EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

FERMILAB-PUB-13-643-CMS

CERN-PH-EP/2013-057
2013/12/03

CMS-QCD-11-003

Measurement of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ and first determination of the strong coupling constant in the TeV range

The CMS Collaboration[*]

Abstract

A measurement is presented of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section as a function of the average transverse momentum, $\langle p_{\mathrm{T}1,2} \rangle$, of the two leading jets in the event. The data sample was collected during 2011 at a proton-proton centre-of-mass energy of 7 TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of $5.0\,\text{fb}^{-1}$. The strong coupling constant at the scale of the Z boson mass is determined to be $\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$, by comparing the ratio in the range $0.42 < \langle p_{\mathrm{T}1,2} \rangle < 1.39\,\text{TeV}$ to the predictions of perturbative QCD at next-to-leading order. This is the first determination of $\alpha_S(M_Z)$ from measurements at momentum scales beyond 0.6 TeV. The predicted ratio depends only indirectly on the evolution of the parton distribution functions of the proton such that this measurement also serves as a test of the evolution of the strong coupling constant. No deviation from the expected behaviour is observed.

Published in the European Physical Journal C as `doi:10.1140/epjc/s10052-013-2604-6`.

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[*] See Appendix A for the list of collaboration members

1 Introduction

As a consequence of the non-Abelian nature of quantum chromodynamics (QCD), the renormalization group equation (RGE) [1–3] predicts that the strong force becomes weaker at short distances corresponding to large momentum transfers, a property of QCD referred to as asymptotic freedom. The strength of the strong force, $\alpha_S(Q)$, at a given distance or momentum scale Q is not predicted and has to be extracted from experiment. Measurements at different Q can then be compared for consistency with QCD via the RGE, which precisely describes the evolution of $\alpha_S(\mu_r)$, where the renormalization scale μ_r is identified with Q. By convention, the consistency is tested by evolving all values of $\alpha_S(Q)$ to the common scale $\mu_r = Q = M_Z$, i.e. the precisely known mass of the Z boson. The current world average value is $\alpha_S(M_Z) = 0.1184 \pm 0.0007$ [4].

Measurements of the *running* of $\alpha_S(Q)$ provide a stringent test of QCD. Previous collider experiments at LEP and HERA have established the validity of the RGE up to momentum transfers Q of 208 GeV [4]. A recent publication by the D0 Collaboration extends this range up to 400 GeV [5]. The determination of $\alpha_S(Q)$ from jet cross sections as in [6] or [7] depends directly on parton distribution functions (PDFs) that have been evolved from small to very high momentum scales via the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations [8–10], which assume the validity of the RGE. This dependence on the evolution of the PDFs can be reduced by investigating cross section ratios. The ratio R_{32} of the inclusive 3-jet cross section to the inclusive 2-jet cross section is proportional to $\alpha_S(Q)$ where Q is defined as the average transverse momentum of the two jets leading in p_{T},

$$Q = \langle p_{\mathrm{T}1,2} \rangle = \frac{p_{\mathrm{T}1} + p_{\mathrm{T}2}}{2}. \tag{1}$$

Many theoretical systematic uncertainties related to the choice of the renormalization and factorization scales, μ_r and μ_f, or to nonperturbative effects are reduced in the cross section ratio. In addition, experimental uncertainties such as those due to the jet energy scale largely cancel in the measurement of R_{32}. The uncertainty on the integrated luminosity measurement cancels completely. The Compact Muon Solenoid (CMS) Collaboration has previously measured R_{32} [11], and the predictions of various Monte Carlo (MC) event generators were found to be in general agreement with the measurement.

This measurement is performed using a sample of multijet events, collected during 2011 by the CMS experiment at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ of pp collisions at a centre-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$. The transverse momentum p_{T} and the rapidity y of a jet with energy E and momentum $\vec{p} = (p_x, p_y, p_z)$ (where p_z is the momentum component along the direction of the anticlockwise proton beam) are defined as $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$ and $y = \frac{1}{2}\ln[(E + p_z)/(E - p_z)]$, respectively. Jets are reconstructed using the infrared- and collinear-safe anti-k_{T} clustering algorithm [12, 13] with a size parameter of 0.7. This measurement uses jets with $p_{\mathrm{T}} > 150\,\mathrm{GeV}$ and $|y| < 2.5$.

The large number of multijet events collected over a wide range of $\langle p_{\mathrm{T}1,2} \rangle$, $420 < \langle p_{\mathrm{T}1,2} \rangle < 1390\,\mathrm{GeV}$, allows $\alpha_S(Q)$ to be determined with only a small dependence on the evolution of the PDFs, thus testing the validity of the RGE in an extended range of transverse momenta.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, providing an axial magnetic field of 3.8 T. The field volume of the solenoid is instrumented with various layers of particle detection systems. Charged particle trajectories are measured by the silicon pixel and strip tracker, with full azimuthal coverage within $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the z axis. Surrounding the trackers are a lead tungstate crystal electromagnetic calorimeter (ECAL) with a preshower detector in the endcaps, and a brass and scintillator hadron calorimeter (HCAL), covering the region $|\eta| < 3$. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry which extends the coverage to $|\eta| = 5$. The steel flux return yoke outside the solenoid is instrumented with gas-ionization detectors used to identify and reconstruct muons. A more detailed description of the CMS detector can be found in [14].

3 Event selection and reconstruction

The CMS detector records events using a two-level trigger system consisting of a hardware-based level-1 (L1) trigger and a software-based high level trigger (HLT). In this study, single-jet triggers that reconstruct jets from calorimeter energy deposits at L1 and HLT are used to select events based on three HLT p_T thresholds, 190, 240, and 370 GeV. All except the highest-threshold trigger were prescaled during the 2011 run. The corresponding integrated luminosity $\mathcal{L}$ for each of the three samples is shown in Table 1. The efficiency of each of the triggers is estimated using lower-p_T-threshold triggers. These three jet trigger thresholds ensure 100% trigger efficiency in the three jet samples for $\langle p_{T1,2} \rangle > 215$, 269, and 409 GeV.

Table 1: The integrated luminosity for each trigger sample.

HLT p_T threshold (GeV)	190	240	370
$\mathcal{L}$ (fb^{-1})	0.15	0.51	5.0

Each event is required to have at least one offline-reconstructed vertex [15] along the beam line that is within 24 cm of the nominal interaction point. The four-vectors of particle candidates reconstructed by the CMS global event reconstruction algorithm (also called particle-flow event reconstruction [16]) are used as input to the jet-clustering algorithm. The clustering is performed by the FASTJET package [13] using four-momentum summation. The global event reconstruction algorithm reconstructs and identifies each particle with an optimized combination of subdetector information. The energy of photons is obtained directly from the ECAL measurements after being corrected for zero-suppression effects. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is derived from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects, and calibrated for the nonlinear response of the calorimeters. Finally, the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energies.

Jet energy corrections [17] are derived using simulated events, generated by PYTHIA 6.4.22 [18] and processed through the CMS detector simulation based on GEANT4 [19], and in situ measurements with dijet, photon+jet, and Z+jet events. An offset correction is applied to take into account the extra energy clustered into jets from additional proton-proton interactions within the same or neighbouring bunch crossings (in-time and out-of-time pileup) [17]. Pileup effects are important only for low-p_{T} jets and become negligible for jets with $p_{\mathrm{T}} > 200\,\mathrm{GeV}$. The current measurement is therefore largely insensitive to pileup effects. The jet energy corrections, which depend on the η and p_{T} of the jet, are applied to the jet four-momentum vector as a multiplicative factor. The multiplicative factor is in general smaller than 1.2, approximately uniform in η, with typical values of 1.1 for jets having $p_{\mathrm{T}} = 100\,\mathrm{GeV}$ and decreasing to 1.0 for higher values of p_{T}.

To suppress nonphysical jets, i.e. jets resulting from noise in the ECAL and/or HCAL calorimeters, tight identification criteria are applied: each jet should contain at least two particles, one of which is a charged hadron, and the jet energy fraction carried by neutral hadrons, photons, muons, and electrons should be less than 90%. These criteria have an efficiency greater than 99% for genuine jets.

The selection of multijet events requires two or more jets with transverse momentum greater than 150 GeV and $|y| < 2.5$. The final sample is extracted by rejecting events if either or both of the leading jets in p_{T} have $|y| > 2.5$.

4 Measurement of R_{32} and comparison with theoretical predictions

The measured ratio R_{32} as a function of $\langle p_{\mathrm{T}1,2} \rangle$ is the ratio of the number of selected inclusive 3-jet events to the number of selected inclusive 2-jet events in each $\langle p_{\mathrm{T}1,2} \rangle$ bin. The ratio R_{32} is corrected for detector smearing effects and unfolded to stable-particle level. The unfolding method is the iterative Bayesian method [20], as implemented in the ROOUNFOLD software package [21]. Unfolding uses a response matrix that maps the true distribution onto the measured one. The response matrix is derived from a simulation, which uses as input the true R_{32} distribution from PYTHIA6 tune Z2 and introduces the smearing effects by taking into account the $\langle p_{\mathrm{T}1,2} \rangle$ resolution [17]. After unfolding R_{32} to stable-particle level, the final statistical uncertainties include the correlation among the various $\langle p_{\mathrm{T}1,2} \rangle$ bins.

Two main sources of systematic uncertainties on R_{32} are considered. The first is due to the jet energy scale (JES) and the second due to the unfolding.

The JES uncertainty has been estimated to be 2.0–2.5% for particle-flow jets [22], depending on the jet p_{T} and η. All mutually uncorrelated JES uncertainty sources are considered following the procedure described in Ref. [23]. The total systematic uncertainty on R_{32} due to the JES uncertainty is 1.2%.

The unfolding method takes into account three different mutually uncorrelated uncertainty sources. The first arises from insufficient knowledge of the simulated inclusive 3-jet and 2-jet $\langle p_{\mathrm{T}1,2} \rangle$ spectra, which are used to construct the simulated ratio R_{32} used in the unfolding. The uncertainty is estimated by varying the 3-jet and 2-jet spectra slopes by $\pm 10\%$. This is a conservative estimate and is motivated by the observed difference in the 3-jet and 2-jet spectra slopes between simulations using the event generators PYTHIA6 tune Z2 and HERWIG++ [24] with its default tune in version 2.3. Simulations of 3-jet and 2-jet spectra using the MADGRAPH [25, 26] event generator are in agreement with those of PYTHIA6 . The second uncertainty arises from the insufficient knowledge of the $\langle p_{\mathrm{T}1,2} \rangle$ resolution and is estimated by varying it by $\pm 10\%$. This variation is motivated by the observed difference between data and simulation in the jet energy resolution [17]. Finally, the third uncertainty arises from non-Gaussian components in the $\langle p_{\mathrm{T}1,2} \rangle$ resolution and is estimated by adding non-Gaussian tails to the simulation. The overall systematic uncertainty on R_{32} due to unfolding is less than 1%. A potential bias originating from the unfolding technique is studied by comparing the unfolding result of the Bayesian method with that of the singular-value decomposition (SVD) method [27]. The bias is found to be negligible.

The theoretical calculation of the ratio R_{32} is based on next-to-leading-order (NLO) perturbative QCD (pQCD) calculations multiplied by a nonperturbative factor, which corrects for multiparton interactions (MPI) and hadronization effects. The NLO calculations assume $N_f = 5$ massless quark flavours and are based on the parton-level generator NLOJET++ [28, 29]. The computations with NLOJET++ are performed within the FASTNLO framework [30, 31] using the following four PDF sets: NNPDF2.1 [32, 33], ABM11 [34], MSTW2008 [35, 36], and CT10 [37, 38]. In each case the PDF version employing next-to-next-to-leading order (NNLO) evolution code is chosen, and for comparisons the respective default values of $\alpha_S(M_Z)$, which are 0.119, 0.1134, 0.1171, and 0.118, are used. NNPDF2.1, MSTW2008, and CT10 utilize a variable-flavour-number scheme with the maximal number of flavours $N_{f,\max}$ equal to 6, 5, and 5 respectively, while the ABM11 PDF set was developed in a fixed-flavour-number scheme with $N_f = 5$. The renormalization and factorization scales are set to the average transverse momentum $\langle p_{\mathrm{T}1,2}\rangle$.

The nonperturbative effects are estimated using the PYTHIA6 tune Z2 and HERWIG++ tune 2.3 event generators. The chosen MC models feature different descriptions of the phenomena and are representative of the possible values of the nonperturbative corrections. The nonperturbative correction (NPC) factor is defined as the ratio of R_{32} predicted with the nominal generator settings to that obtained with the MPI and hadronization switched off. This factor is calculated considering the average of the two MC generators and has typical values of ≈1.02 for $\langle p_{\mathrm{T}1,2}\rangle = 250\,\mathrm{GeV}$, decreasing to 1.0 for higher $\langle p_{\mathrm{T}1,2}\rangle$. The uncertainty is considered to be half of the difference between the NPC values obtained using the two MC generators and amounts to ≈0.1%, leading to a negligible influence on the final result.

Finally, uncertainties due to the renormalization and factorization scales are evaluated by varying from the default choice of $\mu_r = \mu_f = \langle p_{\mathrm{T}1,2}\rangle$ between $\langle p_{\mathrm{T}1,2}\rangle/2$ and $2\langle p_{\mathrm{T}1,2}\rangle$, simultaneously in the numerator and denominator of the ratio R_{32}, in the following six combinations: $(\mu_r/\langle p_{\mathrm{T}1,2}\rangle, \mu_f/\langle p_{\mathrm{T}1,2}\rangle) = (1/2, 1/2), (1/2, 1), (1, 1/2), (1, 2), (2, 1)$, and $(2, 2)$.

Figure 1 presents the measured ratio R_{32} together with NLO predictions using the NNPDF2.1 (top left), the ABM11 (top right), the MSTW2008 (bottom left), and the CT10 (bottom right) NNLO PDF sets. The upper panel of each plot shows the ratio R_{32} (solid circles) together with the NLO prediction (solid line) corrected for nonperturbative effects, the scale uncertainty, and the PDF uncertainty. At the bottom of each plot, the ratio of data over theory is shown together with bands representing the scale (dotted lines) and PDF uncertainties (solid lines). The error bars in the figure correspond to the total uncertainty, for which the statistical and systematic uncertainties are added in quadrature. For each PDF set the respective default value of $\alpha_S(M_Z)$ is used in this comparison as indicated.

The measured ratio rises with increasing $\langle p_{\mathrm{T}1,2}\rangle$ as the phase space opens up for the production of a third jet, reaching a plateau value for $600 < \langle p_{\mathrm{T}1,2}\rangle < 1000\,\mathrm{GeV}$. At higher $\langle p_{\mathrm{T}1,2}\rangle$ R_{32} decreases again because of the running of α_S, smaller gluon fractions in the total parton luminosity, and because 3-jet configurations reach kinematic limits earlier than dijet events.

Scale uncertainties have a very similar behaviour for all PDF sets and dominate the region up to $\langle p_{\mathrm{T}1,2}\rangle \approx 400\,\mathrm{GeV}$. A comparison to jets with a size parameter of $R = 0.5$ reveals consistent results but with larger scale uncertainties.

The PDF uncertainties are different for each individual PDF set. The CT10 set exhibits the

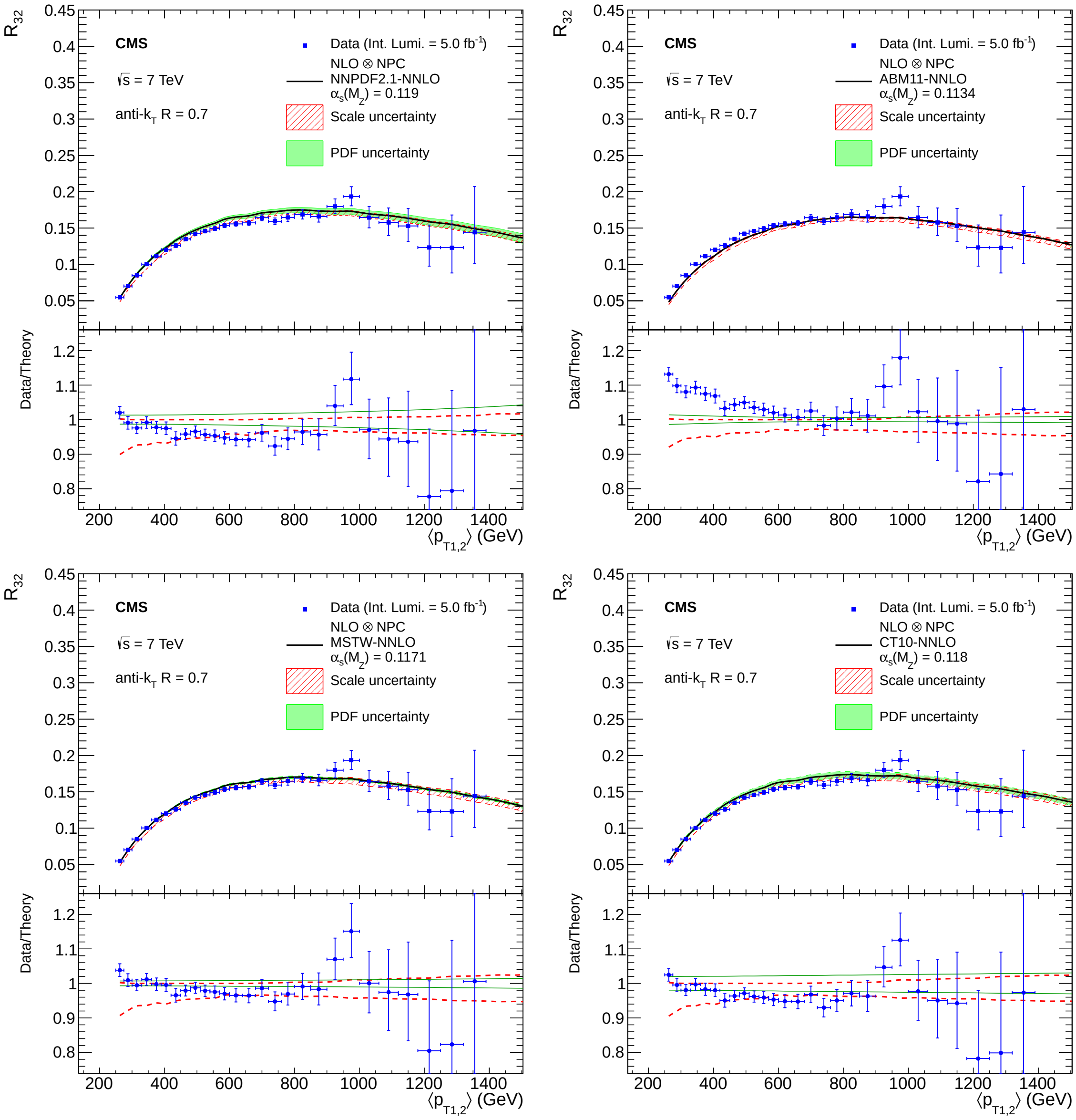

Figure 1: Measurement of R_{32} and NLO predictions using the NNPDF2.1 (top left), the ABM11 (top right), the MSTW2008 (bottom left), and the CT10 (bottom right) NNLO PDF sets. In the upper panel of each plot, the ratio R_{32} (solid circles) together with the NLO prediction (solid line) corrected for nonperturbative effects (NPC), the scale uncertainty, and the PDF uncertainty are shown. The bottom panels show the ratio of data to the theoretical predictions, together with bands representing the scale (dotted lines) and PDF (solid lines) uncertainties. The error bars correspond to the total uncertainty. For each PDF set the respective default value of $\alpha_S(M_Z)$ is used as indicated.

largest PDF uncertainties, which are of the order of 2% at $\langle p_{T1,2} \rangle = 400\,\text{GeV}$, increasing to 2.5% in the 1 TeV region. For the NNPDF2.1 set PDF uncertainties are of the order of 1.5% at 400 GeV, increasing to 2.3% at 1 TeV. Finally, for the MSTW2008 and ABM11 sets PDF uncertainties are of the order of 1% throughout the range of this measurement.

The comparison of data with the predictions of pQCD in Fig. 1 demonstrates that the NLO calculations using the NNPDF2.1, MSTW2008, and CT10 PDF sets are in agreement with the measured ratio R_{32} throughout the range of this measurement. The NLO result employing the ABM11 PDF set underestimates R_{32}, especially for $\langle p_{T1,2} \rangle < 600\,\text{GeV}$.

5 Determination of $\alpha_S(M_Z)$

The measurement of the ratio R_{32} is used for the determination of the strong coupling constant $\alpha_S(M_Z)$. Figure 2 shows the predictions using the NNPDF2.1 (top left), the ABM11 (top right), the MSTW2008 (bottom left), and the CT10 (bottom right) NNLO PDF sets for a series of values of $\alpha_S(M_Z)$, together with the measured R_{32}. The $\alpha_S(M_Z)$ value is varied in the range 0.106–0.124, 0.104–0.120, 0.107–0.127, and 0.110–0.130 in steps of 0.001 for the NNPDF2.1, ABM11, MSTW2008, and CT10 PDF sets, respectively.

From Fig. 2 one observes that the sensitivity of the ratio R_{32} to variations of the strong coupling by $\Delta\alpha_S(M_Z) = \pm 0.001$ is different for each of the four PDF sets. This translates into differences in the experimental uncertainty in the value of $\alpha_S(M_Z)$ obtained for each PDF set.

The value of $\alpha_S(M_Z)$ is determined by minimizing the χ^2 between the experimental measurement and the theoretical predictions. The χ^2 is defined as

$$\chi^2 = M^T C^{-1} M, \tag{2}$$

where M is the vector of the differences between the data (R_{32}^i) and the theoretical values (T_{32}^i) in each bin i,

$$M^i = R_{32}^i - T_{32}^i, \tag{3}$$

and C is the covariance matrix including all experimental (statistical, JES, and unfolding) uncertainties. C is defined as

$$C = \text{Cov}^{\text{Stat}} + \sum \text{Cov}^{\text{JES Sources}} + \sum \text{Cov}^{\text{Unfolding Sources}}, \tag{4}$$

where Cov^{Stat} is the statistical covariance matrix that accounts for the correlations due to unfolding, and $\text{Cov}^{\text{JES Sources}}$, $\text{Cov}^{\text{Unfolding Sources}}$ are the covariance matrices that account for the JES and unfolding systematic uncertainty sources, respectively. Each systematic uncertainty source for the JES and unfolding is treated as 100% correlated across the $\langle p_{T1,2} \rangle$ bins.

To avoid the region with large scale uncertainties close to the minimal jet p_T requirements, visible in Fig. 1, $\alpha_S(M_Z)$ is extracted only for $\langle p_{T1,2} \rangle > 420\,\text{GeV}$. The central result is obtained by minimizing the χ^2 (Eq. (2)) with respect to $\alpha_S(M_Z)$ for the NNPDF2.1 PDF set, which is the only one that permits the propagation of PDF uncertainties to the fits for each value of $\alpha_S(M_Z)$. The experimental uncertainties are obtained from the $\alpha_S(M_Z)$ values for which χ^2 is increased by one with respect to the minimum value. The result of a fit to the region of 420–1390 GeV is

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}), \tag{5}$$

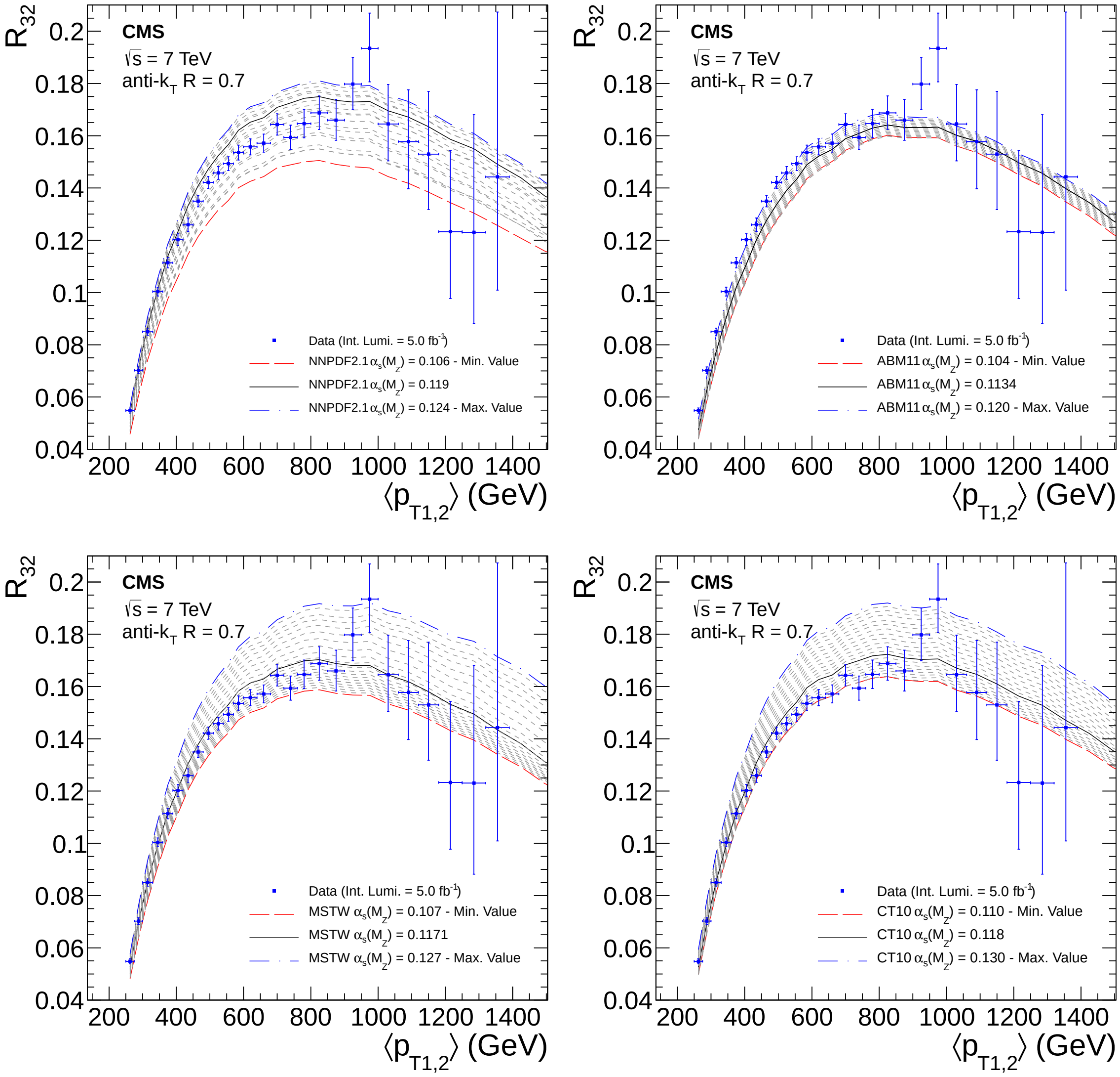

Figure 2: The NLO predictions using the NNPDF2.1 (top left), the ABM11 (top right), the MSTW2008 (bottom left), and the CT10 (bottom right) NNLO PDF sets for a series of values of $\alpha_S(M_Z)$, together with the measured R_{32}. The $\alpha_S(M_Z)$ value is varied in the range 0.106–0.124, 0.104–120, 0.107–0.127, and 0.110–0.130 in steps of 0.001 for the NNPDF2.1, ABM11, MSTW2008, and CT10 PDF sets, respectively.

with $\chi^2/N_{\mathrm{dof}} = 22.0/20$ at minimum. The experimental uncertainty contains the statistical, JES, and unfolding sources (Eq. (4)), with the JES uncertainty being the dominant one.

The contribution of PDFs to the uncertainty of the measurement is evaluated by repeating the fit for each of the 100 PDF replicas of the NNPDF2.1 set at the relevant value for $\alpha_S(M_Z)$. In this way 100 determinations of $\alpha_S(M_Z)$ are obtained, whose distribution corresponds to the propagation of the underlying probability density from the PDFs to the fitted strong coupling. The PDF uncertainty of the measurement is then computed as the standard deviation of this distribution. A more detailed description of the method can be found in Ref. [39].

The uncertainties due to the renormalization and factorization scales are treated separately by varying the default choice of $\mu_r = \mu_f = \langle p_{\mathrm{T}1,2}\rangle$ between $\langle p_{\mathrm{T}1,2}\rangle/2$ and $2\langle p_{\mathrm{T}1,2}\rangle$ in six combinations as explained in Section 4. The χ^2 minimization with respect to $\alpha_S(M_Z)$ is repeated for these six combinations. The contribution from the μ_r, μ_f scale variations to the uncertainty in the measurement is evaluated by considering the differences between the NNPDF2.1 $\alpha_S(M_Z)$ central value and the highest and lowest values found in these six scale combinations. Out of all scale combinations the lowest $\alpha_S(M_Z)$ value corresponds to the default scale choice of $\mu_r = \mu_f = \langle p_{\mathrm{T}1,2}\rangle$ and the highest to the scale choice of $\mu_r = \mu_f = \langle p_{\mathrm{T}1,2}\rangle/2$. The frequent observation of asymmetric scale uncertainties with larger downward uncertainties in the case of NLO cross sections is transformed into a purely upward uncertainty for the ratio, as can be seen in Table 2.

Table 2: The values of $\alpha_S(M_Z)$ at the central scale and for the six scale factor combinations.

$\mu_r/\langle p_{\mathrm{T}1,2}\rangle$	$\mu_f/\langle p_{\mathrm{T}1,2}\rangle$	$\alpha_S(M_Z) \pm$ (exp.)	χ^2/N_{dof}
1	1	0.1148 ± 0.0014	22.0/20
1/2	1/2	0.1198 ± 0.0021	30.6/20
1/2	1	0.1149 ± 0.0014	22.2/20
1	1/2	0.1149 ± 0.0014	22.2/20
1	2	0.1150 ± 0.0015	21.9/20
2	1	0.1159 ± 0.0014	20.7/20
2	2	0.1172 ± 0.0018	21.3/20

A cross check on the impact of the top quark by imposing $N_f = 6$ massless flavours in the NLO matrix elements revealed an increase by $+0.0009$ in the fitted value of $\alpha_S(M_Z)$. Further effects, for example from the evolution of α_S and the PDFs with five or six flavours, multijet production via fully hadronic decays in the reaction $pp \to t\bar{t} + X$, or an incomplete cancellation of electroweak corrections between numerator and denominator, are estimated to contribute each at a ±1% level to the theoretical uncertainty. These residual effects are taken into account by symmetrizing the scale uncertainty such that the largest deviation is adopted as the total symmetric theory uncertainty.

The final result is

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp.}) \pm 0.0018\,(\mathrm{PDF}) \pm 0.0050\,(\mathrm{theory}), \tag{6}$$

in agreement with the world average value of $\alpha_S(M_Z) = 0.1184 \pm 0.0007$ [4], with the Tevatron results [5, 6, 40], and a recent result obtained with LHC data [7].

The determination of $\alpha_S(M_Z)$, which is based on the NNPDF2.1 PDF set, is also in agreement with the results obtained using the MSTW2008 or CT10 PDF sets

$$\begin{aligned} \text{MSTW2008: } \alpha_S(M_Z) &= 0.1141 \pm 0.0022\,(\text{exp.}), \\ \text{CT10: } \alpha_S(M_Z) &= 0.1135 \pm 0.0019\,(\text{exp.}), \end{aligned} \tag{7}$$

with $\chi^2/N_{\text{dof}} = 20.6/20$ and $21.1/20$, respectively. If PDF sets with NLO evolution are used instead the impact on the results of the fits to the ratio observable R_{32} is negligible. This is in contrast to fits to cross sections, where NNLO PDF sets usually lead to smaller values of $\alpha_S(M_Z)$ than NLO ones, and confirms the reduced dependence of R_{32} on details of the PDF evolution.

In the case of the ABM11 PDFs the series in values of $\alpha_S(M_Z)$ ends at 0.120, which is insufficient for a derivation of the complete shape of the χ^2 curve at minimum such that a fit value for $\alpha_S(M_Z)$ including uncertainties can only be extrapolated to give around $\alpha_S(M_Z) = 0.1214 \pm 0.0020\,(\text{exp.})$ with $\chi^2/N_{\text{dof}} = 20.6/20$. For the ABM11 PDF set at NLO with a default value of $\alpha_S(M_Z) = 0.118$, the series in $\alpha_S(M_Z)$ values ends at 0.130 such that a fit can be performed which yields $\alpha_S(M_Z) = 0.1214 \pm 0.0018\,(\text{exp.})$, consistent with the extrapolation above. The fit exhibits, however, a somewhat larger value of $\chi^2/N_{\text{dof}} = 28.5/20$ compared to the other results.

It is observed that with ABM11 PDFs a higher value of $\alpha_S(M_Z)$ is preferred. This is in accord with the fact that the ABM11 gluon density in the phase space relevant for this analysis is significantly smaller than that of all other PDF sets. Thus, the fit favors a larger $\alpha_S(M_Z)$ value to compensate for this effect. In summary, the ABM11 PDF set does not describe the data as well as the alternative PDF sets, as shown in Fig. 1, which leads to an inferior fit quality and a less consistent result for the strong coupling.

To investigate the running of the strong coupling constant in more detail, the fitted region of 420–1390 GeV is split into three bins of $\langle p_{\text{T1,2}} \rangle$ and the fitting procedure is repeated in each of these bins. The three separate extractions of $\alpha_S(M_Z)$ are reported in Table 3. The experimental uncertainties in the three obtained values are correlated. These $\alpha_S(M_Z)$ determinations are then evolved back to the corresponding values $\alpha_S(Q)$ using the 3-loop solution to the RGE from the NNPDF2.1 set. For each fit region the cross-section-weighted average of $\langle p_{\text{T1,2}} \rangle$ from the inclusive dijet calculation at NLO with NLOJET++ is chosen as the momentum scale Q and is computed to be $Q = 474$, 664, and 896 GeV, respectively. These values, derived again with the FASTNLO framework, are identical within about 1 GeV for different PDFs and vary at most by a few GeV when using inclusive 3-jet events.

To emphasize that theoretical uncertainties limit the achievable precision, Table 4 presents the decomposition of the total uncertainty for the three bins in $\langle p_{\text{T1,2}} \rangle$ into the experimental, PDF, and theory components.

Figure 3 presents the strong coupling $\alpha_S(Q)$ (solid line) and its total uncertainty (band) as evolved from the CMS determination, $\alpha_S(M_Z) = 0.1148 \pm 0.0055$, using the 3-loop solution to the RGE from NNPDF2.1, as before. The extractions of $\alpha_S(Q)$ in three separate ranges of Q as presented in Table 3 are also shown. In the same figure the values of α_S at lower scales determined by the H1 [41, 42], ZEUS [43], and D0 [5, 40] Collaborations are shown for comparison. The results on α_S reported here are consistent with the energy dependence predicted by the RGE and extend the range, in which the RGE is tested, to the region of several hundred GeV.

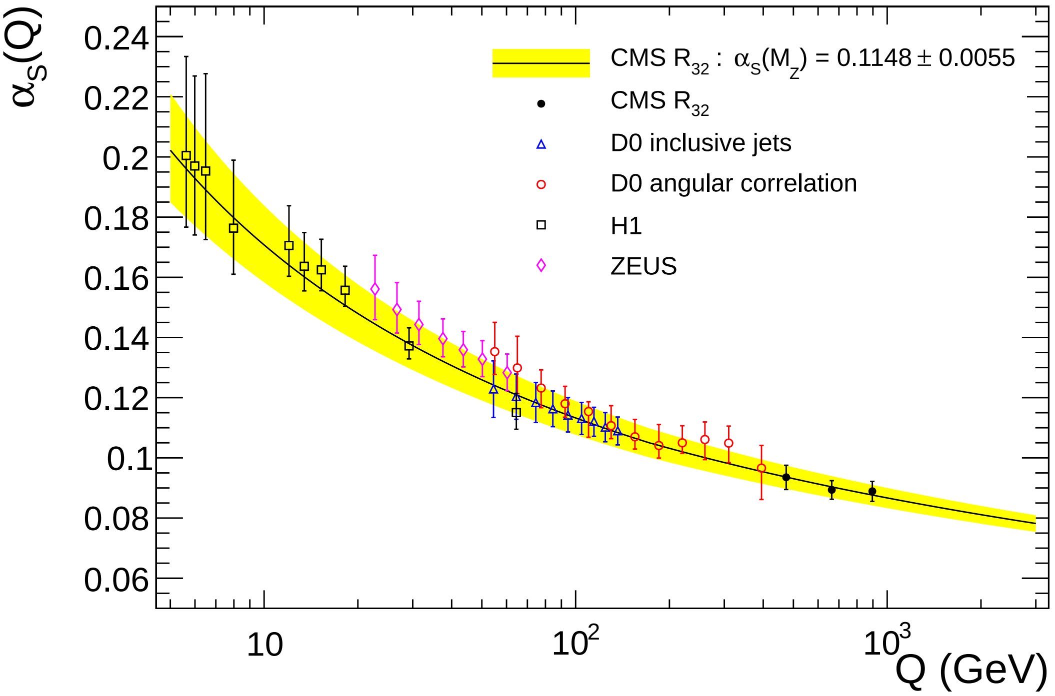

Figure 3: The strong coupling $\alpha_S(Q)$ (solid line) and its total uncertainty (band) evolved from the CMS determination $\alpha_S(M_Z) = 0.1148 \pm 0.0055$ using a 3-loop solution to the RGE as a function of the momentum transfer $Q = \langle p_{T1,2} \rangle$. The extractions of $\alpha_S(Q)$ in three separate ranges of Q as presented in Table 3 are shown together with results from the H1 [41, 42], ZEUS [43], and D0 [5, 40] experiments at the HERA and Tevatron colliders.

Table 3: The separate determinations of α_S in bins of $\langle p_{\mathrm{T}1,2}\rangle$.

$\langle p_{\mathrm{T}1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

Table 4: Uncertainty composition for $\alpha_S(M_Z)$ from the determination of α_S in bins of $\langle p_{\mathrm{T}1,2}\rangle$.

$\langle p_{\mathrm{T}1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	theory
420–600	474	0.1147	±0.0015	±0.0015	±0.0057
600–800	664	0.1132	±0.0018	±0.0025	±0.0039
800–1390	896	0.1170	±0.0024	±0.0021	±0.0048

6 Summary

The ratio R_{32} of the inclusive 3-jet cross section to the inclusive 2-jet cross section, for jets with $p_{\mathrm{T}} > 150\,\mathrm{GeV}$ and $|y| < 2.5$, has been measured in the range $250 < \langle p_{\mathrm{T}1,2}\rangle < 1390\,\mathrm{GeV}$ for proton-proton collisions at a centre-of-mass energy of 7 TeV. The results have been compared with predictions of QCD at NLO obtained with various PDF sets. The NLO calculations using the NNPDF2.1, MSTW2008, and CT10 NNLO PDF sets are in agreement with the measured ratio R_{32} throughout the range of $\langle p_{\mathrm{T}1,2}\rangle$ studied. However, calculations using the ABM11 PDF sets underestimate R_{32} for $\langle p_{\mathrm{T}1,2}\rangle < 600\,\mathrm{GeV}$.

Measurements of R_{32} over the range $420 < \langle p_{\mathrm{T}1,2}\rangle < 1390\,\mathrm{GeV}$ have been used to determine the strong coupling constant α_S at the scale of the Z boson mass. The final result is

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp.}) \pm 0.0018\,(\mathrm{PDF}) \pm 0.0050\,(\mathrm{theory}) = 0.1148 \pm 0.0055,$$

where experimental, PDF, and theory uncertainties have been added quadratically to give the total uncertainty. The result is in agreement with the world average value of $\alpha_S(M_Z) = 0.1184 \pm 0.0007$ [4] and represents the first determination of the strong coupling constant from jet measurements with momenta of the order of 1 TeV. The dominant uncertainties are of theoretical origin and limit the currently achievable precision. The predicted ratio depends only indirectly on the evolution of the parton distribution functions of the proton and consequently this measurement also serves as a test of the evolution of $\alpha_S(Q)$. No deviation from the expected behaviour is observed.

Acknowledgements

We thank Gavin Salam for his valuable comments to this paper. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); the HOMING PLUS programme of Foundation for Polish Science, cofinanced by EU, Regional Development Fund; and the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], I. Krätschmer, D. Liko, I. Mikulec, D. Rabady[2], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, A. Kalogeropoulos, J. Keaveney, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[3], G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[4], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, A. Popov[5], M. Selvaggi, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, J. Chinellato[6], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder, E.J. Tonelli Manganote[6], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
T.S. Anjos[b], C.A. Bernardes[b], F.A. Dias[a,7], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], C. Lagana[a], F. Marinho[a], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a]

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[2], P. Iaydjiev[2], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, C.A. Carrillo Montoya, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina[8], D. Polic, I. Puljak

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[9], A. Ellithi Kamel[10], M.A. Mahmoud[11], A. Mahrous[12], A. Radi[13,14]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[15], P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[16], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[16], F. Drouhin[16], J.-C. Fontaine[16], D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, M. Vander Donckt, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[17]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov[5]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[2], A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[18], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, F. Costanza, C. Diez Pardos, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann[18], B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, J. Salfeld-Nebgen, R. Schmidt[18], T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R.S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille[19], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff[2], C. Hackstein, F. Hartmann[2], T. Hauth[2], M. Heinrich, H. Held,

K.H. Hoffmann, U. Husemann, I. Katkov[5], J.R. Komaragiri, A. Kornmayer[2], P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath[20], B. Radics, F. Sikler, V. Veszpremi, G. Vesztergombi[21], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, R.M. Chatterjee, S. Ganguly, M. Guchait[22], A. Gurtu[23], M. Maity[24], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei[25], H. Bakhshiansohi, S.M. Etesami[26], A. Fahim[25], H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[27], M. Zeinali

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], L. Barbone[a,b], C. Calabria[a,b], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c,2], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[a,b], P. Verwilligen[a], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a,2], M. Meneghelli[a,b], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b], R. Travaglini[a,b]

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

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
P. Fabbricatore[a], R. Musenich[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], F. De Guio[a,b], L. Di Matteo[a,b], S. Fiorendi[a,b], S. Gennai[a,2], A. Ghezzi[a,b], P. Govoni, M.T. Lucchini[2], S. Malvezzi[a], R.A. Manzoni[a,b,2], A. Martelli[a,b,2], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Università della Basilicata (Potenza) [c], Università G. Marconi (Roma) [d], Napoli, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Cosa[a,b,2], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a], P. Bellan[a,b], M. Biasotto[a,28], D. Bisello[a,b], A. Branca[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Fanzago[a], M. Galanti[a,b,2], F. Gasparini[a,b], U. Gasparini[a,b], P. Giubilato[a,b], F. Gonella[a], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Margoni[a,b], A.T. Meneguzzo[a,b], F. Montecassiano[a], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], M. Sgaravatto[a], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], P. Zotto[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b]†, F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,29], P. Azzurri[a], G. Bagliesi[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c,2], R. Dell'Orso[a], F. Fiori[a,c], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c],

T. Lomtadze[a], L. Martini[a,29], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a], C. Vernieri[a,c]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], M. Diemoz[a], C. Fanelli[a,b], M. Grassi[a,b,2], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], L. Soffi[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], N. Cartiglia[a], S. Casasso[a,b], M. Costa[a,b], G. Dellacasa[a], N. Demaria[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a,2], A. Potenza[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a,2], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], D. Montanino[a,b], A. Penzo[a], A. Schizzi[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, Y.D. Oh, H. Park, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, S.K. Park, Y. Roh

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
I. Grigelionis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Rodrigues Antunes, J. Seixas[2], J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[7], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[30], M. Ekmedzic, D. Krpic[30], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas[2], N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, J.F. Benitez, C. Bernet[8], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, S. Colafranceschi[31], D. d'Enterria, A. Dabrowski, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rojo, G. Rolandi[32], C. Rovelli[33], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[34], D. Spiga, M. Stoye, A. Tsirou, G.I. Veres[21], J.R. Vlimant, H.K. Wöhri, S.D. Worm[35], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[36], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov[37], B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland
C. Amsler[38], V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, S.W. Li, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[39], S. Cerci[40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[41], A. Polatoz, K. Sogut[42], D. Sunar Cerci[40], B. Tali[40], H. Topakli[39], M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, G. Karapinar[43], K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak[44], M. Kaya[45], O. Kaya[45], S. Ozkorucuklu[46], N. Sonmez[47]

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar[48], E. Barlas, K. Cankocak, Y.O. Günaydin[49], F.I. Vardarlı, M. Yücel

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold[35], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[50], K.W. Bell, A. Belyaev[50], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas[35], L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko[37], J. Pela, M. Pesaresi, K. Petridis, M. Pioppi[51], D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, USA
J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein[†], E. Takasugi, P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano[2], G. Hanson, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[52], F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, P. Kalavase, D. Kovalskyi, V. Krutelyov, S. Lowette, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[53], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[54], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D.H. Moon, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[55], W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya[56], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, H. Ogul, Y. Onel, F. Ozok[48], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin[57], K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, G. Hu, P. Maksimovic, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, J.S. Wood

Kansas State University, Manhattan, USA
A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu,

M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, G. Bauer, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, Y. Kim, M. Klute, Y.S. Lai, A. Levin, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, R. Gonzalez Suarez, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, K.A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA
L. Antonelli, B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, G. Williams, B.L. Winer, H. Wolfe

Princeton University, Princeton, USA
E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA
E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, F. Wang, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[58], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, R. Loveless, A. Mohapatra, M.U. Mozer, I. Ojalvo, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil

7: Also at California Institute of Technology, Pasadena, USA
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Suez Canal University, Suez, Egypt
10: Also at Cairo University, Cairo, Egypt
11: Also at Fayoum University, El-Fayoum, Egypt
12: Also at Helwan University, Cairo, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at National Centre for Nuclear Research, Swierk, Poland
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Joint Institute for Nuclear Research, Dubna, Russia
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at The University of Kansas, Lawrence, USA
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
23: Now at King Abdulaziz University, Jeddah, Saudi Arabia
24: Also at University of Visva-Bharati, Santiniketan, India
25: Also at Sharif University of Technology, Tehran, Iran
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
31: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
33: Also at INFN Sezione di Roma, Roma, Italy
34: Also at University of Athens, Athens, Greece
35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
36: Also at Paul Scherrer Institut, Villigen, Switzerland
37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
38: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
39: Also at Gaziosmanpasa University, Tokat, Turkey
40: Also at Adiyaman University, Adiyaman, Turkey
41: Also at The University of Iowa, Iowa City, USA
42: Also at Mersin University, Mersin, Turkey
43: Also at Izmir Institute of Technology, Izmir, Turkey
44: Also at Ozyegin University, Istanbul, Turkey
45: Also at Kafkas University, Kars, Turkey
46: Also at Suleyman Demirel University, Isparta, Turkey
47: Also at Ege University, Izmir, Turkey
48: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
49: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
50: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
51: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
52: Also at Utah Valley University, Orem, USA
53: Also at Institute for Nuclear Research, Moscow, Russia

54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
55: Also at Argonne National Laboratory, Argonne, USA
56: Also at Erzincan University, Erzincan, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Kyungpook National University, Daegu, Korea