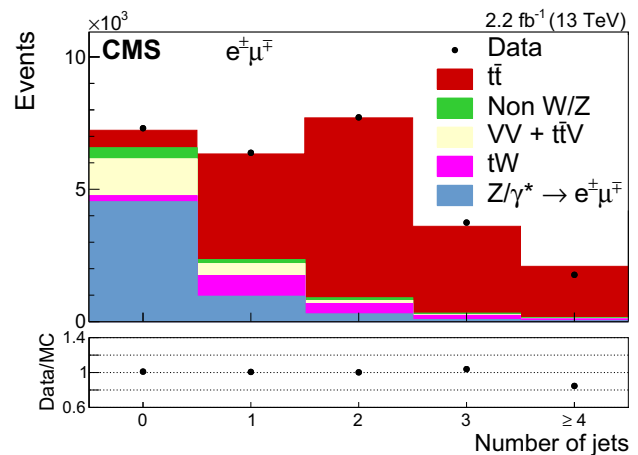


Fig. 1 Distribution of the jet multiplicity in events passing the dilepton selection criteria. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based on control regions in data are applied; the last bin contains the overflow events. The ratio of data to the sum of the expected yields is given at the bottom of the figure. The error bars, which are within the size of the points, indicate the statistical uncertainties

1.4 ± 0.1 (stat). In data, 152 SS events are observed, with a contribution of 79.8 ± 1.9 (stat) prompt lepton SS events as evaluated from simulation. In total 104 ± 8 (stat + syst) events with misidentified leptons contaminating the signal region are predicted. This agrees within the uncertainties with predictions from the simulation.

Figure 1 shows the multiplicity of jets for events passing the dilepton criteria. The MC simulation does not describe well the data for events with ≥ 4 jets, the region in which parton shower effects are expected to dominate the prediction. After requiring at least two jets, Fig. 2 shows the p_T and $|\eta|$ distributions of the selected leptons, and Fig. 3 shows the p_T (a, c) and $|\eta|$ (b, d) distributions of the two most energetic jets; Fig. 3(e) shows the scalar sum of the transverse momenta of all jets (H_T) and Fig. 3(f) the b jet multiplicity. Good agreement between data and the predictions for signal and background is observed.

5 Sources of systematic uncertainty

Table 1 summarizes the statistical uncertainty and the different sources of systematic uncertainties in the measured $t\bar{t}$ production cross section.

The uncertainty in the trigger efficiency SF applied to simulation to correct for differences with respect to data is 1.1%. The uncertainty in the SF applied to correct the electron (muon) identification efficiency is found to be about 1.8% (1.5%), with some dependence on the lepton p_T and η .

The modeling of lepton energy scales was studied using $Z \rightarrow ee/\mu\mu$ events in data and simulation, resulting in

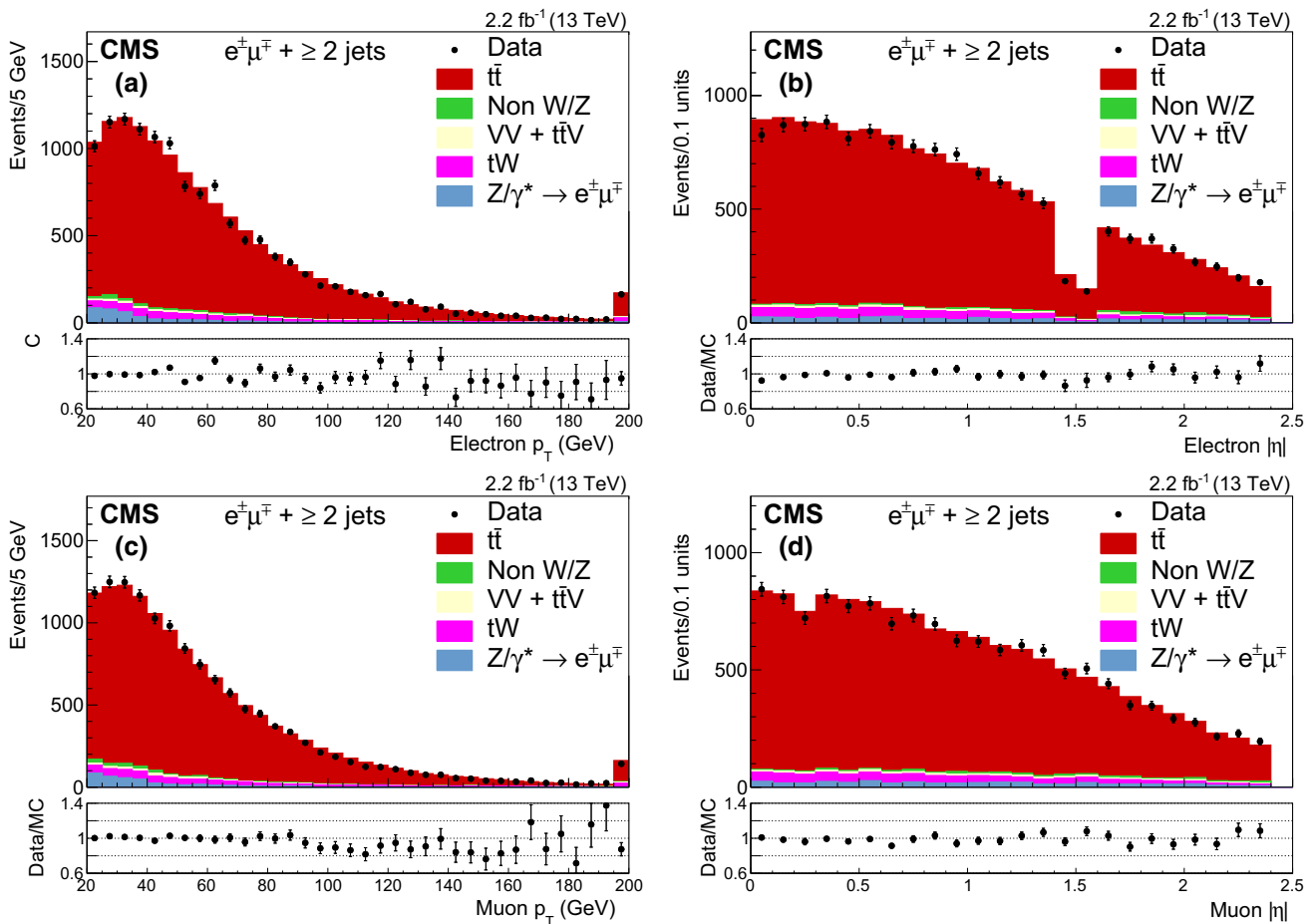


Fig. 2 The distributions of **a** p_T and **b** $|\eta|$ of the electron, and **c** p_T and **d** $|\eta|$ of the muon after the selection of jets and before the b jet requirement. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based on control regions in

data are applied; for the *left plots* (**a, c**) the last bin contains the overflow events. The ratios of data to the sum of the expected yields are given at the *bottom of each panel*. The error bars indicate the statistical uncertainties

an uncertainty for the electron (muon) energy scale of 1.0(0.5)%. These values are used to obtain the effect on the signal acceptance, which is taken as a systematic uncertainty.

The impact of uncertainties in jet energy scale (JES) and jet energy resolution (JER) is estimated from the change observed in the number of simulated $t\bar{t}$ events selected after changing the jet momenta within the JES uncertainties, and for JER by an $|\eta|$ -dependent variation of the JER scale factors within their uncertainties.

The uncertainties resulting from the b tagging efficiency and misidentification rate are determined by varying the b tagging SF of the b jets and the light-flavour jets, respectively. These uncertainties depend on the p_T and η of the jet and amount to approximately 2% for b jets and 10% for mistagged jets [61] in $t\bar{t}$ signal events. They are propagated to the $t\bar{t}$ selection efficiency using simulated events.

The uncertainty assigned to the number of pileup events in simulation is obtained by changing the inelastic proton–

proton cross section, which is used to estimate the pileup in data, by $\pm 5\%$ [62].

The systematic uncertainty related to the missing higher-order diagrams in POWHEG is estimated as follows: the uncertainty in the signal acceptance is determined by changing the μ_F and μ_R scales in POWHEG independently up and down by a factor of two, with the uncertainty taken as the maximum observed difference.

The predictions of the NLO generators POWHEG and MG5_amc@NLO for $t\bar{t}$ production are compared, where both use PYTHIA for hadronization, fragmentation, and additional radiation description. The difference in the signal acceptance between the two is taken as an uncertainty.

The uncertainty arising from the hadronization model mainly affects the JES and the fragmentation of b quark jets. The uncertainty in the JES already contains a contribution from the uncertainty in the hadronization. In addition, we determine a related uncertainty by comparing samples

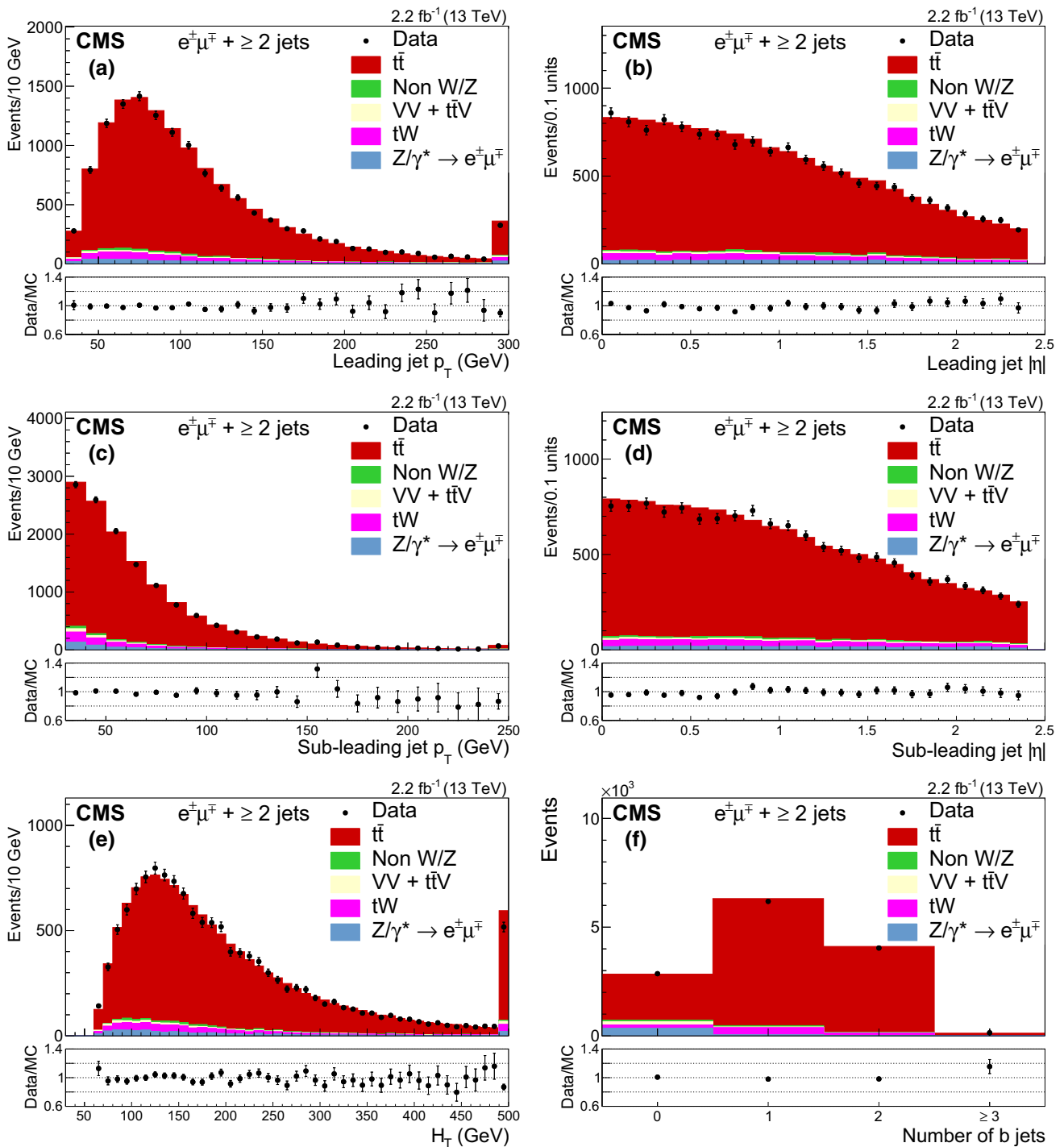


Fig. 3 The distributions of **a** p_T and **b** $|\eta|$ for the leading jet, **c** p_T and **d** $|\eta|$ for the sub-leading jet, **e** H_T , and **f** b jet multiplicity after the jets selection and before the b jet requirement. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based

on control regions in data are applied; in each plot the last bin contains the overflow events. The ratios of data to the sum of the expected yields are given at the *bottom of each panel*. The error bars indicate the statistical uncertainties

of events generated with POWHEG, where the hadronization is modeled with PYTHIA or HERWIG++. In what follows we refer to this difference as the hadronization uncertainty.

The impact of the choice of the parton shower scale is studied by changing the scale of the parton shower (initial and final state radiation) by a factor of 2 and 1/2 from its

Table 1 Summary of the individual contributions to the uncertainty in the $\sigma_{t\bar{t}}$ measurement. The first and second uncertainty corresponds to the total and relative component, respectively. The total uncertainty in the result, calculated as the quadratic sum of the individual components, is also given

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
<i>Experimental</i>		
Trigger efficiencies	9.9	1.2
Lepton efficiencies	18.9	2.3
Lepton energy scale	<1	≤ 0.1
Jet energy scale	17.4	2.1
Jet energy resolution	0.8	0.1
b tagging	11.0	1.3
Mistagging	<1	≤ 0.1
Pileup	1.5	0.2
<i>Modeling</i>		
μ_F and μ_R scales	<1	≤ 0.1
$t\bar{t}$ NLO generator	17.3	2.1
$t\bar{t}$ hadronization	6.0	0.7
Parton shower scale	6.5	0.8
PDF	4.9	0.6
<i>Background</i>		
Single top quark	11.8	1.5
VV	<1	≤ 0.1
Drell–Yan	<1	≤ 0.1
Non-W/Z leptons	2.6	0.3
$t\bar{t}V$	<1	≤ 0.1
Total systematic (no integrated luminosity)	37.8	4.6
Integrated luminosity	18.8	2.3
Statistical	8.5	1.0
Total	43.0	5.3

default value. The maximum variation with respect to the central value of the signal acceptance at particle level [63] for the fiducial volume of the analysis is taken as an uncertainty.

The uncertainty from the choice of PDF is determined by reweighting the sample of simulated $t\bar{t}$ events according to the NNPDF3.0 PDF sets [30]. The root-mean-square of the distribution is taken as an uncertainty.

Based on recent measurements of the production cross section for single top quark [64–66] and VV [67–74] we use an uncertainty of 30% for these background processes. For DY production, an uncertainty of 15%, that covers the difference of the SF at different levels of the selection, is assumed. A 30% systematic uncertainty is estimated for the non-W/Z lepton background derived from the uncertainty in the ratio of the numbers of OS to SS events with misidentified leptons in the MC simulation.

The uncertainty in the integrated luminosity is 2.3% [75].

Table 2 Number of dilepton events obtained after applying the full selection. The results are given for the individual sources of background, $t\bar{t}$ signal with a top quark mass of 172.5 GeV and $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb, and data. The uncertainties correspond to the statistical component

Source	Number of $e^\pm\mu^\mp$ events
Drell–Yan	$46 \pm 5 \pm 7$
Non-W/Z leptons	$104 \pm 8 \pm 31$
Single top quark	$452 \pm 6 \pm 141$
VV	$14 \pm 2 \pm 5$
$t\bar{t}V$	$30 \pm 1 \pm 9$
Total background	$646 \pm 11 \pm 145$
$t\bar{t}$ signal	$9921 \pm 14 \pm 436$
Data	10368

6 Results

The $t\bar{t}$ production cross section is measured by counting events and applying the expression

$$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A}\mathcal{L}},$$

where N is the total number of dilepton events observed in data, N_B is the number of estimated background events, \mathcal{A} is the product of the mean acceptance, the selection efficiency, and the branching fraction into the $e^\pm\mu^\mp$ final state, and \mathcal{L} is the integrated luminosity.

Table 2 shows the total number of events observed in data together with the total number of signal and background events determined from simulation or estimated from data. The value of \mathcal{A} , determined from simulation assuming $m_t = 172.5$ GeV, is $(0.55 \pm 0.03)\%$, including statistical and systematic uncertainties. The measured cross section is

$$\sigma_{t\bar{t}} = 815 \pm 9(\text{stat}) \pm 38(\text{syst}) \pm 19(\text{lumi}) \text{ pb},$$

for a top quark mass of 172.5 GeV.

As a cross-check, analogous measurements have been performed using independent data samples with same-flavour leptons in the final state. The results obtained in the e^+e^- and $\mu^+\mu^-$ channels are consistent with the result in the $e^\pm\mu^\mp$ channel. Given their larger uncertainties, the results are not combined with the main one in the $e^\pm\mu^\mp$ channel.

The measured fiducial cross section for $t\bar{t}$ production with two leptons (one electron and one muon) in the range $p_T > 20$ GeV and $|\eta| < 2.4$, at least two jets with $p_T > 30$ GeV and $|\eta| < 2.4$, and at least one b jet is $\sigma_{t\bar{t}}^{\text{fid}} = 12.4 \pm 0.1(\text{stat}) \pm 0.5(\text{syst}) \pm 0.3(\text{lumi}) \text{ pb}$.

The acceptance has been measured in the range 166.5–178.5 GeV and is parameterized as a linear function of m_t . The cross section varies by 3.7 pb when the top quark mass changes 0.5 GeV.

7 Summary

A measurement of the $t\bar{t}$ production cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV is presented for events containing an oppositely charged electron–muon pair, and two or more jets, of which at least one is tagged as originating from a b quark. The measurement is performed through an event-counting method based on a data sample corresponding to an integrated luminosity of 2.2 fb^{-1} . The measured cross section is

$$\sigma_{t\bar{t}} = 815 \pm 9 \text{ (stat)} \pm 38 \text{ (syst)} \pm 19 \text{ (lumi)} \text{ pb,}$$

with a total relative uncertainty of 5.3%. The measurement, that supersedes [12], is consistent with recent measurements from the ATLAS [24] and CMS [12] experiments and with the standard model prediction of $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb for a top quark mass of 172.5 GeV.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2013/11/B/ST2/04202, 2014/13/B/ST2/02543 and 2014/15/B/ST2/03998, Sonata-bis 2012/07/E/ST2/01406; the Thalys and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by

Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References

1. CMS Collaboration, First measurement of the cross section for top–quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B* **695**, 424 (2010). doi:[10.1016/j.physletb.2010.11.058](https://doi.org/10.1016/j.physletb.2010.11.058)
2. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section and the top quark mass in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV. *J. High Energy Phys.* **07**, 049 (2011). doi:[10.1007/JHEP07\(2011\)049](https://doi.org/10.1007/JHEP07(2011)049)
3. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV using the kinematic properties of events with leptons and jets. *Eur. Phys. J. C* **71**, 1721 (2011). doi:[10.1140/epjc/s10052-011-1721-3](https://doi.org/10.1140/epjc/s10052-011-1721-3)
4. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in pp collisions at 7 TeV in lepton + jets events using b -quark jet identification. *Phys. Rev. D* **84**, 092004 (2011). doi:[10.1103/PhysRevD.84.092004](https://doi.org/10.1103/PhysRevD.84.092004)
5. CMS Collaboration, Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states containing a τ . *Phys. Rev. D* **85**, 112007 (2012). doi:[10.1103/PhysRevD.85.112007](https://doi.org/10.1103/PhysRevD.85.112007). arXiv:[1203.6810](https://arxiv.org/abs/1203.6810)
6. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP* **11**, 067 (2012). doi:[10.1007/JHEP11\(2012\)067](https://doi.org/10.1007/JHEP11(2012)067). arXiv:[1208.2671](https://arxiv.org/abs/1208.2671)
7. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV with lepton + jets final states. *Phys. Lett. B* **720**, 83 (2013). doi:[10.1016/j.physletb.2013.02.021](https://doi.org/10.1016/j.physletb.2013.02.021). arXiv:[1212.6682](https://arxiv.org/abs/1212.6682)
8. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the τ +jets channel in pp collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C* **73**, 2386 (2013). doi:[10.1140/epjc/s10052-013-2386-x](https://doi.org/10.1140/epjc/s10052-013-2386-x)
9. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP* **05**, 065 (2013). doi:[10.1007/JHEP05\(2013\)065](https://doi.org/10.1007/JHEP05(2013)065). arXiv:[1302.0508](https://arxiv.org/abs/1302.0508)
10. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 8$ TeV. *JHEP* **02**, 024 (2014). doi:[10.1007/JHEP02\(2014\)024](https://doi.org/10.1007/JHEP02(2014)024). arXiv:[1312.7582](https://arxiv.org/abs/1312.7582). [Erratum: doi:[10.1007/JHEP02\(2014\)102](https://doi.org/10.1007/JHEP02(2014)102)]
11. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV in dilepton final states containing one τ lepton. *Phys. Lett. B* **739**, 23 (2014). doi:[10.1016/j.physletb.2014.10.032](https://doi.org/10.1016/j.physletb.2014.10.032). arXiv:[1407.6643](https://arxiv.org/abs/1407.6643)
12. CMS Collaboration, Measurement of the top quark pair production cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. Lett.* **116**, 052002 (2016). doi:[10.1103/PhysRevLett.116.052002](https://doi.org/10.1103/PhysRevLett.116.052002). arXiv:[1510.05302](https://arxiv.org/abs/1510.05302)
13. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the $e\mu$ channel in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV. *JHEP* **08**, 029 (2016). doi:[10.1007/JHEP08\(2016\)029](https://doi.org/10.1007/JHEP08(2016)029). arXiv:[1603.02303](https://arxiv.org/abs/1603.02303)

14. ATLAS Collaboration, Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C* **71**, 1577 (2011). doi:[10.1140/epjc/s10052-011-1577-6](https://doi.org/10.1140/epjc/s10052-011-1577-6). arXiv:[1012.1792](https://arxiv.org/abs/1012.1792)
15. ATLAS Collaboration, Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states with ATLAS. *Phys. Lett. B* **707**, 459 (2012). doi:[10.1016/j.physletb.2011.12.055](https://doi.org/10.1016/j.physletb.2011.12.055). arXiv:[1108.3699](https://arxiv.org/abs/1108.3699)
16. ATLAS Collaboration, Measurement of the top quark pair production cross-section with ATLAS in the single lepton channel. *Phys. Lett. B* **711**, 244 (2012). doi:[10.1016/j.physletb.2012.03.083](https://doi.org/10.1016/j.physletb.2012.03.083). arXiv:[1201.1889](https://arxiv.org/abs/1201.1889)
17. ATLAS Collaboration, Measurement of the cross section for top-quark pair production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector using final states with two high- p_T leptons. *JHEP* **05**, 059 (2012). doi:[10.1007/JHEP05\(2012\)059](https://doi.org/10.1007/JHEP05(2012)059). arXiv:[1202.4892](https://arxiv.org/abs/1202.4892)
18. ATLAS Collaboration, Measurement of $t\bar{t}$ production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Eur. Phys. J. C* **72**, 2043 (2012). doi:[10.1140/epjc/s10052-012-2043-9](https://doi.org/10.1140/epjc/s10052-012-2043-9). arXiv:[1203.5015](https://arxiv.org/abs/1203.5015)
19. ATLAS Collaboration, Measurement of the top quark pair cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV using final states with an electron or a muon and a hadronically decaying τ lepton. *Phys. Lett. B* **717**, 89 (2012). doi:[10.1016/j.physletb.2012.09.032](https://doi.org/10.1016/j.physletb.2012.09.032). arXiv:[1205.2067](https://arxiv.org/abs/1205.2067)
20. ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross section in the tau+jets channel using the ATLAS detector. *Eur. Phys. J. C* **73**, 2328 (2013). doi:[10.1140/epjc/s10052-013-2328-7](https://doi.org/10.1140/epjc/s10052-013-2328-7). arXiv:[1211.7205](https://arxiv.org/abs/1211.7205)
21. ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b -tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector. *Eur. Phys. J. C* **74**, 3109 (2014). doi:[10.1140/epjc/s10052-014-3109-7](https://doi.org/10.1140/epjc/s10052-014-3109-7). arXiv:[1406.5375](https://arxiv.org/abs/1406.5375)
22. ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section as a function of jet multiplicity and jet transverse momentum in 7 TeV proton–proton collisions with the ATLAS detector. *JHEP* **01**, 020 (2015). doi:[10.1007/JHEP01\(2015\)020](https://doi.org/10.1007/JHEP01(2015)020). arXiv:[1407.0891](https://arxiv.org/abs/1407.0891)
23. ATLAS Collaboration, Measurement of the top pair production cross section in 8 TeV proton–proton collisions using kinematic information in the lepton+jets final state with ATLAS. *Phys. Rev. D* **91**, 112013 (2015). doi:[10.1103/PhysRevD.91.112013](https://doi.org/10.1103/PhysRevD.91.112013). arXiv:[1504.04251](https://arxiv.org/abs/1504.04251)
24. ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b -tagged jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Lett. B* **761**, 136 (2016). doi:[10.1016/j.physletb.2016.08.019](https://doi.org/10.1016/j.physletb.2016.08.019). arXiv:[1606.02699](https://arxiv.org/abs/1606.02699)
25. M. Czakon, M.L. Mangano, A. Mitov, J. Rojo, Constraints on the gluon PDF from top quark pair production at hadron colliders. *JHEP* **07**, 167 (2013). doi:[10.1007/JHEP07\(2013\)167](https://doi.org/10.1007/JHEP07(2013)167). arXiv:[1303.7215](https://arxiv.org/abs/1303.7215)
26. ATLAS Collaboration, ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider. *Eur. Phys. J. C* **75**, 510 (2015). doi:[10.1140/epjc/s10052-015-3726-9](https://doi.org/10.1140/epjc/s10052-015-3726-9). arXiv:[1506.08616](https://arxiv.org/abs/1506.08616). [Erratum: doi:[10.1140/epjc/s10052-016-3935-x](https://doi.org/10.1140/epjc/s10052-016-3935-x)]
27. CMS Collaboration, The CMS experiment at the CERN LHC. *JINST* **3**, S08004 (2008). doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004)
28. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. *JHEP* **11**, 070 (2007). doi:[10.1088/1126-6708/2007/11/070](https://doi.org/10.1088/1126-6708/2007/11/070). arXiv:[0709.2092](https://arxiv.org/abs/0709.2092)
29. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *JHEP* **06**, 043 (2010). doi:[10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043). arXiv:[1002.2581](https://arxiv.org/abs/1002.2581)
30. F. Demartin et al., The impact of PDF and α_s uncertainties on Higgs production in gluon fusion at hadron colliders. *Phys. Rev. D* **82**, 014002 (2010). doi:[10.1103/PhysRevD.82.014002](https://doi.org/10.1103/PhysRevD.82.014002). arXiv:[1004.0962](https://arxiv.org/abs/1004.0962)
31. T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual. *JHEP* **05**, 026 (2006). doi:[10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026). arXiv:[hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175)
32. T. Sjöstrand et al., An introduction to PYTHIA 8.2. *Comput. Phys. Commun.* **191**, 159 (2015). doi:[10.1016/j.cpc.2015.01.024](https://doi.org/10.1016/j.cpc.2015.01.024). arXiv:[1410.3012](https://arxiv.org/abs/1410.3012)
33. CMS Collaboration, Underlying event tunes and double parton scattering. CMS Physics Analysis Summary CMS-PAS-GEN-14-001 (2014). <https://cds.cern.ch/record/1697700>
34. P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 tune. *Eur. Phys. J. C* **74**, 3024 (2014). doi:[10.1140/epjc/s10052-014-3024-y](https://doi.org/10.1140/epjc/s10052-014-3024-y). arXiv:[1404.5630](https://arxiv.org/abs/1404.5630)
35. M. Bähr et al., Herwig++ physics and manual. *Eur. Phys. J. C* **58**, 639 (2008). doi:[10.1140/epjc/s10052-008-0798-9](https://doi.org/10.1140/epjc/s10052-008-0798-9). arXiv:[0803.0883](https://arxiv.org/abs/0803.0883)
36. 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**, 079 (2014). doi:[10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079). arXiv:[1405.0301](https://arxiv.org/abs/1405.0301)
37. P. Artoisenet, R. Frederix, O. Mattelaer, R. Rietkerk, Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations. *JHEP* **03**, 015 (2013). doi:[10.1007/JHEP03\(2013\)015](https://doi.org/10.1007/JHEP03(2013)015). arXiv:[1212.3460](https://arxiv.org/abs/1212.3460)
38. S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s - and t -channel contributions. *JHEP* **09**, 111 (2009). doi:[10.1088/1126-6708/2009/09/111](https://doi.org/10.1088/1126-6708/2009/09/111). arXiv:[0907.4076](https://arxiv.org/abs/0907.4076). [Erratum: doi:[10.1007/JHEP02\(2010\)011](https://doi.org/10.1007/JHEP02(2010)011)]
39. E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method. *Eur. Phys. J. C* **71**, 1547 (2011). doi:[10.1140/epjc/s10052-011-1547-z](https://doi.org/10.1140/epjc/s10052-011-1547-z). arXiv:[1009.2450](https://arxiv.org/abs/1009.2450)
40. N. Kidonakis, Top quark production. in *Proceedings, Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons (HQ 2013)* (2014), p. 139. doi:[10.3204/DESY-PROC-2013-03/Kidonakis](https://doi.org/10.3204/DESY-PROC-2013-03/Kidonakis). arXiv:[1311.0283](https://arxiv.org/abs/1311.0283)
41. S. Frixione et al., Single-top hadroproduction in association with a W boson. *JHEP* **07**, 029 (2008). doi:[10.1088/1126-6708/2008/07/029](https://doi.org/10.1088/1126-6708/2008/07/029). arXiv:[0805.3067](https://arxiv.org/abs/0805.3067)
42. J.M. Campbell, R.K. Ellis, MCFM for the Tevatron and the LHC. *Nucl. Phys. Proc. Suppl.* **205–206**, 10 (2010). doi:[10.1016/j.nuclphysbps.2010.08.011](https://doi.org/10.1016/j.nuclphysbps.2010.08.011). arXiv:[1007.3492](https://arxiv.org/abs/1007.3492)
43. M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders. *Comput. Phys. Commun.* **185**, 2930 (2014). doi:[10.1016/j.cpc.2014.06.021](https://doi.org/10.1016/j.cpc.2014.06.021). arXiv:[1112.5675](https://arxiv.org/abs/1112.5675)
44. M. Czakon, P. Fiedler, A. Mitov, The total top quark production cross-section at hadron colliders through $O(\alpha_s^4)$. *Phys. Rev. Lett.* **110**, 252004 (2013). doi:[10.1103/PhysRevLett.110.252004](https://doi.org/10.1103/PhysRevLett.110.252004). arXiv:[1303.6254](https://arxiv.org/abs/1303.6254)
45. S. Alekhin et al., The PDF4LHC working group interim report (2011). arXiv:[1101.0536](https://arxiv.org/abs/1101.0536)
46. M. Botje et al., The PDF4LHC working group interim recommendations (2011). arXiv:[1101.0538](https://arxiv.org/abs/1101.0538)
47. A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Parton distributions for the LHC. *Eur. Phys. J. C* **63**, 189 (2009). doi:[10.1140/epjc/s10052-009-1072-5](https://doi.org/10.1140/epjc/s10052-009-1072-5). arXiv:[0901.0002](https://arxiv.org/abs/0901.0002)
48. A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Uncertainties on α_s in global PDF analyses and implications for predicted hadronic cross sections. *Eur. Phys. J. C* **64**, 653 (2009). doi:[10.1140/epjc/s10052-009-1164-2](https://doi.org/10.1140/epjc/s10052-009-1164-2). arXiv:[0905.3531](https://arxiv.org/abs/0905.3531)
49. H.-L. Lai et al., New parton distributions for collider physics. *Phys. Rev. D* **82**, 074024 (2010). doi:[10.1103/PhysRevD.82.074024](https://doi.org/10.1103/PhysRevD.82.074024). arXiv:[1007.2241](https://arxiv.org/abs/1007.2241)

50. J. Gao et al., CT10 next-to-next-to-leading order global analysis of QCD. *Phys. Rev. D* **89**, 033009 (2014). doi:[10.1103/PhysRevD.89.033009](https://doi.org/10.1103/PhysRevD.89.033009). arXiv:[1302.6246](https://arxiv.org/abs/1302.6246)
51. NNPDF Collaboration, Parton distributions with LHC data. *Nucl. Phys. B* **867**, 244 (2013). doi:[10.1016/j.nuclphysb.2012.10.003](https://doi.org/10.1016/j.nuclphysb.2012.10.003). arXiv:[1207.1303](https://arxiv.org/abs/1207.1303)
52. CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and MET. CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009). <http://cdsweb.cern.ch/record/1194487>
53. CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector. CMS Physics Analysis Summary CMS-PAS-PFT-10-001 (2010). <http://cdsweb.cern.ch/record/1247373>
54. CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV. *JINST* **10**, P06005 (2015). doi:[10.1088/1748-0221/10/06/P06005](https://doi.org/10.1088/1748-0221/10/06/P06005)
55. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV. *JINST* **7**, P10002 (2012). doi:[10.1088/1748-0221/7/10/P10002](https://doi.org/10.1088/1748-0221/7/10/P10002). arXiv:[1206.4071](https://arxiv.org/abs/1206.4071)
56. CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP* **01**, 080 (2011). doi:[10.1007/JHEP01\(2011\)080](https://doi.org/10.1007/JHEP01(2011)080). arXiv:[1012.2466](https://arxiv.org/abs/1012.2466)
57. M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm. *JHEP* **04**, 063 (2008). doi:[10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063). arXiv:[0802.1189](https://arxiv.org/abs/0802.1189)
58. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. *Eur. Phys. J. C* **72**, 1896 (2012). doi:[10.1140/epjc/s10052-012-1896-2](https://doi.org/10.1140/epjc/s10052-012-1896-2). arXiv:[1111.6097](https://arxiv.org/abs/1111.6097)
59. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV. *JINST* **12**, P02014 (2017). doi:[10.1088/1748-0221/12/02/P02014](https://doi.org/10.1088/1748-0221/12/02/P02014)
60. CMS Collaboration, Identification of b-quark jets with the CMS experiment. *JINST* **8**, P04013 (2013). doi:[10.1088/1748-0221/8/04/P04013](https://doi.org/10.1088/1748-0221/8/04/P04013). arXiv:[1211.4462](https://arxiv.org/abs/1211.4462)
61. CMS Collaboration, Identification of b quark jets at the CMS experiment in the LHC Run2. CMS Physics Analysis Summary CMS-PAS-BTV-15-001 (2016). <http://cdsweb.cern.ch/record/1427161>
62. ATLAS Collaboration, Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC. *Phys. Rev. Lett.* **117**, 182002 (2016). doi:[10.1103/PhysRevLett.117.182002](https://doi.org/10.1103/PhysRevLett.117.182002). arXiv:[1606.02625](https://arxiv.org/abs/1606.02625)
63. CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV. *Eur. Phys. J. C* **75**, 542 (2015). doi:[10.1140/epjc/s10052-015-3709-x](https://doi.org/10.1140/epjc/s10052-015-3709-x). arXiv:[1505.04480](https://arxiv.org/abs/1505.04480)
64. CMS Collaboration, Measurement of the single-top-quark t -channel cross section in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP* **12**, 035 (2012). doi:[10.1007/JHEP12\(2012\)035](https://doi.org/10.1007/JHEP12(2012)035). arXiv:[1209.4533](https://arxiv.org/abs/1209.4533)
65. CMS Collaboration, Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s} = 8$ TeV. *Phys. Rev. Lett.* **112**, 231802 (2014). doi:[10.1103/PhysRevLett.112.231802](https://doi.org/10.1103/PhysRevLett.112.231802)
66. CMS Collaboration, Evidence for associated production of a single top quark and W boson in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. Lett.* **110**, 022003 (2013). doi:[10.1103/PhysRevLett.110.022003](https://doi.org/10.1103/PhysRevLett.110.022003)
67. CMS Collaboration, Measurement of the W^+W^- and ZZ production cross section in pp collisions at $\sqrt{s} = 8$ TeV. *Phys. Lett. B* **721**, 190 (2013). doi:[10.1016/j.physletb.2013.03.027](https://doi.org/10.1016/j.physletb.2013.03.027). arXiv:[1301.4698](https://arxiv.org/abs/1301.4698)
68. CMS Collaboration, Measurement of the W^+W^- cross section in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous WW γ and WWZ couplings. *Eur. Phys. J. C* **73**, 2610 (2013). doi:[10.1140/epjc/s10052-013-2610-8](https://doi.org/10.1140/epjc/s10052-013-2610-8). arXiv:[1306.1126](https://arxiv.org/abs/1306.1126)
69. CMS Collaboration, Measurement of W^+W^- production and search for the Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B* **699**, 25 (2011). doi:[10.1016/j.physletb.2011.03.056](https://doi.org/10.1016/j.physletb.2011.03.056)
70. CMS Collaboration, Measurement of the ZZ production cross section and $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B* **763**, 280 (2016). doi:[10.1016/j.physletb.2016.10.054](https://doi.org/10.1016/j.physletb.2016.10.054)
71. CMS Collaboration, Measurement of the WZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B* **766**, 268 (2017). doi:[10.1016/j.physletb.2017.01.011](https://doi.org/10.1016/j.physletb.2017.01.011)
72. ATLAS Collaboration, Measurement of the WW cross section in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings. *Phys. Lett. B* **712**, 289 (2012). doi:[10.1016/j.physletb.2012.05.003](https://doi.org/10.1016/j.physletb.2012.05.003). arXiv:[1203.6232](https://arxiv.org/abs/1203.6232)
73. ATLAS Collaboration, Measurement of the $W^{\pm}Z$ production cross section and limits on anomalous triple gauge couplings in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Lett. B* **709**, 341 (2012). doi:[10.1016/j.physletb.2012.02.053](https://doi.org/10.1016/j.physletb.2012.02.053). arXiv:[1111.5570](https://arxiv.org/abs/1111.5570)
74. ATLAS Collaboration, Measurement of the ZZ production cross section and limits on anomalous neutral triple gauge couplings in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Rev. Lett.* **108**, 041804 (2012). doi:[10.1103/PhysRevLett.108.041804](https://doi.org/10.1103/PhysRevLett.108.041804). arXiv:[1110.5016](https://arxiv.org/abs/1110.5016)
75. CMS Collaboration, CMS luminosity measurement for the 2015 data taking period. CMS Physics Analysis Summary CMS-PAS-LUM-15-001 (2016). <https://cds.cern.ch/record/2138682>

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

O. Dvornikov, V. Makarenko, V. Zykunov

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

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

Universiteit Antwerpen, Antwerp, Belgium

S. Alderweireldt, E. A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussels, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Brussels, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

H. Bakhshiansohi, C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W. L. Aldá Júnior, F. L. Alves, G. A. Alves, L. Brito, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E. M. Da Costa, G. G. Da Silveira⁵, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote⁴, A. Vilela Pereira

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

S. Ahuja^a, C. A. Bernardes^b, S. Dogra^a, T. R. Fernandez Perez Tomei^a, E. M. Gregores^b, P. G. Mercadante^b, C. S. Moon^a, S. F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J. C. Ruiz Vargas, S. Cittolin⁶

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁶

Institute of High Energy Physics, Beijing, China

M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, Y. Chen⁷, T. Cheng, C. H. Jiang, D. Leggat, Z. Liu, F. Romeo, S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

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

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogotá, Colombia

C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, C. F. González Hernández, J. D. Ruiz Alvarez, J. C. Sanabria

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

N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano, T. Sculac

Faculty of Science, University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech RepublicM. Finger⁸, M. Finger Jr.⁸**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, EgyptY. Assran^{9,10}, T. Elkafrawy¹¹, A. Mahrous¹²**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, FranceJ.-L. Agram¹³, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte¹³, X. Coubez, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, A.-C. Le Bihan, K. Skovpen, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C. A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, A. Popov¹⁴, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret**Georgian Technical University, Tbilisi, Georgia**T. Toriashvili¹⁵

Tbilisi State University, Tbilisi, GeorgiaZ. Tsamalaidze⁸**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**C. Autermann, S. Beranek, L. Feld, A. Heister, M. K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J. Schulz, T. Verlage, H. Weber, V. Zhukov¹⁴**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teysier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyV. Cherepanov, G. Flügge, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, I. M. Nugent, C. Pistone, O. Pooth, A. Stahl¹⁶**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. A. Bin Anuar, K. Borras¹⁷, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J. M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁹, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G. P. Van Onsem, R. Walsh, C. Wissing**University of Hamburg, Hamburg, Germany**V. Blobel, M. Centis Vignali, A. R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁶, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann¹⁶, S. M. Heindl, U. Husemann, I. Katkov¹⁴, S. Kudella, P. Lobelle Pardo, H. Mildner, M. U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H. J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**

G. Anagnostou, G. Daskalakis, T. Gerasis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioannina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

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

N. Filipovic

Wigner Research Centre for Physics, Budapest, HungaryG. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A. J. Zsigmond**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, HungaryM. Bartók²¹, P. Raics, Z. L. Trocsanyi, B. Ujvari**National Institute of Science Education and Research, Bhubaneswar, India**S. Bahinipati, S. Choudhury²³, P. Mal, K. Mandal, A. Nayak²⁴, D. K. Sahoo, N. Sahoo, S. K. Swain**Panjab University, Chandigarh, India**

S. Bansal, S. B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J. B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, A. Bhardwaj, B. C. Choudhary, R. B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P. K. Behera

Bhabha Atomic Research Centre, Mumbai, IndiaR. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty¹⁶, P. K. Netrakanti, L. M. Pant, P. Shukla, A. Topkar**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G. B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, IndiaS. Banerjee, S. Bhowmik²⁵, R. K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, IranH. Behnamian, S. Chenarani²⁷, E. Eskandari Tadavani, S. M. Etesami²⁷, A. Fahim²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁹, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, ItalyM. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,16}, R. Venditti^{a,b}, P. Verwilligen^a**INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy**G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F. R. Cavallo^a, S. S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G. M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F. L. Navarria^{a,b}, A. Perrotta^a, A. M. Rossi^{a,b}, T. Rovelli^{a,b}, G. P. Siroli^{a,b}, N. Tosi^{a,b,16}**INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy**S. Albergo^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}**INFN Sezione di Firenze^a, Università di Firenze^b, Florence, Italy**G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^{a,b,16}**INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶

INFN Sezione di Genova^a, Università di Genova^b, Genoa, ItalyV. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M. R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}**INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milan, Italy**L. Brianza¹⁶, M. E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti, S. Malvezzi^a, R. A. Manzoni^{a,b,16}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Pigazzini, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}**INFN Sezione di Napoli^a, Università di Napoli ‘Federico II’^b Naples, Italy, Università della Basilicata^c, Potenza, Italy, Università G. Marconi^d, Rome, Italy**S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A. O. M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen**INFN Sezione di Padova^a, Università di Padova^b, Padua, Italy, Università di Trento^c, Trento, Italy**P. Azzi^{a,16}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall’Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A. T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti, P. Zotto^{a,b}, G. Zumerle^{a,b}**INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy**A. Braghieri^a, A. Magnani^{a,b}, P. Montagna^{a,b}, S. P. Ratti^{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**L. Alunni Solestizi^{a,b}, G. M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}**INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy**K. Androsov^{a,31}, P. Azzurri^{a,16}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M. A. Ciocci^{a,31}, R. Dell’Orso^a, S. Donato^{a,c}, G. Fedi, A. Giassi^a, M. T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P. G. Verdini^a**INFN Sezione di Roma^a, Università di Roma^b, Rome, Italy**L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b,16}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}**INFN Sezione di Torino^a, Università di Torino^b, Turin, Italy, Università del Piemonte Orientale^c, Novara, Italy**N. Amapane^{a,b}, R. Arcidiacono^{a,c,16}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G. L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}**INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy**S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a**Kyungpook National University, Daegu, Korea**

D. H. Kim, G. N. Kim, M. S. Kim, S. Lee, S. W. Lee, Y. D. Oh, S. Sekmen, D. C. Son, Y. C. Yang

Chonbuk National University, Jeonju, Korea

A. Lee

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

H. Kim

Hanyang University, Seoul, Korea

J. A. Brochero Cifuentes, T. J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, H. Lee, S. B. Oh, B. C. Radburn-Smith, S. h. Seo, U. K. Yang, H. D. Yoo, G. B. Yu

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z. A. Ibrahim, J. R. Komaragiri, M. A. B. Md Ali³³, F. Mohamad Idris³⁴, W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P. H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H. R. Hoorani, W. A. Khan, A. Saddique, M. A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

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

K. Bunkowski, A. Byzuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P. G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M. V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

V. Alexakhin, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{37,38}, V. V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, A. Zarubin

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

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

A. Bylinkin³⁸

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

M. Chadeeva⁴¹, O. Markin, E. Popova

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan, A. Leonidov³⁸, S. V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, A. Ershov, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴³, Y. Skovpen⁴³

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

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

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

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekoic

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

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M. S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

J. F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J. M. Vizán Garcia

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

I. J. Cabrillo, A. Calderon, J. R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D’Alfonso, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴⁵, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁶, M. J. Kortelainen, K. Kousouris, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M. T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁶, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁷, M. Rovere, M. Ruan,

H. Sakulin, J. B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas⁴⁸, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁹, G. I. Veres²¹, N. Wardle, H. K. Wöhri, A. Zagozdinska³⁶, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M. T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁵⁰, V. R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T. K. Aarrestad, C. Amsler⁵¹, L. Caminada, M. F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, T. H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C. M. Kuo, W. Lin, Y. J. Lu, A. Pozdnyakov, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, P. Chang, Y. H. Chang, Y. W. Chang, Y. Chao, K. F. Chen, P. H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J. F. Tsai, Y. M. Tzeng

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

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

A. Adiguzel, M. N. Bakirci⁵², S. Cerci⁵³, S. Damarseckin, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos, E. E. Kangal⁵⁴, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁵, K. Ozdemir⁵⁶, B. Tali⁵³, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁷, G. Karapinar⁵⁸, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, E. A. Yetkin⁶¹, T. Yetkin⁶²

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶³

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

B. Grynyov

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, UK

R. Aggleton, F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G. P. Heath, H. F. Heath, J. Jacob, L. Kreczko, C. Lucas, D. M. Newbold⁶⁴, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK

K. W. Bell, A. Belyaev⁶⁵, C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams

Imperial College, London, UK

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall,

G. Iles, T. James, R. Lane, C. Laner, R. Lucas⁶⁴, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁵⁰, J. Pela, B. Penning, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁶, T. Virdee¹⁶, J. Wright, S. C. Zenz

Brunel University, Uxbridge, UK

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

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA

O. Charaf, S. I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J. M. Hogan, O. Jesus, K. H. M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

University of California, Davis, Davis, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

C. Bravo, R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

K. Burt, R. Clare, J. Ellison, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O. R. Long, M. Olmedo Negrete, M. I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J. G. Branson, G. B. Cerati, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁷, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S. D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J. M. Lawhorn, A. Mott, H. B. Newman, C. Pena, M. Spiropulu, J. R. Vlimant, S. Xie, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M. B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J. P. Cumalat, W. T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S. R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S. M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla, K. Burkett, J. N. Butler, H. W. K. Cheung, F. Chlebana, S. Cihangir[†], M. Cremonesi, V. D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J. M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R. D. Field, I. K. Furic, J. Konigsberg, A. Korytov, J. F. Low, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

Florida State University, Tallahassee, USA

A. Ackert, J. R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K. F. Johnson, A. Khatiwada, H. Prosper, A. Santra

Florida Institute of Technology, Melbourne, USA

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶⁸, M. Hohmann, D. Noonan, T. Roy, F. Yumiceva

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

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, K. Jung, P. Kurt, C. O'Brien, I. D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA

B. Bilki⁶⁹, W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA

A. Al-Bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R. P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J. D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, S. Khalil, Y. Maravin, A. Mohammadi, L. K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S. C. Eno, C. Ferraioli, J. A. Gomez, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A. C. Mignerey, F. Ricci-Tam, Y. H. Shin, A. Skuja, M. B. Tonjes, S. C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I. A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G. M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y. S. Lai, Y.-J. Lee, A. Levin, P. D. Luckey, B. Maier, A. C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G. S. F. Stephens, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T. W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA

A. C. Benvenuti, R. M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S. C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, R. Bartek, K. Bloom, D. R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J. E. Siado, G. R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D. M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, K. A. Hahn, A. Kubik, A. Kumar, N. Mucia, N. Odell, B. Pollack, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B. L. Winer, H. W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, J. Mc Donald, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

University of Puerto Rico, Mayaguez, USA

S. Malik

Purdue University, West Lafayette, USA

A. Barker, V. E. Barnes, S. Folgueras, L. Gutay, M. K. Jha, M. Jones, A. W. Jung, D. H. Miller, N. Neumeister, J. F. Schulte, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, B. Akgun, Z. Chen, K. M. Ecklund, F. J. M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K. H. Lo, P. Tan, M. Verzetti

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

A. Agapitos, J. P. Chou, E. Contreras-Campana, Y. Gershtein, T. A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A. G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷³, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P. R. Duderø, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S. W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M. W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P. E. Karchin, J. Sturdy

University of Wisconsin-Madison, Madison, WI, USA

D. A. Belknap, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W. H. Smith, D. Taylor, N. Woods

† Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- 3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 6: Also at Université Libre de Bruxelles, Brussels, Belgium
- 7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Suez University, Suez, Egypt
- 10: Now at British University in Egypt, Cairo, Egypt
- 11: Also at Ain Shams University, Cairo, Egypt
- 12: Now at Helwan University, Cairo, Egypt
- 13: Also at Université de Haute Alsace, Mulhouse, France
- 14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 15: Also at Tbilisi State University, Tbilisi, Georgia
- 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 18: Also at University of Hamburg, Hamburg, Germany
- 19: Also at Brandenburg University of Technology, Cottbus, Germany
- 20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 23: Also at Indian Institute of Science Education and Research, Bhopal, India
- 24: Also at Institute of Physics, Bhubaneswar, India
- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at University of Ruhuna, Matara, Sri Lanka
- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 29: Also at Yazd University, Yazd, Iran

- 30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 31: Also at Università degli Studi di Siena, Siena, Italy
- 32: Also at Purdue University, West Lafayette, USA
- 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, USA
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Roma; Università di Roma, Rome, Italy
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 47: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Riga Technical University, Riga, Latvia
- 50: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 51: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 52: Also at Gaziosmanpasa University, Tokat, Turkey
- 53: Also at Adiyaman University, Adiyaman, Turkey
- 54: Also at Mersin University, Mersin, Turkey
- 55: Also at Cag University, Mersin, Turkey
- 56: Also at Piri Reis University, Istanbul, Turkey
- 57: Also at Ozyegin University, Istanbul, Turkey
- 58: Also at Izmir Institute of Technology, Izmir, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Yildiz Technical University, Istanbul, Turkey
- 63: Also at Hacettepe University, Ankara, Turkey
- 64: Also at Rutherford Appleton Laboratory, Didcot, UK
- 65: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 66: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 67: Also at Utah Valley University, Orem, USA
- 68: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
- 69: Also at Argonne National Laboratory, Argonne, USA
- 70: Also at Erzincan University, Erzincan, Turkey
- 71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 72: Also at Texas A&M University at Qatar, Doha, Qatar
- 73: Also at Kyungpook National University, Daegu, Korea