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Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV

The ATLAS collaboration and the CMS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A combination of measurements of the inclusive top-quark pair production cross-section performed by ATLAS and CMS in proton–proton collisions at centre-of-mass energies of 7 and 8 TeV at the LHC is presented. The cross-sections are obtained using top-quark pair decays with an opposite-charge electron–muon pair in the final state and with data corresponding to an integrated luminosity of about 5 fb^{-1} at $\sqrt{s} = 7$ TeV and about 20 fb^{-1} at $\sqrt{s} = 8$ TeV for each experiment. The combined cross-sections are determined to be 178.5 ± 4.7 pb at $\sqrt{s} = 7$ TeV and $243.3^{+6.0}_{-5.9}$ pb at $\sqrt{s} = 8$ TeV with a correlation of 0.41, using a reference top-quark mass value of 172.5 GeV. The ratio of the combined cross-sections is determined to be $R_{8/7} = 1.363 \pm 0.032$. The combined measured cross-sections and their ratio agree well with theory calculations using several parton distribution function (PDF) sets. The values of the top-quark pole mass (with the strong coupling fixed at 0.118) and the strong coupling (with the top-quark pole mass fixed at 172.5 GeV) are extracted from the combined results by fitting a next-to-next-to-leading-order plus next-to-next-to-leading-log QCD prediction to the measurements. Using a version of the NNPDF3.1 PDF set containing no top-quark measurements, the results obtained are $m_t^{\mathrm{pole}} = 173.4^{+1.8}_{-2.0}$ GeV and $\alpha_s(m_Z) = 0.1170^{+0.0021}_{-0.0018}$.

Keywords: Hadron-Hadron Scattering, Top Physics

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Contents

1 Introduction

The top quark is the most massive known fundamental particle, with a mass close to the scale of the electroweak symmetry breaking [1]. Studying the production and decay of the top quark in proton–proton (pp) collisions is a crucial element of the CERN LHC physics programme and provides precise tests of the Standard Model (SM). At the LHC, top quarks are produced mostly in quark–antiquark pairs ($t\bar{t}$). For this production mode, precise predictions at next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) including resummation of next-to-next-to-leading-log (NNLL) soft-gluon terms are available [2–7]. Consequently, precise measurements of the $t\bar{t}$ production cross-section ($\sigma_{t\bar{t}}$) may reveal contributions from non-SM processes that modify $\sigma_{t\bar{t}}$, such as those in supersymmetric models with R-parity conservation [8]. Moreover, measurements of $\sigma_{t\bar{t}}$ can provide constraints on essential parameters of the SM, such as the top-quark pole mass (m_t^{pole}) and the strong coupling (α_s), and on parton distribution functions (PDFs).

The predicted $t\bar{t}$ production cross-section in pp collisions depends on the PDF set. Table 1 shows the predictions for the NNLO PDF sets CT14 [9], MMHT14 [10], and NNPDF3.1NNLO_ascorr_notop (referred to as NNPDF3.1_a) [11].[1] The precision of the

[1] The PDF sets NNPDF3.1_a and CT14 do not include any top-quark-related measurements, such that any potential bias can be avoided when using them together with the combined cross-sections to extract a top-quark mass and the strong coupling. The MMHT14 PDF set does include information from the $t\bar{t}$ cross-section at the LHC (but no alternative PDF sets were provided by the authors).

PDF set	$\sigma_{t\bar{t}}$ ($\sqrt{s} = 7$ TeV) [pb]	$\sigma_{t\bar{t}}$ ($\sqrt{s} = 8$ TeV) [pb]	$R_{8/7}$
CT14	$181.7\,^{+10.6}_{-10.3}$	$258.9\,^{+13.8}_{-14.3}$	$1.425\,^{+0.007}_{-0.008}$
MMHT14	$181.2\,^{+9.6}_{-10.3}$	$258.1\,^{+12.8}_{-14.1}$	$1.424\,^{+0.005}_{-0.004}$
NNPDF3.1_a	$178.8\,^{+7.8}_{-8.8}$	$255.3\,^{+10.6}_{-12.2}$	$1.428\,^{+0.005}_{-0.004}$

Table 1. Predicted $t\bar{t}$ production cross-sections at different centre-of-mass energies and for different PDF sets. The uncertainties comprise PDF and α_s uncertainties as well as uncertainties in the renormalisation and factorisation scales. The ratio of the predicted $t\bar{t}$ production cross-sections at $\sqrt{s} = 8$ TeV and 7 TeV, $R_{8/7}$, is also shown. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements.

prediction depends on the uncertainties in the PDF set, the dependence of the PDF set and the calculation on α_s, and the choice of factorisation and renormalisation scales. These predictions are calculated at NNLO+NNLL accuracy in QCD for a top-quark pole mass of 172.5 GeV with Top++ [12]. The quoted scale uncertainty is derived from the envelope obtained by independently varying the renormalisation and factorisation scales from m_t^{pole} by factors of 0.5 and 2.0. Variations where these scales differ from each other by a factor of more than two are not included.

Measurements of $\sigma_{t\bar{t}}$ were performed previously by the ATLAS [13] and CMS [14] Collaborations at $\sqrt{s} = 7$ TeV and 8 TeV in various decay channels [15–28]. Each top quark decays almost exclusively into a W boson and a b-quark. The subsequent decays of the W bosons define the $t\bar{t}$ final-state topology to be either fully hadronic, with one, or with two leptonic decays. In this paper, ATLAS and CMS present a combination of their most precise measurements of $\sigma_{t\bar{t}}$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV, obtained using $t\bar{t}$ decays into electron–muon ($e\mu$) pairs [15, 19]. The final-state topology of this decay mode is defined by the two leptons of opposite charge and different flavour, two jets which are identified as originating from final-state b-quarks (b-tagged jets), and missing transverse momentum from the undetected neutrinos. This final state also includes small contributions from $W \to \tau\nu_\tau$ with subsequent leptonic τ decays. The combined $\sigma_{t\bar{t}}$ values are then used to extract m_t^{pole} and α_s through comparison with NNLO+NNLL predictions for various PDF sets.

The individual input measurements are briefly summarised in sections 2 and 3. The combination method and the correlation assumptions used for the systematic uncertainties from ATLAS and CMS are described in section 4. The combined results are presented in section 5, along with the extraction of m_t^{pole} and α_s. The summary and conclusions can be found in section 6.

2 ATLAS measurements

The most precise measurements of the inclusive $t\bar{t}$ cross-section in pp collisions at $\sqrt{s} = 7$ and 8 TeV from the ATLAS Collaboration used events with an opposite-charge $e\mu$ pair and one or two b-tagged jets [15]. The $t\bar{t}$ production cross-section was determined by counting the numbers of opposite-charge $e\mu$ events formed from an isolated electron and isolated muon with exactly one (N_1) or with exactly two (N_2) b-tagged jets. A working point of

70% efficiency for tagging b-jets from top-quark decays, corresponding to a rejection factor of about 140 against light-quark and gluon jets, was used. The two event counts can be expressed as

$$\begin{aligned} N_1 &= L\sigma_{t\bar{t}}\, \epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}, \\ N_2 &= L\sigma_{t\bar{t}}\, \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}, \end{aligned} \tag{2.1}$$

where L is the integrated luminosity of the sample and $\epsilon_{e\mu}$ is the efficiency for a $t\bar{t}$ event to pass the opposite-charge $e\mu$ preselection. The combined probability for a jet from the quark q in the $t \to Wq$ decay to fall within the acceptance of the detector, be reconstructed as a jet with transverse momentum $p_{\mathrm{T}} > 25$ GeV and pseudorapidity $|\eta| < 2.5$, and be tagged as a b-jet, is denoted by ϵ_b. If the decays of the two top quarks and the subsequent reconstruction of the two b-tagged jets are completely independent, the probability to tag both b-jets is given by ${\epsilon_b}^2$. In practice, small correlations are present for both physical and instrumental reasons, and these are taken into account with the b-tagging correlation factor C_b. This correlation factor is close to unity such that a value greater than one corresponds to a positive correlation (i.e., where a second jet is more likely to be selected if the first one is already selected). The background sources also contribute to the event counts N_1 and N_2. These contributions are represented by the terms N_1^{bkg} and N_2^{bkg}. The preselection efficiency $\epsilon_{e\mu}$ and tagging correlation C_b were taken from $t\bar{t}$ event simulation, assuming a top-quark mass of 172.5 GeV, and the background contributions N_1^{bkg} and N_2^{bkg} were estimated using a combination of simulation and data-driven methods, allowing the two equations in eq. (2.1) to be solved for $\sigma_{t\bar{t}}$ and ϵ_b, independently for 7 and 8 TeV. The effect of the small contributions from $t\bar{t}$ production in association with other heavy-flavour quarks ($c\bar{c}$ or $b\bar{b}$) was absorbed into C_b.

The largest systematic uncertainties in these measurements came from $t\bar{t}$ modelling, PDFs, and imperfect knowledge of the integrated luminosities. A summary of the uncertainties in $\sigma_{t\bar{t}}$ is shown in table 2. The uncertainty from each source was evaluated by repeatedly solving eqs. (2.1) with all their parameters simultaneously changed according to the parameter's dependence on a variation of ± 1 standard deviation (σ) of that particular source. Correlated effects of the parameters variations on the measurements were thus taken into account. The total uncertainties in $\sigma_{t\bar{t}}$ and ϵ_b were calculated by adding the statistical uncertainties and effects of all the individual systematic components in quadrature, assuming them to be independent. In order to facilitate the combination with the CMS measurements, several ATLAS uncertainties are merged in quadrature compared to the list of uncertainties presented in ref. [15].

The cross-sections were measured to be

$$\begin{aligned} \sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\mathrm{TeV}) &= 182.9 \pm 3.1\ (\mathrm{stat.}) \pm 4.2\ (\mathrm{exp.{+}theo.}) \pm 3.6\ (\mathrm{lumi.})\ \mathrm{pb}\ \ \text{and} \\ \sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\mathrm{TeV}) &= 242.9 \pm 1.7\ (\mathrm{stat.}) \pm 5.5\ (\mathrm{exp.{+}theo.}) \pm 5.1\ (\mathrm{lumi.})\ \mathrm{pb}, \end{aligned}$$

where the three uncertainties arose from the statistical power of the data, experimental and theoretical systematic effects, and imperfect knowledge of the integrated luminosity, respectively. Although included in the original references, the LHC beam energy uncertainty is not used in the combination presented in this paper due to its reduced value as

ATLAS	Merged uncertainty [%]	
Source	7 TeV	8 TeV
Trigger	0.2	0.2
Lepton (mis-)ID/isolation	0.9	0.8
Lepton energy scale	0.3	0.5
JES flavour composition/specific response	0.2	0.4
JES modelling	0.04	0.2
JES central/forward balance	0.03	0.1
JES pile-up	0.03	0.2
Other JES	0.03	0.2
Jet energy resolution	0.3	0.5
b-jet ID	0.4	0.4
b-jet mis-ID	0.02	0.02
tW background	0.8	0.8
Drell–Yan background	0.05	0.02
Diboson background	0.1	0.1
$t\bar{t}$ scale choice	0.3	0.3
$t\bar{t}$ generator modelling	1.4	1.2
PDF	1.0	1.1
Integrated luminosity	2.0	2.1
Statistical	1.7	0.7
Total uncertainty	**3.5**	**3.2**

Table 2. Summary of the relative statistical, systematic and total uncertainties in the ATLAS measurements of the $t\bar{t}$ production cross-section, $\sigma_{t\bar{t}}$, at $\sqrt{s} = 7$ and 8 TeV from ref. [15], where ID stands for identification and JES for jet-energy scale. The grouping of the systematic uncertainties is modified with respect to ref. [15] to allow for the combination with the CMS measurements.

shown in refs. [29, 30].[2] The results are consistent with theoretical QCD calculations at NNLO+NNLL accuracy.

3 CMS measurements

The CMS measurements of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 7$ and 8 TeV were based on a binned likelihood fit to final-state observables and were also performed in the $e\mu$ channel [19]. All events with an oppositely charged pair formed from an isolated electron and isolated muon were divided into three categories in b-tagged jet multiplicity (N_b). The event counts in the categories with exactly one or two b-tagged jets were expressed using eq. (2.1). The remaining events were assigned to a category with either zero or more than two b-tagged jets ($N_{0,\geq 3}$), for which the event count was given by

$$N_{0,\geq 3} = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} - (N_1 - N_1^{\text{bkg}}) - (N_2 - N_2^{\text{bkg}}) + N_{0,\geq 3}^{\text{bkg}}, \tag{3.1}$$

where $N_{0,\geq 3}^{\text{bkg}}$ is the number of background events in the category with either zero or more than two b-tagged jets. For b-tagging, a high-purity working point with a 0.1% average

[2] This was a 1.8% uncertainty in the $t\bar{t}$ cross-section value for a 0.66% uncertainty in beam energy, while the beam energy is now known to an accuracy of 0.1%.

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misidentification rate for light-flavour quark and gluon jets was used, such that the contribution from events with three or more b-tagged jets in this category is negligible. The variables $\epsilon_{e\mu}$, C_b, and ϵ_b in eqs. (2.1) and (3.1) were centred at the values predicted by the simulation and varied according to the uncertainties assigned to the simulation as opposed to determining ϵ_b and $\sigma_{t\bar{t}}$ by solving the equations as is done for the ATLAS measurement.

In each N_b category, the events were further categorised according to the number of additional non-b-tagged jets. The cross-section extraction was performed treating all systematic uncertainties as nuisance parameters in a binned profile likelihood fit. As input to this fit, the p_{T} distribution of the lowest-p_{T} additional jet was used, if present, to tighten the constraints on jet-energy scale (JES) uncertainties. In subcategories with zero additional jets, only the total event yield was fitted. The cross-sections were determined simultaneously at $\sqrt{s} = 7$ and 8 TeV. For this purpose, systematic uncertainties partially correlated between $\sqrt{s} = 7$ and 8 TeV were split into a correlated component and two uncorrelated contributions, one for each centre-of-mass energy. Uncertainties were only constrained in the fiducial phase space defined by the kinematic acceptance for the $e\mu$ pair. Additional uncertainties were assigned to the extrapolation to the full phase space and were added in quadrature. The largest contributions to the total uncertainty stem from trigger and lepton efficiencies, the Drell–Yan background modelling, and imperfect knowledge of the luminosity.

The final results, assuming a top-quark mass of 172.5 GeV, were

$$\sigma_{t\bar{t}}\,(\sqrt{s} = 7\,\mathrm{TeV}) = 173.6 \pm 2.1\ (\mathrm{stat.})^{+4.5}_{-4.0}\ (\mathrm{exp.{+}theo.}) \pm 3.8\ (\mathrm{lumi.})\ \mathrm{pb\ and}$$
$$\sigma_{t\bar{t}}\,(\sqrt{s} = 8\,\mathrm{TeV}) = 244.9 \pm 1.4\ (\mathrm{stat.})^{+6.3}_{-5.5}\ (\mathrm{exp.{+}theo.}) \pm 6.4\ (\mathrm{lumi.})\ \mathrm{pb},$$

where the uncertainties arose from the statistical power of the data, experimental and theoretical systematic effects, and imperfect knowledge of the integrated luminosity, respectively. As a result of the combined fit of the nuisance parameters and cross-sections, correlations were introduced among all fitted parameters, described by a covariance matrix which included the uncertainties in the nuisance parameters as well as the uncertainties in the cross-sections. For illustration, the impact of groups of related uncertainties is summarised in table 3. The impact of each group of systematic uncertainties was estimated by fixing the corresponding parameters to their best-fit values, repeating the combination to assess the remaining uncertainty, and hence the size of an uncorrelated additional uncertainty that would reproduce the original total uncertainty. The latter estimate was taken as the impact of that uncertainty group, and only served as an illustrative estimate, since the full information is only contained in the full covariance matrix. For the statistical component, all nuisance parameters were fixed to their best-fit value and the remaining uncertainty contribution from statistics alone was evaluated. The results are in good agreement with theoretical QCD calculations at NNLO+NNLL accuracy.

4 Combination method and assumptions

The CMS measurement was performed with simultaneously profiled uncertainties, leading to non-negligible post-fit correlations between them. Commonly used BLUE combination

CMS	Uncertainty [%]	
Source	7 TeV	8 TeV
Trigger	1.3	1.2
Lepton (mis-)ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
JES total	0.8	0.9
Jet energy resolution	0.1	0.1
b-jet ID	0.5	0.5
b-jet mis-ID	0.2	0.1
Pile-up	0.3	0.3
tW background	1.0	0.6
Drell–Yan background	1.4	1.3
Non-$e\mu$ $t\bar{t}$	0.1	0.1
$t\bar{t}V$ background	0.1	0.1
Diboson background	0.2	0.6
W+jets/QCD background	0.1	0.2
$t\bar{t}$ scale choice	0.3	0.6
ME/PS matching	0.1	0.1
ME generator	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top-quark p_{T} modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6
$t\bar{t}$ scale choice (extrapolation)	$^{+0.1}_{-0.4}$	$^{+0.2}_{-0.1}$
ME/PS matching (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.3}$
Top-quark p_{T} (extrapolation)	$^{+0.5}_{-0.3}$	$^{+0.6}_{-0.3}$
PDF (extrapolation)	$^{+0.1}_{-0.1}$	$^{+0.1}_{-0.1}$
Total uncertainty	$^{+3.6}_{-3.5}$	$^{+3.7}_{-3.5}$

Table 3. Illustrative summary of the individual contributions to the total uncertainty in the CMS $t\bar{t}$ cross-section measurements from ref. [19], where ID stands for identification, JES for jet-energy scale, ME for matrix element and PS for parton shower.

techniques [31, 32] provide no method to account for these correlations, and it is known that neglecting these correlations can lead to severe biases and incorrect uncertainty estimates [33]. Therefore, the combination is performed using an algorithm which allows the consistent modelling of these correlations, implemented in the software tool Convino [33] using the covariance matrices of the individual measurements. It is performed using a Pearson χ^2 [34] minimisation, where the systematic uncertainties are represented by nuisance parameters. The χ^2 is defined using three terms: one representing the results of each

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measurement and their statistical uncertainties, another one describing the correlations between the nuisance parameters and constraints on them from the data for each measurement, and finally a term incorporating prior knowledge of the systematic uncertainties and the assumed correlations between uncertainties, modelled by a multivariate Gaussian with non-zero correlations. The method takes as input the full covariance matrix provided by CMS, in addition to the publicly available data. For the ATLAS measurements, where the systematic uncertainties are unconstrained in the fit procedure, the uncertainties are either fully correlated or uncorrelated between $\sqrt{s} = 7$ and 8 TeV, and the correlated uncertainty sources are modelled by a single parameter per source.

The covariance matrix C for a measurement can be expressed using four components

$$C = \begin{pmatrix} U & \kappa^T \\ \kappa & M \end{pmatrix},$$

where the first diagonal block matrix U describes the (co)variance of the nuisance parameters representing the systematic uncertainties. In the ATLAS case it is an identity matrix since the parameters describing the uncertainties are uncorrelated and are normalised to unity. A second block M describes the measured cross-sections, and also has diagonal form, with entries representing the variance of the individual measurements. The last part of the matrix, denoted by κ, describes the impact of a 1σ variation of a nuisance parameter on each of the cross-section measurements. The asymmetric extrapolation uncertainties in the CMS measurements have not been part of the fit to the data. These uncertainties are symmetrised by taking the maximum absolute impact as the symmetric uncertainty and are incorporated into the CMS covariance matrix using the same procedure. The components of the covariance matrix C as well as the covariance matrix of the CMS input measurement are available in HEPdata [35].

In this representation, the combination can be performed accounting for the correlation between the measurements as well as for the correlations and constraints within each individual measurement. For this purpose, the constraints from the data are separated from the prior assumptions on the nuisance parameters within Convino. These prior assumptions are assumed to follow a Gaussian distribution and express the range of a 1σ variation of the respective parameters within the profile likelihood fit. After separating these terms, the individual χ^2 terms of the ATLAS and CMS measurements are combined. The Gaussian terms are reintroduced through a covariance matrix in which the assumed correlations between the systematic uncertainties from the ATLAS and CMS measurements are also included. A more detailed description of the method, including a validation based on pseudo-experiments, can be found in ref. [33].

4.1 ATLAS and CMS systematic uncertainties

The differences in the sizes of the systematic uncertainties between the input ATLAS and CMS measurements (tables 2 and 3) arise from differences in the analysis methods and in the trigger and event selections. Full descriptions of each of the systematic uncertainties used in the individual measurements are available in refs. [15, 19]. As mentioned above, in order to facilitate the combination with the CMS measurements, several of the original

ATLAS uncertainties are merged through summation in quadrature, while taking into account the correlations between the ATLAS $\sqrt{s} = 7$ and 8 TeV uncertainties. Given that all CMS uncertainties are all to some degree correlated, it is not possible to sum them into groups by adding them in quadrature. Instead, each component, or set of components has to be correlated with the corresponding merged uncertainty in the ATLAS measurement as described in the following section.

4.2 Correlation assumptions

Several systematic uncertainties are assumed to be correlated between the ATLAS and CMS measurements. The correlation assumptions used in this combination are summarised in table 4. For each correlated systematic uncertainty, except that in the integrated luminosity, the level of correlation is set to be one of the following values: LOW (0.25), HALF (0.5), HIGH (0.75) and FULL (1.0). Moreover, the correlations have also been scanned, one at a time, in a range around the given assumption value, bounded by the adjacent levels of correlation, e.g., two parameters correlated with a correlation coefficient of 0.5 are scanned from 0.25 to 0.75. No such variation changes the results significantly. The largest change originates from the luminosity correlation coefficient, which changes the total uncertainty by only 0.15% when increased from 0.1 to 0.25. In cases where the sign of the correlation could not be determined unambiguously, the sign that maximises the total uncertainty of the combined result is chosen. This is the case for the correlation of, e.g., the matrix-element generator uncertainty of the CMS measurement with the generator uncertainty of the ATLAS result. Therefore, a conservative estimate is used in these cases.

Trigger: ATLAS uses single-lepton triggers, while CMS only considers dilepton triggers ($e\mu$). In addition, the techniques used to derive the trigger efficiencies are very different: in the case of ATLAS, the single-lepton trigger efficiencies are measured using tag-and-probe techniques, while for CMS, the efficiencies are derived from an orthogonal set of trigger paths based on missing transverse momentum. Therefore, the trigger uncertainties are considered to be uncorrelated.

Lepton-related uncertainties: for both the ATLAS and CMS measurements, the lepton energy scale, resolution, identification and isolation efficiencies are studied using $Z \to ee/\mu\mu$, J/$\Psi \to ee/\mu\mu$, and $W \to e\nu$ events. Parts of the corresponding uncertainties are detector- and algorithm-specific; however, other parts are systematic uncertainties related to the measurement methods, which are similar for the two experiments. Therefore, the correlation is considered to be HALF for the lepton-related uncertainties.

Jet-energy scale: the correlations between the JES uncertainties from ATLAS and CMS follow the guidelines explained in refs. [36, 37]. Many components of the uncertainties, such as statistical and detector-related uncertainties from in situ techniques, pile-up uncertainties, high-p_{T} uncertainties, and jet fragmentation energy scale uncertainties, are considered uncorrelated, including the ATLAS b-jet energy scale uncertainty. Three remaining components are taken as partially correlated. The first component refers to the JES flavour composition uncertainties. These account for the flavour composition of the

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ATLAS merged uncertainties	Value	CMS uncertainties
Lepton ID and energy resolution	HALF	Lepton ID and energy resolution
JES flavour composition/specific response	HIGH	JES flavour composition
	−LOW	b-jet fragmentation tune
	LOW	b-jet neutrino decay fraction
JES modelling	HALF	JES: AbsoluteMPFBias 7 TeV
	HALF	JES: AbsoluteMPFBias 8 TeV
JES central/forward balance	HIGH	JES: RelativeFSR 7 TeV
	HIGH	JES: RelativeFSR 8 TeV
tW background	HIGH	tW single top quark correlated
	LOW	tW single top quark 7 TeV
	LOW	tW single top quark 8 TeV
Diboson	HIGH	Diboson correlated
	LOW	Diboson 7 TeV
	LOW	Diboson 8 TeV
$t\bar{t}$ scale choice	HALF	$t\bar{t}$ scale choice
	HALF	$t\bar{t}$ scale choice (extrapolation)
$t\bar{t}$ generator	LOW	Top-quark p_{T}
	LOW	Top-quark p_{T} (extrapolation)
	−LOW	ME generator
	LOW	ME/PS matching
	LOW	ME/PS matching (extrapolation)
	−LOW	Colour reconnection
	−LOW	Underlying-event tune
Each PDF CT10 eigenvector	FULL	Each PDF CT10 eigenvector
Integrated luminosity	0.1	Integrated luminosity

Table 4. Assumed correlations between ATLAS and CMS systematic uncertainties. The assigned sign is based on the nature of the systematic uncertainty (e.g., minus for an 'up' variation in the ATLAS measurement that corresponds to a 'down' variation in the CMS measurement due to conventions within the collaborations). If the sign is ambiguous, the sign maximising the total uncertainty in the combined cross-section is chosen. Any uncertainties not included in the table are considered uncorrelated.

jets and the calorimeter response to jets of different flavours. In addition, for the CMS measurement, a variation of the b-hadron neutrino decay fraction as well as a variation of the b-quark fragmentation tune is also performed, which is assigned a LOW correlation with the flavour-dependent jet response in the ATLAS analysis. In this case, the sign of the chosen correlation coefficient cannot be determined unambiguously. Therefore, a negative correlation, which maximises the total uncertainty in the combined values, is chosen. The second component includes the CMS *AbsoluteMPFBias*, which refers to the part of the absolute JES uncertainty related with the p_{T}-dependent calibration coming from a potential bias in the Missing Projection Fraction (MPF) method [37]. The corresponding merged uncertainty in ATLAS is estimated with a mix of the same MPF method and a method using p_{T}-balance between a jet and either a Z or γ reference object in the central η region; this uncertainty is referred to as *JES modelling*. The recommended correlation between

ATLAS and CMS from refs. [36, 37] for this uncertainty is between 0 and 0.5, therefore the correlation assigned is HALF.

The third component includes the CMS *RelativeFSR*, which refers to the part of the relative JES uncertainty related to the η-dependent calibration and comes from the modelling of the final-state radiation effects. ATLAS refers to this transferring of the calibration to the forward region as *JES central/forward balance* (also referred to as the *η-intercalibration modelling* in some references). The recommended correlation between ATLAS and CMS from refs. [36, 37] for this uncertainty is between 0.5 and 1.0. This component is considered uncorrelated between $\sqrt{s} = 7$ and 8 TeV in the case of the CMS measurements, and it is considered correlated between $\sqrt{s} = 7$ and 8 TeV for the ATLAS measurements. Because of this inconsistency between the two experiments, the highest correlation which does not lead to a non-positive-definite covariance matrix is 0.7 (HIGH), which is used in this combination. The effect of this choice is negligible since the contribution from RelativeFSR uncertainties is below 5% of the total uncertainty for each input measurement.

***b*-jet identification:** the b-jet identification uncertainties also include uncertainties due to c-jet, light-flavour jet and gluon jet identification. In the ATLAS measurement, the b-jet identification efficiencies for signal events are determined in situ by solving eq. (2.1), consequently uncertainties affect the background contributions and the b-tagging correlation C_b, both derived from simulation. In the CMS measurement, the b-jet identification efficiencies are corrected by comparing efficiencies in data and simulation using a combination of several independent methods and calibration samples [38]. Therefore, these uncertainties are considered to be uncorrelated.

Backgrounds: the ATLAS tW background uncertainty is the combination of four separate uncertainties assessed in the original ATLAS measurement: an uncertainty in the tW cross-section, an uncertainty associated with the scheme handling the tW and $t\bar{t}$ interference, an uncertainty from the impact of initial- and final-state radiation on the tW background, and an uncertainty from the generator used to simulate the tW background. For both the tW background and the diboson background, CMS includes an uncertainty component which is correlated between the measurements at $\sqrt{s} = 7$ and 8 TeV since Monte Carlo (MC) simulations are used to estimate the uncertainties from these backgrounds. This component is assigned a HIGH correlation with the corresponding ATLAS uncertainty because both experiments use a method relying on simulation. In addition, an uncertainty component specific to each centre-of-mass energy is used in the CMS measurement, for example related to using different MC parameters and parton shower tunings in the event generation for those backgrounds. This latter component is assigned a LOW correlation with the corresponding ATLAS uncertainty. Finally, due to the different event selections employed by ATLAS and CMS, the contributions from the Drell–Yan background are also different and in both analyses partly constrained by data control regions. The uncertainties associated with this background are considered as uncorrelated between ATLAS and CMS.

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$t\bar{t}$ modelling: the scale uncertainty refers to the uncertainties estimated by varying the factorisation and renormalisation scales in the $t\bar{t}$ signal simulation by a factor of two. ATLAS uses the POWHEG BOX [39–41] generator where the default scale is defined using the top-quark mass and transverse momentum as $Q^2 = m_t^2 + p_{\mathrm{T},t}^2$ while CMS uses the MADGRAPH [42] generator where the default scale is $Q^2 = m_t^2 + \Sigma p_{\mathrm{T}}^2$, where the sum runs over all additional final-state partons in the matrix-element calculations. Due to this slightly different Q^2 definition and also due to the fact that ATLAS varies the scales independently while CMS varies them simultaneously, the correlation is assumed to be HALF. The $t\bar{t}$ generator uncertainty corresponds in the ATLAS case to comparing a sample of $t\bar{t}$ events generated with POWHEG BOX interfaced to PYTHIA 6 [43] with a sample generated with MC@NLO [44, 45] interfaced to HERWIG [46], thereby incorporating different matrix-element treatments as well as different parton shower and hadronisation modelling. In the CMS case, the equivalent uncertainty was calculated by varying relevant parameters within the MADGRAPH generator. In addition to affecting the fit of the cross-section in the fiducial phase space, these variations are applied a second time when extrapolating to the full phase space. Since both methods address similar physical effects it is expected that the $t\bar{t}$ modelling uncertainties will be somewhat correlated; however, since the methods and generators used to obtain them are different, the correlation is assumed to be LOW. Another contribution to the modelling uncertainties is the variation of the underlying-event and colour-reconnection tunes, as well as a comparison between different matrix-element generators and the reweighting of the simulated top-quark p_{T} spectrum to match the one observed in data in the case of the CMS measurement. These individual sources are assigned a LOW correlation with the combined ATLAS generator uncertainty. Also, here the sign of some components is chosen such that the total uncertainty is maximised.

PDF: for the purpose of the combination, the ATLAS $t\bar{t}$ PDF uncertainty is split into two components: an uncertainty from the CT10 eigenvectors only, which is considered fully correlated with the CMS PDF CT10 uncertainties, and a remainder PDF uncertainty (from MSTW2008 and NNPDF2.3) which is uncorrelated with the CMS PDF uncertainty. The sum in quadrature of these two ATLAS components equals the original ATLAS PDF uncertainty.

Integrated luminosity: the integrated-luminosity uncertainty affects the determination of the signal yield and most background yields. This uncertainty is assumed to be uncorrelated between the $\sqrt{s} = 7$ and 8 TeV data by both the ATLAS and CMS measurements as well as in the combination. For the $\sqrt{s} = 7$ TeV (8 TeV) running period, the luminosity uncertainty for ATLAS is 1.8% (1.9%) [47, 48], with 1.5% (1.2%) estimated from the van der Meer scan analysis and 0.9% (1.5%) from the long-term luminosity monitoring and the transfer of the luminosity scale from the van der Meer regime to the physics regime. For CMS the uncertainties are 2.2% (2.6%) for 7 TeV (8 TeV) [49, 50], of which 1.8% (2.3%) is estimated from the van der Meer scan analysis, and 1.2% (1.2%) from the luminosity-monitoring uncertainty. The uncertainty estimated from the long-term luminosity monitoring is detector-specific and thus uncorrelated between ATLAS and CMS. The uncertainty estimated from the van der Meer scan analysis is partially correlated. For the

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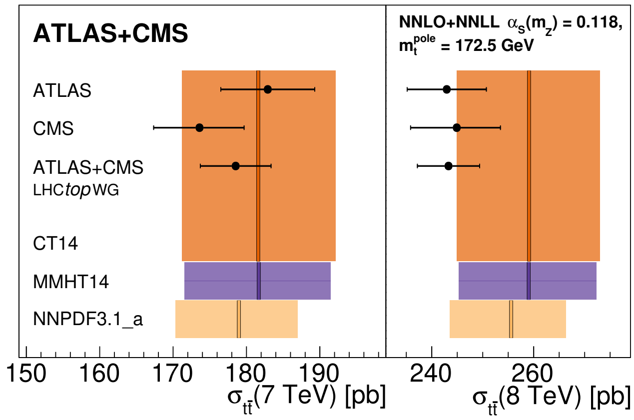

Figure 1. Measured $t\bar{t}$ production cross-sections at $\sqrt{s} = 7$ and 8 TeV compared with predictions using different PDF sets. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements. The shaded bands represent the total uncertainties in the predictions.

$\sqrt{s} = 7$ TeV (8 TeV) running period, the correlated components amount to 0.5% (0.6%) and 0.5% (0.7%) for ATLAS and CMS, respectively; they arise from the measurement of the bunch intensities based on a common device, the correction for beam-to-beam-induced biases extracted from a common simulation, and the models used to fit the visible interaction rate as a function of the separation between the beams, referred to as beam modelling. Taking into account the covariance matrix built from those correlations, the resulting correlation coefficients are computed to be 0.065 for the 7 TeV running period and 0.085 for the 8 TeV running period. Both values are rounded to 0.1 for this combination.

5 Results

5.1 Cross-section combination

The combination of the cross-sections is performed simultaneously at $\sqrt{s} = 7$ and 8 TeV, such that the corresponding correlations are taken into account. The resulting cross-sections are

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}) = 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}) = 243.3^{+6.0}_{-5.9}\ \text{pb},$$

with a correlation between the $\sqrt{s} = 7$ and 8 TeV values of $\rho = 0.41$ and minimum Pearson χ^2 of 1.6 for two degrees of freedom. A comparison of the combined result with the input measurements and the prediction using different PDF sets is shown in figure 1.

The impact of individual groups of uncertainties on the combined results is estimated as is done for the CMS input measurement, described in section 3. The resulting impacts are listed in table 5. The integrated luminosity is still the dominant uncertainty although its impact is reduced by up to 35% compared to the individual results. The statistical uncertainty is reduced by up to 40% by the combination. The next largest uncertainty

Uncertainty	$\Delta\sigma_{t\bar{t}}$(7 TeV) [%]	$\Delta\sigma_{t\bar{t}}$(8 TeV) [%]
Trigger	0.6	0.5
Lepton (mis-)ID, isolation and energy	1.0	0.9
JES flavour composition	0.4	0.4
JES modelling	< 0.1	0.1
JES central/forward balance	0.2	0.2
b-jet (mis-)ID	0.4	0.4
Pile-up	0.2	0.2
tW background	0.8	0.6
Drell–Yan background	0.7	0.4
Diboson background	0.2	0.4
$t\bar{t}$ generator	0.8	0.8
$t\bar{t}$ scale choice	0.4	0.4
PDF	0.4	0.3
Integrated luminosity	1.7	1.7
Statistical	1.0	0.4
Total uncertainty	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$

Table 5. Illustration of the impact $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ of the dominant groups of systematic uncertainties on the combined cross-sections at $\sqrt{s} = 7$ and 8 TeV.

in the ATLAS measurement was the $t\bar{t}$ generator uncertainty, which is reduced by 40% by the combination, while for CMS the next largest uncertainty was associated with the lepton ID and energy, and is also reduced by up to 40% by the combination. Overall, the nuisance parameter constraints are similar to the ones coming from the CMS input measurement. The observed reduction of the luminosity uncertainty on the combined cross-section is consistent with the expected reduction factor for this weighted average, given the magnitude of the correlated and uncorrelated components of the ATLAS and CMS luminosity measurements. Relative to the most precise input measurements, the combination improves the precision by 25% (28%) at $\sqrt{s} = 7$ TeV (8 TeV), and therefore the combined results are the most precise measurements of the inclusive $t\bar{t}$ cross-section to date at those centre-of-mass energies. The experimental uncertainty is smaller than the theoretical uncertainty of the NNLO+NNLL predictions for the corresponding cross-sections.

The ratio of the cross-section at $\sqrt{s} = 8$ TeV to that at 7 TeV is determined to be

$$R_{8/7} = 1.363 \pm 0.015 \text{ (stat.)} \pm 0.028 \text{ (syst.)},$$

based on the fitted values of the individual cross-sections, and accounting for the correlated uncertainties.

The measured ratio is compared with predictions using different PDF sets in figure 2. Since correlated uncertainties cancel out in the ratio, uncorrelated sources, such as the statistical uncertainty, play a larger role. The cross-section ratio therefore benefits most from the combination, with the precision improving by 45% relative to the most precise input measurements. Both the individual cross-sections and their ratio are in agreement

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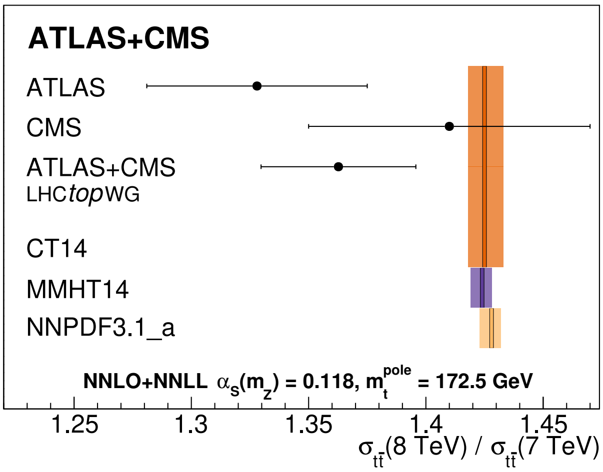


Figure 2. Measured ratios of the $t\bar{t}$ production cross-sections at $\sqrt{s}$ = 7 and 8 TeV compared with predictions using different PDF sets. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements. The shaded bands represent the total uncertainties in the predictions.

with the SM prediction. The level of agreement observed when comparing the measured 7 TeV cross-section, the 8 TeV cross-section and the ratio with the corresponding predictions is found to be 0.3σ, 1.0σ and 1.9σ respectively, using $m_t^{\text{pole}} = 172.5$ GeV, the CT14 PDF, and taking into account the uncertainties in the combined cross-sections and the predictions. The uncertainties in the predicted ratios include the effects on the cross-section calculations from the renormalisation and factorisation scale uncertainties (treated as correlated between $\sqrt{s}$ = 7 and 8 TeV), the PDF uncertainty (the ratio is evaluated for each individual PDF eigenvector and the relevant prescription for the given PDF set is applied), $\alpha_s(m_Z) = 0.118 \pm 0.001$, and a top-quark pole mass uncertainty of 1.0 GeV with 172.5 GeV as the central value (both treated as fully correlated between $\sqrt{s} = 7$ and 8 TeV). The predicted ratio's uncertainty is smaller than the uncertainty in the measured ratio since those effects mostly cancel out in the ratio, and it is dominated by the PDF uncertainty, while variations of the pole mass and $\alpha_s(m_Z)$ do not contribute significantly to the predicted ratio's uncertainty (also described in ref. [51]).

5.2 Top-quark pole mass and strong coupling

The predicted value of the inclusive cross-section for $t\bar{t}$ production is very sensitive to m_t^{pole} and $\alpha_s(m_Z)$. The estimates of m_t^{pole} and $\alpha_s(m_Z)$ from the inclusive cross-section measurement are fully correlated. Therefore, the measured cross-sections can only be used to extract a measurement of $\alpha_s(m_Z)$ by using an assumed value for m_t^{pole} and vice versa. Either parameter can be determined by comparing the combined cross-sections with their predictions as a function of that parameter while fixing the other. While a few percent change in $\alpha_s(m_Z)$ in the matrix-element calculation leads to a negligible change in the measured cross-section, the extrapolation to the full phase space has a mild residual dependence of the order of 0.2% per GeV on the top-quark mass for both the ATLAS and CMS measurements. The parameterisation of this dependence is different for each experiment, although the dependence is almost identical for m_t^{pole} between 170 and 180 GeV. To account for the different functional forms, the combination is performed assuming top-quark masses of 166.5 GeV and 178.5 GeV, in addition to the nominal value of 172.5 GeV. For each of the three mass points, weights for the ATLAS and CMS measurements are determined based on their contribution to the combination at that mass point. The weights at other mass points are interpolated or extrapolated linearly from the values at the reference points. The final parameterisation used for the parameter extraction is calculated as a weighted mean of the ATLAS and CMS parameterisations, using the weights from this linear interpolation or extrapolation. The relative uncertainty in the combined results is also interpolated or extrapolated linearly over the mass range, and is almost constant. Finally, the ambiguities in the interpretation of the top-quark mass involved in MC and fixed-order calculations imply an additional uncertainty obtained by shifting the mass in the acceptance dependence by ± 1.0 GeV [53]. Due to the mild dependence of the measurements on this mass assumption, this contribution is negligible in the final result.

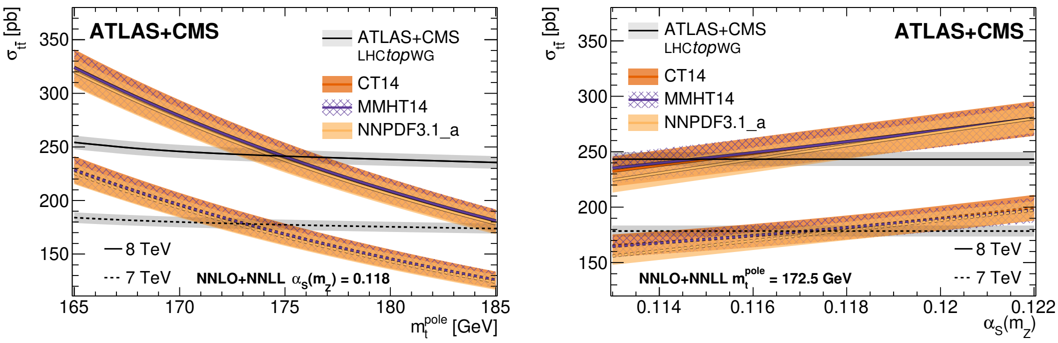
The predicted dependence of the $t\bar{t}$ cross-section on the top-quark pole mass is evaluated using Top++, assuming $\alpha_{\text{s}}(m_Z) = 0.118$ as a baseline. The dependence is derived using ten mass points. In addition, the prediction is evaluated for five different values of $\alpha_{\text{s}}(m_Z)$, assuming $m_t^{\text{pole}} = 172.5$ GeV, by varying $\alpha_{\text{s}}(m_Z)$ consistently in the PDF and the calculation. In each case the cross-section is fitted with a fourth-order polynomial. The relative effects of these variations are assumed to be independent. The comparisons with the combined cross-sections are shown in figure 3. The relative variations with m_t^{pole} and $\alpha_{\text{s}}(m_Z)$ are very similar for different PDF sets and the mild dependence of the measured cross-sections on m_t^{pole} is visible.

The values of $\alpha_{\text{s}}(m_Z)$ and m_t^{pole} are extracted from the combined cross-sections using a χ^2 minimisation technique. The χ^2 is defined as

$$\chi^2 = \frac{1}{1-\rho^2}\Big(\Delta(7\text{ TeV})^2 + \Delta(8\text{ TeV})^2 - 2\rho\Delta(7\text{ TeV})\Delta(8\text{ TeV})\Big), \text{ with} \tag{5.1}$$

$$\Delta = \frac{\sigma_{t\bar{t}}(m_t^{\text{pole}}) - \sigma_{t\bar{t}}^{\text{p}}(m_t^{\text{pole}}, \alpha_{\text{s}}(m_Z))}{\delta}, \tag{5.2}$$

and where $\sigma_{t\bar{t}}^{\text{p}}$ is the predicted $t\bar{t}$ cross-section as a function of m_t^{pole} and $\alpha_{\text{s}}(m_Z)$, $\sigma_{t\bar{t}}(m_t^{\text{pole}})$ is the measured cross-section with a residual pole mass dependence, δ represents the experimental uncertainty of the combined cross-section, and ρ is the correlation coefficient (0.41) between the combined cross-section values. The uncertainties in the $t\bar{t}$ cross-section prediction from each renormalisation and factorisation scale and PDF eigenvector variation are propagated to the final result by re-extracting the top-quark pole mass with different assumptions about the scales and PDF. The total scale uncertainty is determined from the envelope of its individual contributions, and the total PDF uncertainty is calculated using the prescription of the corresponding PDF set. For the case of the CT14 PDF set, the uncertainties are rescaled to 68% CL, as appropriate for this PDF set. Figure 4 shows the constraints in the $\alpha_{\text{s}}(m_Z)$–m_t^{pole} plane from the combined cross-sections. The



(a) (b)

Figure 3. Dependence of the predicted cross-section and the combined measured cross-section on (a) the top-quark pole mass m_t^{pole} and (b) the strong coupling $\alpha_s(m_Z)$. The prediction is evaluated for three different PDF sets and assumes (a) $\alpha_s(m_Z) = 0.118 \pm 0.001$ or (b) $m_t^{\text{pole}} = 172.5 \pm 1.0$ GeV. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements. The uncertainty bands include the effects of the uncertainties in the combined cross-sections (interpolated or extrapolated linearly from the values at the reference points) and of the factorisation and renormalisation scale and PDF uncertainties in the predicted cross-sections.

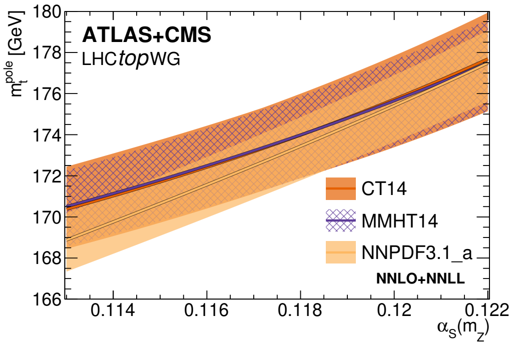


Figure 4. Dependence of the top-quark pole mass, m_t^{pole}, on the assumed value for the strong coupling, $\alpha_s(m_Z)$, including constraints from the combined measured cross-sections for three different PDF sets. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements. The shaded band represents the 68% CL uncertainty on the extracted $\alpha_s(m_Z)$ when fixing m_t^{pole} and on m_t^{pole} when fixing $\alpha_s(m_Z)$. The uncertainty bands include the effects of the uncertainties in the combined cross-sections and of the renormalisation and factorisation scale and PDF uncertainties in the predicted cross-sections.

uncertainty bands include the effects of the uncertainties in the combined cross-sections and of the renormalisation and factorisation scale and PDF uncertainties in the predicted cross-sections.

The dependence shown in figure 4 is used subsequently to extract either m_t^{pole} or $\alpha_s(m_Z)$. The confidence intervals cover the negligible difference that results from minimising eq. (5.1) with respect to m_t^{pole} while stepping over values of α_s instead of minimising with respect to α_s while stepping over values of m_t^{pole}. Therefore, figure 4 can

PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0\ ^{+2.3}_{-2.3}$ GeV	$0.1161\ ^{+0.0030}_{-0.0033}$
MMHT2014	$174.0\ ^{+2.1}_{-2.3}$ GeV	$0.1160\ ^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4\ ^{+1.8}_{-2.0}$ GeV	$0.1170\ ^{+0.0021}_{-0.0018}$

Table 6. Measured m_t^{pole} and $\alpha_s(m_Z)$ values for each PDF set using the measured 7 and 8 TeV combined cross-sections. NNPDF3.1_a is a version of this PDF set containing no top-quark measurements.

be used to extract $\alpha_s(m_Z)$ for a fixed value of m_t^{pole} and vice versa. When extracting m_t^{pole}, $\alpha_s(m_Z) = 0.118 \pm 0.001$ is used, whereas when determining $\alpha_s(m_Z)$, m_t^{pole} is assumed to be $m_t^{\text{pole}} = 172.5 \pm 1.0$ GeV. The corresponding results for each PDF set are reported in table 6. These results represent the most precise determinations of $\alpha_s(m_Z)$ at the scale of inclusive $t\bar{t}$ production ($\mathcal{O}(2m_t^{\text{pole}})$), being more precise than the previous measurements reported by CMS in refs. [52, 54], and are among the most precise top-quark pole mass measurements. The results for m_t^{pole} are compatible with the values reported in refs. [15, 19].

6 Summary and conclusions

A combination of measurements of the inclusive $t\bar{t}$ production cross-section performed by the ATLAS and CMS experiments at $\sqrt{s} = 7$ and 8 TeV is presented, accounting for correlations between the measurements from different experiments as well as correlations within the ATLAS and CMS measurements. The resulting cross-sections are

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}) = 178.5 \pm 4.7 \text{ pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}) = 243.3^{+6.0}_{-5.9} \text{ pb}.$$

The combined results improve on the precision of the most precise individual results by 25% at $\sqrt{s} = 7$ TeV, and by 28% at $\sqrt{s} = 8$ TeV, making these combined results the most precise measurements of the inclusive $t\bar{t}$ cross-section to date at those respective centre-of-mass energies. The correlation between the combined cross-sections values is 0.41, and their ratio is determined to be

$$R_{8/7} = 1.363 \pm 0.032.$$

Furthermore, the combined values for $\sigma_{t\bar{t}}$ are used to determine the top-quark pole mass and the strong coupling by comparing them with the predicted evolution of $\sigma_{t\bar{t}}$ as a function of m_t^{pole} and $\alpha_s(m_Z)$, for different PDF sets. The measurement yields the most precise values, $m_t^{\text{pole}} = 173.4^{+1.8}_{-2.0}$ GeV (1.2% relative uncertainty) and $\alpha_s(m_Z) = 0.1170^{+0.0021}_{-0.0018}$ (1.8% relative uncertainty), when using the NNPDF3.1_a PDF set. The extracted $\alpha_s(m_Z)$ value is more precise than previous measurements performed using top-quark events.

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Shimmin[168], Y. Shimogama[164], J.D. Shinner[92], I.P.J. Shipsey[122], S. Shirabe[54], M. Shiyakova[36,aj], J. Shlomi[165], M.J. Shochet[37], J. Shojaii[102], D.R. Shope[141], S. Shrestha[115], E.M. Shrif[31f], M.J. Shroff[161], E. Shulga[165], P. Sicho[127], A.M. Sickles[158], E. Sideras Haddad[31f], O. Sidiropoulou[34], A. Sidoti[21b], F. Siegert[48], Dj. Sijacki[14], J.M. Silva[19], M.V. Silva Oliveira[34], S.B. Silverstein[45a], S. Simion[64], R. Simoniello[34], N.D. Simpson[95], S. Simsek[11b], P. Sinervo[152], V. Sinetckii[35], S. Singh[139], S. Singh[152], S. Sinha[46], S. Sinha[31f], M. Sioli[21b,21a], I. Siral[119], S.Yu. Sivoklokov[35,*], J. Sjölin[45a,45b], A. Skaf[53], E. Skorda[95], P. Skubic[116], M. Slawinska[83], K. Sliwa[155], V. Smakhtin[165], B.H. Smart[130], J. Smiesko[129], S.Yu. Smirnov[35], Y. Smirnov[35], L.N. Smirnova[35,a], O. Smirnova[95], E.A. Smith[37], H.A. Smith[122], M. Smizanska[88], K. Smolek[128], A. Smykiewicz[83], A.A. Snesarev[35], H.L. Snoek[111], S. Snyder[27], R. Sobie[161,w], A. Soffer[148], F. Sohns[53], C.A. Solans Sanchez[34], E.Yu. Soldatov[35], U. Soldevila[159], A.A. Solodkov[35], S. Solomon[52], A. Soloshenko[36], O.V. Solovyanov[35], V. Solovyev[35], P. Sommer[136], H. Son[155], A. Sonay[12], W.Y. Song[153b], A. Sopczak[128], A.L. Sopio[93], F. Sopkova[26b], S. Sottocornola[70a,70b], R. Soualah[66a,66c], Z. Soumaimi[33e], D. South[46], S. Spagnolo[67a,67b], M. Spalla[107], M. Spangenberg[163], F. Spanò[92], D. Sperlich[52], T.M. Spieker[61a], G. Spigo[34], M. Spina[143], D.P. Spiteri[57], M. Spousta[129], A. Stabile[68a,68b], R. Stamen[61a], M. Stamenkovic[111], A. Stampekis[19], M. Standke[22], E. Stanecka[83], B. Stanislaus[34], M.M. Stanitzki[46], M. Stankaityte[122], B. Stapf[46], E.A. Starchenko[35], G.H. Stark[132], J. Stark[99,ak], D.M. Starko[153b], P. Staroba[127], P. Starovoitov[61a], S. Stärz[101], R. Staszewski[83], G. Stavropoulos[44], P. Steinberg[27], A.L. Steinhebel[119], B. Stelzer[139,153a], H.J. Stelzer[125], O. Stelzer-Chilton[153a], H. Stenzel[56], T.J. Stevenson[143], G.A. Stewart[34], M.C. Stockton[34], G. Stoicea[25b], M. Stolarski[126a], S. Stonjek[107], A. Straessner[48], J. Strandberg[141], S. Strandberg[45a,45b], M. Strauss[116], T. Strebler[99], P. Strizenec[26b], R. Ströhmer[162], D.M. Strom[119], L.R. Strom[46], R. Stroynowski[42], A. Strubig[45a,45b], S.A. Stucci[27], B. Stugu[15], J. Stupak[116], N.A. Styles[46], D. Su[140], S. Su[60a], W. Su[60d,135,60c], X. Su[60a], K. Sugizaki[150], V.V. Sulin[35], M.J. Sullivan[89], D.M.S. Sultan[54], L. Sultanaliyeva[35], S. Sultansoy[3c], T. Sumida[84], S. Sun[103], S. Sun[166], X. Sun[98], O. Sunneborn Gudnadottir[157], C.J.E. Suster[144], M.R. Sutton[143], M. Svatos[127], M. Swiatlowski[153a], T. Swirski[162], I. Sykora[26a], M. Sykora[129], T. Sykora[129], D. Ta[97], K. Tackmann[46,u], A. Taffard[156], R. Tafirout[153a], R.H.M. Taibah[123], R. Takashima[85], K. Takeda[81], T. Takeshita[137], E.P. Takeva[50], Y. Takubo[80], M. Talby[99], A.A. Talyshev[35], K.C. Tam[62b], N.M. Tamir[148], A. Tanaka[150], J. Tanaka[150], R. Tanaka[64], J. Tang[60c], Z. Tao[160], S. Tapia Araya[78], S. Tapprogge[97], A. Tarek Abouelfadl Mohamed[104], S. Tarem[147], K. Tariq[60b], G. Tarna[25b], G.F. Tartarelli[68a], P. Tas[129], M. Tasevsky[127], E. Tassi[41b,41a], G. Tateno[150], Y. Tayalati[33e], G.N. Taylor[102], W. Taylor[153b], H. Teagle[89], A.S. Tee[166], R. Teixeira De Lima[140], P. Teixeira-Dias[92], H. Ten Kate[34], J.J. Teoh[111], K. Terashi[150], J. Terron[96], S. Terzo[12], M. Testa[51], R.J. Teuscher[152,w], N. Themistokleous[50], T. Theveneaux-Pelzer[17], O. Thielmann[167], D.W. Thomas[92], J.P. Thomas[19], E.A. Thompson[46], P.D. Thompson[19], E. Thomson[124], E.J. Thorpe[91], Y. Tian[53], V. Tikhomirov[35,a], Yu.A. Tikhonov[35], S. Timoshenko[35], P. Tipton[168], S. Tisserant[99], S.H. Tlou[31f], A. Tnourji[38], K. Todome[21b,21a], S. Todorova-Nova[129], S. Todt[48], M. Togawa[80], J. Tojo[86], S. Tokár[26a], K. Tokushuku[80], E. Tolley[115], R. Tombs[30], M. Tomoto[80,108], L. Tompkins[140,al], P. Tornambe[100], E. Torrence[119], H. Torres[48], E. Torró Pastor[159], M. Toscani[28], C. Tosciri[37], J. Toth[99,v], D.R. Tovey[136], A. Traeet[15], C.J. Treado[113], T. Trefzger[162], A. Tricoli[27], I.M. Trigger[153a], S. Trincaz-Duvoid[123], D.A. Trischuk[160], B. Trocmé[58], A. Trofymov[64], C. Troncon[68a], F. Trovato[143], L. Truong[31c], M. Trzebinski[83], A. Trzupek[83], F. Tsai[142], A. Tsiamis[149], P.V. Tsiareshka[35,a], A. Tsirigotis[149,s], V. Tsiskaridze[142], E.G. Tskhadadze[146a], M. Tsopoulou[149], I.I. Tsukerman[35], V. Tsulaia[16a], S. Tsuno[80], O. Tsur[147],

D. Tsybychev[142], Y. Tu[62b], A. Tudorache[25b], V. Tudorache[25b], A.N. Tuna[34], S. Turchikhin[36], I. Turk Cakir[3a], R.J. Turner[19], R. Turra[68a], P.M. Tuts[39], S. Tzamarias[149], P. Tzanis[9], E. Tzovara[97], K. Uchida[150], F. Ukegawa[154], G. Unal[34], M. Unal[10], A. Undrus[27], G. Unel[156], F.C. Ungaro[102], K. Uno[150], J. Urban[26b], P. Urquijo[102], G. Usai[7], R. Ushioda[151], M. Usman[105], Z. Uysal[11d], V. Vacek[128], B. Vachon[101], K.O.H. Vadla[121], T. Vafeiadis[34], C. Valderanis[106], E. Valdes Santurio[45a,45b], M. Valente[153a], S. Valentinetti[21b,21a], A. Valero[159], L. Valéry[46], R.A. Vallance[19], A. Vallier[99,ak], J.A. Valls Ferrer[159], T.R. Van Daalen[135], P. Van Gemmeren[5], S. Van Stroud[93], I. Van Vulpen[111], M. Vanadia[73a,73b], W. Vandelli[34], M. Vandenbroucke[131], E.R. Vandewall[117], D. Vannicola[148], L. Vannoli[55b,55a], R. Vari[72a], E.W. Varnes[6], C. Varni[16a], T. Varol[145], D. Varouchas[64], K.E. Varvell[144], M.E. Vasile[25b], L. Vaslin[38], G.A. Vasquez[161], F. Vazeille[38], D. Vazquez Furelos[12], T. Vazquez Schroeder[34], J. Veatch[53], V. Vecchio[98], M.J. Veen[111], I. Veliscek[122], L.M. Veloce[152], F. Veloso[126a,126c], S. Veneziano[72a], A. Ventura[67a,67b], A. Verbytskyi[107], M. Verducci[71a,71b], C. Vergis[22], M. Verissimo De Araujo[79b], W. Verkerke[111], A.T. Vermeulen[111], J.C. Vermeulen[111], C. Vernieri[140], P.J. Verschuuren[92], M. Vessella[100], M.L. Vesterbacka[113], M.C. Vetterli[139,af], A. Vgenopoulos[149], N. Viaux Maira[133e], T. Vickey[136], O.E. Vickey Boeriu[136], G.H.A. Viehhauser[122], L. Vigani[61b], M. Villa[21b,21a], M. Villaplana Perez[159], E.M. Villhauer[50], E. Vilucchi[51], M.G. Vincter[32], G.S. Virdee[19], A. Vishwakarma[50], C. Vittori[21b,21a], I. Vivarelli[143], V. Vladimirov[163], E. Voevodina[107], M. Vogel[167], P. Vokac[128], J. Von Ahnen[46], E. Von Toerne[22], V. Vorobel[129], K. Vorobev[35], M. Vos[159], J.H. Vossebeld[89], M. Vozak[98], L. Vozdecky[91], N. Vranjes[14], M. Vranjes Milosavljevic[14], V. Vrba[128,*], M. Vreeswijk[111], R. Vuillermet[34], O. Vujinovic[97], I. Vukotic[37], S. Wada[154], C. Wagner[100], W. Wagner[167], S. Wahdan[167], H. Wahlberg[87], R. Wakasa[154], M. Wakida[108], V.M. Walbrecht[107], J. Walder[130], R. Walker[106], S.D. Walker[92], W. Walkowiak[138], A.M. Wang[59], A.Z. Wang[166], C. Wang[60a], C. Wang[60c], H. Wang[16a], J. Wang[62a], P. Wang[42], R.-J. Wang[97], R. Wang[59], R. Wang[112], S.M. Wang[145], S. Wang[60b], T. Wang[60a], W.T. Wang[77], W.X. Wang[60a], X. Wang[13c], X. Wang[158], Y. Wang[60a], Z. Wang[103], C. Wanotayaroj[34], A. Warburton[101], C.P. Ward[30], R.J. Ward[19], N. Warrack[57], A.T. Watson[19], M.F. Watson[19], G. Watts[135], B.M. Waugh[93], A.F. Webb[10], C. Weber[27], M.S. Weber[18], S.A. Weber[32], S.M. Weber[61a], C. Wei[60a], Y. Wei[122], A.R. Weidberg[122], J. Weingarten[47], M. Weirich[97], C. Weiser[52], T. Wenaus[27], B. Wendland[47], T. Wengler[34], S. Wenig[34], N. Wermes[22], M. Wessels[61a], K. Whalen[119], A.M. Wharton[88], A.S. White[59], A. White[7], M.J. White[1], D. Whiteson[156], L. Wickremasinghe[120], W. Wiedenmann[166], C. Wiel[48], M. Wielers[130], N. Wieseotte[97], C. Wiglesworth[40], L.A.M. Wiik-Fuchs[52], D.J. Wilbern[116], H.G. Wilkens[34], L.J. Wilkins[92], D.M. Williams[39], H.H. Williams[124], S. Williams[30], S. Willocq[100], P.J. Windischhofer[122], I. Wingerter-Seez[4], F. Winklmeier[119], B.T. Winter[52], M. Wittgen[140], M. Wobisch[94], A. Wolf[97], R. Wölker[122], J. Wollrath[156], M.W. Wolter[83], H. Wolters[126a,126c], V.W.S. Wong[160], A.F. Wongel[46], S.D. Worm[46], B.K. Wosiek[83], K.W. Woźniak[83], K. Wraight[57], J. Wu[13a,13d], S.L. Wu[166], X. Wu[54], Y. Wu[60a],

Z. Wu[131,60a], J. Wuerzinger[122], T.R. Wyatt[98], B.M. Wynne[50], S. Xella[40], L. Xia[13c], M. Xia[13b], J. Xiang[62c], X. Xiao[103], M. Xie[60a], X. Xie[60a], I. Xiotidis[143], D. Xu[13a], H. Xu[60a], H. Xu[60a], L. Xu[60a], R. Xu[124], T. Xu[60a], W. Xu[103], Y. Xu[13b], Z. Xu[60b], Z. Xu[140], B. Yabsley[144], S. Yacoob[31a], N. Yamaguchi[86], Y. Yamaguchi[151], M. Yamatani[150], H. Yamauchi[154], T. Yamazaki[16a], Y. Yamazaki[81], J. Yan[60c], S. Yan[122], Z. Yan[23], H.J. Yang[60c,60d], H.T. Yang[16a], S. Yang[60a], T. Yang[62c], X. Yang[60a], X. Yang[13a], Y. Yang[150], Z. Yang[60a,103], W-M. Yao[16a], Y.C. Yap[46], H. Ye[13c], J. Ye[42], S. Ye[27], I. Yeletskikh[36], M.R. Yexley[88], P. Yin[39], K. Yorita[164], K. Yoshihara[78], C.J.S. Young[52], C. Young[140], R. Yuan[60b,j], X. Yue[61a], M. Zaazoua[33e], B. Zabinski[83], G. Zacharis[9], E. Zaid[50], T. Zakareishvili[146b], N. Zakharchuk[32], S. Zambito[34], D. Zanzi[52], S.V. Zeißner[47], C. Zeitnitz[167], J.C. Zeng[158], D.T. Zenger Jr[24], O. Zenin[35], T. Ženiš[26a], S. Zenz[91], S. Zerradi[33a], D. Zerwas[64], B. Zhang[13c], D.F. Zhang[13b], G. Zhang[13b], J. Zhang[5], K. Zhang[13a,13d], L. Zhang[13c], M. Zhang[158], R. Zhang[166], S. Zhang[103], X. Zhang[60c], X. Zhang[60b], Z. Zhang[64], P. Zhao[49], Y. Zhao[132], Z. Zhao[60a], A. Zhemchugov[36], Z. Zheng[140], D. Zhong[158], B. Zhou[103], C. Zhou[166], H. Zhou[6], N. Zhou[60c], Y. Zhou[6], C.G. Zhu[60b], C. Zhu[13a,13d], H.L. Zhu[60a], H. Zhu[13a], J. Zhu[103], Y. Zhu[60a], X. Zhuang[13a], K. Zhukov[35], V. Zhulanov[35], D. Zieminska[65], N.I. Zimine[36], S. Zimmermann[52,*], J. Zinsser[61b], M. Ziolkowski[138], L. Živković[14], A. Zoccoli[21b,21a], K. Zoch[54], T.G. Zorbas[136], O. Zormpa[44], W. Zou[39], L. Zwalinski[34]

[1] *Department of Physics, University of Adelaide, Adelaide; Australia*
[2] *Department of Physics, University of Alberta, Edmonton AB; Canada*
[3] [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul;* [(c)] *Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye*
[4] *LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France*
[5] *High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America*
[6] *Department of Physics, University of Arizona, Tucson AZ; United States of America*
[7] *Department of Physics, University of Texas at Arlington, Arlington TX; United States of America*
[8] *Physics Department, National and Kapodistrian University of Athens, Athens; Greece*
[9] *Physics Department, National Technical University of Athens, Zografou; Greece*
[10] *Department of Physics, University of Texas at Austin, Austin TX; United States of America*
[11] [(a)] *Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;* [(b)] *Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;* [(c)] *Department of Physics, Bogazici University, Istanbul;* [(d)] *Department of Physics Engineering, Gaziantep University, Gaziantep; Türkiye*
[12] *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain*
[13] [(a)] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* [(b)] *Physics Department, Tsinghua University, Beijing;* [(c)] *Department of Physics, Nanjing University, Nanjing;* [(d)] *University of Chinese Academy of Science (UCAS), Beijing; China*
[14] *Institute of Physics, University of Belgrade, Belgrade; Serbia*
[15] *Department for Physics and Technology, University of Bergen, Bergen; Norway*
[16] [(a)] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;* [(b)] *University of California, Berkeley CA; United States of America*
[17] *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*
[18] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland*

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[19] *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*
[20] [(a)] *Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;* [(b)] *Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia*
[21] [(a)] *Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;* [(b)] *INFN Sezione di Bologna; Italy*
[22] *Physikalisches Institut, Universität Bonn, Bonn; Germany*
[23] *Department of Physics, Boston University, Boston MA; United States of America*
[24] *Department of Physics, Brandeis University, Waltham MA; United States of America*
[25] [(a)] *Transilvania University of Brasov, Brasov;* [(b)] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* [(c)] *Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;* [(d)] *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;* [(e)] *University Politehnica Bucharest, Bucharest;* [(f)] *West University in Timisoara, Timisoara; Romania*
[26] [(a)] *Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;* [(b)] *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic*
[27] *Physics Department, Brookhaven National Laboratory, Upton NY; United States of America*
[28] *Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina*
[29] *California State University, CA; United States of America*
[30] *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*
[31] [(a)] *Department of Physics, University of Cape Town, Cape Town;* [(b)] *iThemba Labs, Western Cape;* [(c)] *Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;* [(d)] *National Institute of Physics, University of the Philippines Diliman (Philippines);* [(e)] *University of South Africa, Department of Physics, Pretoria;* [(f)] *School of Physics, University of the Witwatersrand, Johannesburg; South Africa*
[32] *Department of Physics, Carleton University, Ottawa ON; Canada*
[33] [(a)] *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, Casablanca;* [(b)] *Faculté des Sciences, Université Ibn-Tofail, Kénitra;* [(c)] *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;* [(d)] *LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;* [(e)] *Faculté des sciences, Université Mohammed V, Rabat; Morocco*
[34] *CERN, Geneva; Switzerland*
[35] *Affiliated with an institute covered by a cooperation agreement with CERN*
[36] *Affiliated with an international laboratory covered by a cooperation agreement with CERN*
[37] *Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America*
[38] *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France*
[39] *Nevis Laboratory, Columbia University, Irvington NY; United States of America*
[40] *Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark*
[41] [(a)] *Dipartimento di Fisica, Università della Calabria, Rende;* [(b)] *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy*
[42] *Physics Department, Southern Methodist University, Dallas TX; United States of America*
[43] *Physics Department, University of Texas at Dallas, Richardson TX; United States of America*
[44] *National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece*
[45] [(a)] *Department of Physics, Stockholm University;* [(b)] *Oskar Klein Centre, Stockholm; Sweden*
[46] *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany*
[47] *Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany*
[48] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany*
[49] *Department of Physics, Duke University, Durham NC; United States of America*
[50] *SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom*
[51] *INFN e Laboratori Nazionali di Frascati, Frascati; Italy*
[52] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany*

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[53] *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany*
[54] *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland*
[55] [(a)] *Dipartimento di Fisica, Università di Genova, Genova;* [(b)] *INFN Sezione di Genova; Italy*
[56] *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany*
[57] *SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom*
[58] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France*
[59] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America*
[60] [(a)] *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;* [(b)] *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;* [(c)] *School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;* [(d)] *Tsung-Dao Lee Institute, Shanghai; China*
[61] [(a)] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [(b)] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany*
[62] [(a)] *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;* [(b)] *Department of Physics, University of Hong Kong, Hong Kong;* [(c)] *Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China*
[63] *Department of Physics, National Tsing Hua University, Hsinchu; Taiwan*
[64] *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France*
[65] *Department of Physics, Indiana University, Bloomington IN; United States of America*
[66] [(a)] *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;* [(b)] *ICTP, Trieste;* [(c)] *Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy*
[67] [(a)] *INFN Sezione di Lecce;* [(b)] *Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy*
[68] [(a)] *INFN Sezione di Milano;* [(b)] *Dipartimento di Fisica, Università di Milano, Milano; Italy*
[69] [(a)] *INFN Sezione di Napoli;* [(b)] *Dipartimento di Fisica, Università di Napoli, Napoli; Italy*
[70] [(a)] *INFN Sezione di Pavia;* [(b)] *Dipartimento di Fisica, Università di Pavia, Pavia; Italy*
[71] [(a)] *INFN Sezione di Pisa;* [(b)] *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy*
[72] [(a)] *INFN Sezione di Roma;* [(b)] *Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy*
[73] [(a)] *INFN Sezione di Roma Tor Vergata;* [(b)] *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy*
[74] [(a)] *INFN Sezione di Roma Tre;* [(b)] *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy*
[75] [(a)] *INFN-TIFPA;* [(b)] *Università degli Studi di Trento, Trento; Italy*
[76] *Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria*
[77] *University of Iowa, Iowa City IA; United States of America*
[78] *Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America*
[79] [(a)] *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;* [(b)] *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* [(c)] *Instituto de Física, Universidade de São Paulo, São Paulo; Brazil*
[80] *KEK, High Energy Accelerator Research Organization, Tsukuba; Japan*
[81] *Graduate School of Science, Kobe University, Kobe; Japan*
[82] [(a)] *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;* [(b)] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland*
[83] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland*
[84] *Faculty of Science, Kyoto University, Kyoto; Japan*
[85] *Kyoto University of Education, Kyoto; Japan*
[86] *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan*
[87] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina*
[88] *Physics Department, Lancaster University, Lancaster; United Kingdom*

[89] *Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom*
[90] *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia*
[91] *School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom*
[92] *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*
[93] *Department of Physics and Astronomy, University College London, London; United Kingdom*
[94] *Louisiana Tech University, Ruston LA; United States of America*
[95] *Fysiska institutionen, Lunds universitet, Lund; Sweden*
[96] *Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain*
[97] *Institut für Physik, Universität Mainz, Mainz; Germany*
[98] *School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom*
[99] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*
[100] *Department of Physics, University of Massachusetts, Amherst MA; United States of America*
[101] *Department of Physics, McGill University, Montreal QC; Canada*
[102] *School of Physics, University of Melbourne, Victoria; Australia*
[103] *Department of Physics, University of Michigan, Ann Arbor MI; United States of America*
[104] *Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
[105] *Group of Particle Physics, University of Montreal, Montreal QC; Canada*
[106] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*
[107] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*
[108] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*
[109] *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*
[110] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands*
[111] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*
[112] *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*
[113] *Department of Physics, New York University, New York NY; United States of America*
[114] *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan*
[115] *Ohio State University, Columbus OH; United States of America*
[116] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*
[117] *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*
[118] *Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic*
[119] *Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America*
[120] *Graduate School of Science, Osaka University, Osaka; Japan*
[121] *Department of Physics, University of Oslo, Oslo; Norway*
[122] *Department of Physics, Oxford University, Oxford; United Kingdom*
[123] *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France*
[124] *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*
[125] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*
[126] [(a)] *Laboratório de Instrumentação e Física Experimental de Partículas — LIP, Lisboa;* [(b)] *Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;* [(c)] *Departamento de Física, Universidade de Coimbra, Coimbra;* [(d)] *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* [(e)] *Departamento de Física, Universidade do Minho, Braga;* [(f)] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);* [(g)] *Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica;* [(h)] *Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal*
[127] *Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic*
[128] *Czech Technical University in Prague, Prague; Czech Republic*

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[129] *Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*
[130] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom*
[131] *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France*
[132] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America*
[133] [(a)] *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* [(b)] *Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;* [(c)] *Universidad Andres Bello, Department of Physics, Santiago;* [(d)] *Instituto de Alta Investigación, Universidad de Tarapacá, Arica;* [(e)] *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile*
[134] *Universidade Federal de São João del Rei (UFSJ), São João del Rei; Brazil*
[135] *Department of Physics, University of Washington, Seattle WA; United States of America*
[136] *Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom*
[137] *Department of Physics, Shinshu University, Nagano; Japan*
[138] *Department Physik, Universität Siegen, Siegen; Germany*
[139] *Department of Physics, Simon Fraser University, Burnaby BC; Canada*
[140] *SLAC National Accelerator Laboratory, Stanford CA; United States of America*
[141] *Department of Physics, Royal Institute of Technology, Stockholm; Sweden*
[142] *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America*
[143] *Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom*
[144] *School of Physics, University of Sydney, Sydney; Australia*
[145] *Institute of Physics, Academia Sinica, Taipei; Taiwan*
[146] [(a)] *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* [(b)] *High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia*
[147] *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*
[148] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*
[149] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*
[150] *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*
[151] *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*
[152] *Department of Physics, University of Toronto, Toronto ON; Canada*
[153] [(a)] *TRIUMF, Vancouver BC;* [(b)] *Department of Physics and Astronomy, York University, Toronto ON; Canada*
[154] *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*
[155] *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*
[156] *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*
[157] *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*
[158] *Department of Physics, University of Illinois, Urbana IL; United States of America*
[159] *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain*
[160] *Department of Physics, University of British Columbia, Vancouver BC; Canada*
[161] *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*
[162] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*
[163] *Department of Physics, University of Warwick, Coventry; United Kingdom*
[164] *Waseda University, Tokyo; Japan*
[165] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel*
[166] *Department of Physics, University of Wisconsin, Madison WI; United States of America*
[167] *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*
[168] *Department of Physics, Yale University, New Haven CT; United States of America*

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN
[b] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America
[c] Also at Bruno Kessler Foundation, Trento; Italy
[d] Also at Center for High Energy Physics, Peking University; China
[e] Also at Centro Studi e Ricerche Enrico Fermi; Italy
[f] Also at CERN, Geneva; Switzerland
[g] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[h] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain
[i] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece
[j] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[k] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America
[l] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel
[m] Also at Department of Physics, California State University, East Bay; United States of America
[n] Also at Department of Physics, California State University, Fresno; United States of America
[o] Also at Department of Physics, California State University, Sacramento; United States of America
[p] Also at Department of Physics, King's College London, London; United Kingdom
[q] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland
[r] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria
[s] Also at Hellenic Open University, Patras; Greece
[t] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain
[u] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany
[v] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary
[w] Also at Institute of Particle Physics (IPP); Canada
[x] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
[y] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia
[z] Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain
[aa] Also at Istanbul University, Dept. of Physics, Istanbul; Türkiye
[ab] Also at Physics Department, An-Najah National University, Nablus; Palestine
[ac] Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[ad] Also at The City College of New York, New York NY; United States of America
[ae] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China
[af] Also at TRIUMF, Vancouver BC; Canada
[ag] Also at Università di Napoli Parthenope, Napoli; Italy
[ah] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China
[ai] Also at Yeditepe University, Physics Department, Istanbul; Türkiye
[aj] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria
[ak] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France
[al] Also at Department of Physics, Stanford University, Stanford CA; United States of America
[*] Deceased

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth[2], M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[2], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], E.A. De Wolf, T. Janssen, T. Kello[4], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, J. D'Hondt, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

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

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[7], A. Vilela Pereira

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

C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D. S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

T. Cheng, T. Javaid[8], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen, Z. Hu, J. Martins[9], Y. Wang, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China

E. Chapon, G.M. Chen[8], H.S. Chen[8], M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu[12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

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

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

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You

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

X. Gao[4], H. Okawa

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[13], T. Susa

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

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[14,15], E. Salama[16,17]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

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IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[18], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, J. Motta, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[19], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine[19], U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[20], Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[22], T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, K. Borras[23], D. Brunner,

A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[24], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari[25], N.Z. Jomhari, A. Kasem[23], M. Kasemann, H. Kaveh, C. Kleinwort, D. Krücker, W. Lange, J. Lidrych, K. Lipka, W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[27], V. Scheurer, P. Schütze, C. Schwanenberger[24], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann[22], C. Heidecker, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, A. Nürnberg, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

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

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

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MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[28], S. Lökös[29], P. Major, K. Mandal, A. Mehta, G. Pásztor, A.J. Rádl, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[30], G. Bencze, C. Hajdu, D. Horvath[31], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi[30], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi[32], B. Ujvari

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[33], F. Nemes[33], T. Novak

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

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[34], R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[35], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[36], M. Maity[37], P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh[35], S.Thakur[35]

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

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar[38], P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, M. Kumar, G.B. Mohanty

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[39], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[40], A. Nayak[40], P. Saha, N. Sur, S.K. Swain, D. Vats[40]

Indian Institute of Science Education and Research (IISER), Pune, India
K. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[41], E. Khazaie, M. Zeinali[42]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[43], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,14], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], M. Gul[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], J.A. Merlin[a], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,44], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Albergo[a,b,45], S. Costa[a,b,45], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,45], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

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INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy

M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy

A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,22], D. Zuolo[a,b]

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

S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,22], P. Paolucci[a,22], B. Rossi[a], C. Sciacca[a,b]

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

P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], S.Y. Hoh[a,b], L. Layer[a,46], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy

C. Aime'[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy

P. Asenov[a,47], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,47], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

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

P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], E. Bossini[a,b], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

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INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], J. Berenguer Antequera[a,b], C. Biino[a], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], A. Vagnerini[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b], F. Vazzoler[a,b]

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

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

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

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

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim

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

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, M.S. Ryu, D. Song, Watson, I.J., S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, V. Veckalns

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[48], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic[49], N. Raicevic

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

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[50], M. Dordevic, P. Milenovic, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, N. Trevisani, C. Vico Villalba

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda, B. Kailasapathy[51], D.U.J. Sonnadara, D.D.C. Wickramarathna

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon†, D. Barney, J. Bendavid, M. Bianco, A. Bocci, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[52], D. Fasanella, A. Florent, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, K. Long, C. Lourenço, B. Maier, L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[53], S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, G.P. Van Onsem, J. Wanczyk[54], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada[55], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, M. Missiroli[55], L. Noehte[55], T. Rohe

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

K. Androsov[54], M. Backhaus, P. Berger, A. Calandri, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann,

C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, V. Stampf, J. Steggemann[54], R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler[56], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[57], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[37], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[58], Z.S. Demiroglu, F. Dolek, I. Dumanoglu[59], E. Eskut, Y. Guler[60], E. Gurpinar Guler[60], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[61], A. Polatoz, A.E. Simsek, B. Tali[62], U.G. Tok, S. Turkcapar, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[63], G. Karapinar[64], K. Ocalan[65], M. Yalvac[66]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[67], O. Kaya[68], Ö. Özçelik, S. Tekten[69], E.A. Yetkin[70]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[59], Y. Komurcu, S. Sen[71]

Istanbul University, Istanbul, Turkey
S. Cerci[62], I. Hos[72], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[62], C. Zorbilmez

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
B. Grynyov

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National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[73], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[74], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal[75], D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, D.G. Monk, J. Nash[76], M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee[22], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[77], C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

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Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[78], T. KWON, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir[79], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara — Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, F. Setti, J. Sheplock, D. Stuart, S. Wang

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

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

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

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, Y. Cheng, D.J. Cranshaw, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

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Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena[80], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

University of Florida, Gainesville, Florida, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, J. Rotter, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

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

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[17], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz[81], R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[82], J. Nachtman, H. Ogul[83], Y. Onel, A. Penzo, C. Snyder, E. Tiras[84]

Johns Hopkins University, Baltimore, Maryland, USA
O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

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The University of Kansas, Lawrence, Kansas, USA
A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, J.D. Tapia Takaki, Q. Wang, Z. Warner, J. Williams, G. Wilson

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

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

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, C. Palmer, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, M. Musich, I. Reed, J.E. Siado, G.R. Snow†, W. Tabb, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

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

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Northwestern University, Evanston, Illinois, USA

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

University of Notre Dame, Notre Dame, Indiana, USA

R. Band, R. Bucci, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, Y. Musienko[13], R. Ruchti, P. Siddireddy, A. Townsend, M. Wayne, A. Wightman, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA

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

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, D. Kondratyev, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen, N. Parashar

Rice University, Houston, Texas, USA

A. Baty, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, W. Shi, A.G. Stahl Leiton, S. Yang, L. Zhang, Y. Zhang

University of Rochester, Rochester, New York, USA

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

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[85], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[86], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, Virginia, USA
M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald, S. White, E. Wolfe

Wayne State University, Detroit, Michigan, USA
N. Poudyal

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

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[87], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, O. Bychkova, V. Chekhovsky, R. Chistov[87], M. Danilov[87], A. Dermenev, T. Dimova[87], I. Dremin, M. Dubinin[80], L. Dudko, V. Epshteyn[88], A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev[87], V. Karjavine, A. Karneyeu, V. Kim[87], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, D. Konstantinov, V. Korenkov, N. Korneeva, A. Kozyrev[87], N. Krasnikov, E. Kuznetsova[89], A. Lanev, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[87], V. Murzin, A. Nikitenko[90], S. Obraztsov, V. Okhotnikov, V. Oreshkin, A. Oskin, I. Ovtin[87], V. Palichik, P. Parygin[91], A. Pashenkov, V. Perelygin, M. Perfilov, G. Pivovarov, S. Polikarpov[87], V. Popov, O. Radchenko[87], M. Savina, V. Savrin, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[87],

S. Slabospitskii, I. Smirnov, V. Smirnov, D. Sosnov, A. Stepennov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, M. Toms[92], A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov[93], P. Volkov, S. Volkov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[94], A. Zarubin, I. Zhizhin, A. Zhokin

† *Deceased*
[1] *Also at Yerevan State University, Yerevan, Armenia*
[2] *Also at TU Wien, Vienna, Austria*
[3] *Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*
[4] *Also at Université Libre de Bruxelles, Bruxelles, Belgium*
[5] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[6] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[7] *Also at The University of the State of Amazonas, Manaus, Brazil*
[8] *Also at University of Chinese Academy of Sciences, Beijing, China*
[9] *Also at UFMS, Nova Andradina, Brazil*
[10] *Also at Nanjing Normal University Department of Physics, Nanjing, China*
[11] *Now at The University of Iowa, Iowa City, Iowa, USA*
[12] *Also at University of Chinese Academy of Sciences, Beijing, China*
[13] *Also at an institute or an international laboratory covered by a cooperation agreement with CERN*
[14] *Also at Helwan University, Cairo, Egypt*
[15] *Now at Zewail City of Science and Technology, Zewail, Egypt*
[16] *Also at British University in Egypt, Cairo, Egypt*
[17] *Now at Ain Shams University, Cairo, Egypt*
[18] *Also at Purdue University, West Lafayette, Indiana, USA*
[19] *Also at Université de Haute Alsace, Mulhouse, France*
[20] *Also at Tbilisi State University, Tbilisi, Georgia*
[21] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[22] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[23] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[24] *Also at University of Hamburg, Hamburg, Germany*
[25] *Also at Isfahan University of Technology, Isfahan, Iran*
[26] *Also at Brandenburg University of Technology, Cottbus, Germany*
[27] *Also at Forschungszentrum Jülich, Juelich, Germany*
[28] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[29] *Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[30] *Also at Institute of Physics, University of Debrecen, Debrecen, Hungary*
[31] *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[32] *Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[33] *Also at Wigner Research Centre for Physics, Budapest, Hungary*
[34] *Also at G.H.G. Khalsa College, Punjab, India*
[35] *Also at Shoolini University, Solan, India*
[36] *Also at University of Hyderabad, Hyderabad, India*
[37] *Also at University of Visva-Bharati, Santiniketan, India*
[38] *Also at Indian Institute of Technology (IIT), Mumbai, India*
[39] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[40] *Also at Institute of Physics, Bhubaneswar, India*
[41] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[42] *Also at Sharif University of Technology, Tehran, Iran*
[43] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
[44] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic*

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Development, Bologna, Italy
[45] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[46] *Also at Università di Napoli 'Federico II', Napoli, Italy*
[47] *Also at Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
[48] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[49] *Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[50] *Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[51] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[52] *Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
[53] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[54] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[55] *Also at Universität Zürich, Zurich, Switzerland*
[56] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[57] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[58] *Also at Şırnak University, Sirnak, Turkey*
[59] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[60] *Also at Konya Technical University, Konya, Turkey*
[61] *Also at Izmir Bakircay University, Izmir, Turkey*
[62] *Also at Adiyaman University, Adiyaman, Turkey*
[63] *Also at Ozyegin University, Istanbul, Turkey*
[64] *Also at Izmir Institute of Technology, Izmir, Turkey*
[65] *Also at Necmettin Erbakan University, Konya, Turkey*
[66] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[67] *Also at Marmara University, Istanbul, Turkey*
[68] *Also at Milli Savunma University, Istanbul, Turkey*
[69] *Also at Kafkas University, Kars, Turkey*
[70] *Also at Istanbul Bilgi University, Istanbul, Turkey*
[71] *Also at Hacettepe University, Ankara, Turkey*
[72] *Also at Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[73] *Also at Vrije Universiteit Brussel, Brussel, Belgium*
[74] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[75] *Also at IPPP Durham University, Durham, United Kingdom*
[76] *Also at Monash University, Faculty of Science, Clayton, Australia*
[77] *Also at Università di Torino, Torino, Italy*
[78] *Also at Bethel University, St. Paul, Minnesota, USA*
[79] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[80] *Also at California Institute of Technology, Pasadena, California, USA*
[81] *Also at Bingol University, Bingol, Turkey*
[82] *Also at Georgian Technical University, Tbilisi, Georgia*
[83] *Also at Sinop University, Sinop, Turkey*
[84] *Also at Erciyes University, Kayseri, Turkey*
[85] *Also at Texas A&M University at Qatar, Doha, Qatar*
[86] *Also at Kyungpook National University, Daegu, Korea*
[87] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[88] *Now at Istanbul University, Istanbul, Turkey*
[89] *Now at University of Florida, Gainesville, Florida, USA*
[90] *Also at Imperial College, London, United Kingdom*
[91] *Now at University of Rochester, Rochester, New York, USA*
[92] *Now at Baylor University, Waco, Texas, USA*
[93] *Now at INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy*
[94] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

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