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Letter

Determination of the strong coupling and its running from measurements of inclusive jet production

The CMS Collaboration *

CERN, Geneva, Switzerland

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ABSTRACT

The value of the strong coupling α_S is determined in a comprehensive analysis at next-to-next-to-leading order accuracy in quantum chromodynamics. The analysis uses double-differential cross section measurements from the CMS Collaboration at the CERN LHC of inclusive jet production in proton-proton collisions at centre-of-mass energies of 2.76, 7, 8, and 13 TeV, combined with inclusive deep-inelastic data from HERA. The value $\alpha_S(m_Z) = 0.1176^{+0.0014}_{-0.0016}$ is obtained at the scale of the Z boson mass. By using the measurements in different intervals of jet transverse momentum, the running of α_S is probed for energies between 100 and 1600 GeV.

1. Introduction

Collimated sprays of particles, conventionally called jets, are abundantly produced in high-energy proton-proton (pp) collisions at the CERN LHC. At sufficiently high transverse momenta (p_T), jet production is described by quantum chromodynamics (QCD) using perturbative techniques (pQCD), which have now reached next-to-next-to-leading order (NNLO) accuracy.

Predictions of jet production in hadronic collisions depend on the value of the strong coupling α_S and an accurate understanding of the proton structure, encoded in the parton distribution functions (PDFs). Precise measurements of jet production provide a means to determine the strong coupling constant at the mass of the Z boson, $\alpha_S(m_Z)$, and the PDFs up to high values of x, which is the proton momentum fraction carried by the struck parton.

Inclusive jet production, $pp \to jet + X$, refers to events with at least one jet with p_T above a certain threshold in the final state and is a key process to test pQCD calculations up to the highest accessible energy scales.

In pp collisions at the LHC, inclusive jet production has been extensively studied by the CMS [1–6] and ATLAS [7–12] Collaborations at several centre-of-mass energies over a wide kinematic range.

This Letter presents a determination of $\alpha_S(m_Z)$ simultaneously obtained with the PDFs in a comprehensive QCD analysis at NNLO, where the CMS measurements of inclusive jet production in pp collisions at $\sqrt{s} = 2.76$ [1], 7 [2,3], 8 [4], and 13 TeV [5] are used together with cross section measurements of inclusive deep-inelastic scattering (DIS) at the DESY HERA [13]. The simultaneous extraction of PDFs and $\alpha_S(m_Z)$ mitigates their correlation and avoids a potential bias in the determination of $\alpha_S(m_Z)$ [14]. Furthermore, the running of α_S as a function of the energy scale is demonstrated at NNLO up to 1.6 TeV.

2. The CMS detector

The CMS apparatus [15,16] is a multipurpose, nearly hermetic detector, designed to trigger on [17–19] and identify electrons, muons, photons, and (charged and neutral) hadrons [20–22]. A particle-flow (PF) algorithm [23] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker, the crystal electromagnetic (ECAL) and the brass-scintillator hadron calorimeters (HCAL) that operate inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed PF particles are used to build τ leptons, jets, and missing transverse momentum [24–26].

3. Inclusive jet measurements

In this work, four CMS measurements of the double-differential inclusive jet cross section as functions of the individual jet p_T and absolute rapidity $|y|$ are included. These measurements use jets clustered with the anti-k_T [27] algorithm as implemented in the FastJet [28] program with a distance parameter of $R = 0.7$. For each of the measurements, the corresponding integrated luminosity $\mathcal{L}$, the number of data points

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

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Table 1
The CMS inclusive jet measurements used in this analysis. The columns show the centre-of-mass energy, the integrated luminosity, the number of measured data points, the ranges of individual jet p_T and $|y|$, and the reference to the corresponding publication.

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	N_p	p_T [GeV]	$\lvert y \rvert$	Ref.
2.76	0.0054	80	74–592	0.0–3.0	[1]
7	5.0	130	114–2116	0.0–2.5	[2,3]
8	20	165	74–1784	0.0–3.0	[4]
13	33.5	78	97–3103	0.0–2.0	[5]

N_p, and the ranges in p_T and $|y|$ are listed in Table 1. Although the measurement at $\sqrt{s} = 8$ TeV extended up to 2.5 TeV in p_T, the range from 1784 to 2500 GeV was excluded from the fit in the original analysis [4] due to very large statistical correlations in these bins.

The primary source of experimental systematic uncertainty in jet measurements comes from the calibration of the jet energy scale (JES) and the jet energy resolution (JER). These calibrations and their associated uncertainties are determined using test beam data, Monte Carlo (MC) simulations, and measurements of dijet, Z+jet, γ+jet, and multijet production [25,29]. We estimate the correlations between these uncertainties across p_T and $|y|$ intervals within individual measurements and among the measurements at various $\sqrt{s}$, and include them in the QCD analysis. This analysis results in a recommendation for the use of these correlations in future global QCD analyses of CMS inclusive jet measurements.

The JES uncertainties are grouped into eight main categories. A detailed description of the JES calibration and the corresponding uncertainties is given in Refs. [25,29]. The naming scheme of the uncertainty sources follows from previous publications [1–5] and is identical to the implementation in xFitter [30,31]. Additional uncertainties specific to each individual measurement are discussed in the original publications.

- Uncertainties related to the absolute scale are associated with the JES correction within the barrel region, corresponding to pseudorapidities $|\eta| < 1.3$. This correction (*AbsoluteScale*) is obtained from a global fit using Z+jet, γ+jet, and multijet data. It includes a correction for initial-state (ISR) and final-state radiation (FSR) (*AbsoluteMPFBias*). Extrapolations to high p_T beyond the reach of the measurements are performed by using MC simulations. Additional uncertainties are introduced to address response variations from different MC event generators (*Fragmentation*) and the single-particle response in the ECAL and HCAL (*SinglePionECAL*, *SinglePionHCAL*).
- Relative JER uncertainties represent the η-dependent uncertainty of the JES from the JER corrections (*RelativeJER*).
- The relative η correction of the JES calibration ensures a uniform detector response across different detector regions. In addition, it includes a log-linear p_T dependence. An uncertainty associated with the choice of the p_T-dependent shape is included. (*RelativePt*).
- The relative contribution *RelativeFSR* corresponds to an uncertainty in the η-dependent corrections for ISR and FSR.
- The statistical uncertainties in the determination of the relative corrections in various regions of η for multiple uncertainty sources are merged into one uncertainty (*RelativeStat*).
- Differences in the simulated detector response to jets from different quark flavours and gluons result in the *FlavourQCD* uncertainty. It is derived from differences between data and MC simulations when the corresponding corrections are applied to various mixtures of jet flavours. The uncertainty is based on response differences to jets from uds/c/b quarks and gluons between pythia [32] and herwig [33].
- Two time-dependent uncertainties address the JES variation over time during the data-taking periods (*TimePt* and *TimeEta*).
- Uncertainties associated with the corrections for additional pp interactions within the same or nearby bunch crossings (pileup) are included.

The correlation scheme for JES-related uncertainties across the different CMS measurements used in this analysis is described below and illustrated in Appendix A. The uncertainties in pileup, the relative statistical contribution *RelativeStat*, and the time-dependent sources *TimePt* and *TimeEta* are considered uncorrelated across the measurements. For the measurement at $\sqrt{s} = 7$ TeV [2], the correlation scheme for JES-related uncertainties is used as described in Ref. [3]. In particular, the *SinglePionECAL* and *SinglePionHCAL* sources are decorrelated as a function of η. The correlations in the remaining JES uncertainties between different data sets are implemented as follows.

- The *AbsoluteMPFBias* uncertainty is fully correlated between the 2.76, 8, and 13 TeV measurements. In the 7 TeV analysis, a combined source of uncertainty is used by including uncertainties from the *AbsoluteScale*, ISR and FSR, and a statistical component associated with the *AbsoluteScale* correction [3]. This combined source of uncertainty in the 7 TeV analysis is uncorrelated with uncertainties in the other measurements.
- The *AbsoluteScale*, *SinglePionECAL*, *SinglePionHCAL*, and *RelativeJER* uncertainties are fully correlated between the 2.76 and 8 TeV measurements, since the corresponding corrections were obtained using 8 TeV data and applied to both measurements. These uncertainties are uncorrelated with other data sets, for which the corrections were specifically derived.
- The *RelativeFSR* and *Fragmentation* uncertainties are fully correlated between the 2.76, 7, and 8 TeV measurements, but uncorrelated with the 13 TeV measurement, because of the use of different MC tunes and event generators.
- The *RelativePt* uncertainties are uncorrelated across the measurements, since these account for the differences between linear and logarithmic fits in the p_T extrapolation of the residual corrections, which vary across data-taking periods.
- The *FlavourQCD* uncertainty is treated as fully correlated between the 7 and 8 TeV measurements because these used identical uncertainties, but uncorrelated with the 2.76 and 13 TeV ones to account for differences in simulation setup, including centre-of-mass energy, pileup, and MC tunes.

The JER uncertainties are treated as uncorrelated across measurements at different energies. Furthermore, within each individual measurement, the JER uncertainties have been decorrelated across $|y|$ for the 2.76, 7, and 8 TeV measurements. This approach is motivated by the unaccounted residual $|y|$ dependence in these data sets. The JER uncertainty is considered correlated among $|y|$ and p_T for the 13 TeV measurement [5]. An additional uncorrelated component of 1.5% is assigned to the JER uncertainty in the 2.76 TeV measurement to take into account a statistical contribution to the JER uncertainty.

4. Theoretical predictions

The NNLO pQCD calculations used in this study are performed assuming five active massless quark flavours in the leading-colour (LC) and leading-flavour-number approximation using the nnlojet program [34]. The subleading colour contributions for the NNLO corrections, neglected in Ref. [34], have been recently calculated [35] and have a very small impact on inclusive jet production with $R = 0.7$. The renormalization, μ_r, and factorization, μ_f, scales in the calculation are set to the individual jet p_T, following the studies of Ref. [36]. The cross section predictions for intervals in p_T and $|y|$ of the respective measurements are stored in the form of interpolation grids in the APPLfast [37] format, allowing for a fast evaluation of the predictions under variations of α_S, PDFs, or the μ_r and μ_f scales. The numerical uncertainty in the grids is below 1% in most intervals and increases to about 5% in the forward region at high p_T, remaining significantly smaller than the statistical uncertainties in the measurements. However, in the forward region, predictions in a few intervals at the highest values of p_T have numerical grid uncertainties exceeding 10% and are, therefore, excluded from the QCD interpretation. When the interpolation grids for this analysis were produced, the recent improvements in the merging procedure of NNLOJET that aim to reject outliers without biasing the result in multidimensional MC integrations were not available. To account for the remaining point-to-point fluctuations, the numerical uncertainty has been increased by a factor of two. However, its impact on the fit is negligible.

The QCD predictions are modified with a multiplicative correction for contributions of the dominant electroweak (EW) effects. These arise from the virtual exchange of soft or collinear massive weak gauge bosons, calculated at next-to-leading-order precision [38]. The contribution of EW effects becomes important at large jet p_T, reaching 11% at the highest p_T probed in the 13 TeV measurement. Subleading EW effects from the emissions of real weak gauge bosons have been estimated in the 13 TeV measurement to be smaller than 1% at high p_T and are neglected. The EW corrections for the 13 TeV measurement are taken from the original publication [5]. For the 7 and 8 TeV measurements, these corrections have been updated using more recent PDF sets. The EW corrections are omitted for the 2.76 TeV measurement because of their negligible impact for p_T smaller than 600 GeV.

To compare the fixed-order predictions to the measured particle-level cross sections, these are corrected for the nonperturbative (NP) effects from hadronization and the underlying event. These NP corrections have been derived as cross section ratios from event generators with parton showers, in which NP effects are switched on and off. These corrections are applied through p_T- and $|y|$-dependent correction factors as provided in the original publications [1,3–5] of the individual measurements. In each measurement, the generator tune used is the one providing the best match to the data. The NP corrections have a size between 5 and 20% at low p_T, with their effect decreasing with increasing p_T. The associated uncertainties range from 1 to 4% at low p_T, depending on $|y|$, and are negligible at high p_T. The uncertainties related to NP corrections are treated correlated in ranges of p_T and $|y|$ in each individual measurement and uncorrelated across the measurements. Despite slight differences in the way the NP corrections were obtained for each measurement, the impact of the NP corrections in the $\alpha_S(m_Z)$ and PDF determination is insignificant considering their uncertainties. In particular, the impact of the NP corrections in the QCD analysis was studied by performing individual fits with a subset of measurements with jet $p_T > 150$, 200, and 300 GeV. In this way, the kinematic ranges with decreasing importance of NP corrections are consecutively probed. The difference in the results is negligible. The main result is based on the full p_T spectra probed by the CMS jet data.

5. The QCD analysis

In the QCD analysis, the four CMS measurements of the double-differential cross sections of inclusive jet production are used together with the combined neutral current (NC) and charged current (CC) electron-proton DIS cross sections measured at HERA [13], following the general strategy of Refs. [13,39].

Theoretical predictions for the DIS cross sections are calculated at fixed order in QCD at NNLO accuracy using the QCDNUM code [40], with μ_r and μ_f set to the squared four-momentum transfer Q^2. The contribution of massive c and b quarks to the DIS cross sections is treated in the Thorne–Roberts general-mass variable-flavour number scheme [41–43]. The masses of c and b quarks are set as $m_c = 1.47 \pm 0.06$ GeV and $m_b = 4.5 \pm 0.25$ GeV, respectively. The fraction of the strange quark in the sea $f_s = x\bar{s}/(x\bar{d} + x\bar{s})$ is assumed to be 0.40, as in the HERAPDF2.0 analysis [13] and varied within $0.32 \leq f_s \leq 0.48$. The low-Q^2 region in DIS, where resummation effects from small-x logarithms become important, is removed from the fit by using only the DIS measurements with $Q^2 > 10\,\mathrm{GeV}^2$. This cutoff is varied by $2.5\,\mathrm{GeV}^2$ up and down. While the central values and the variations of m_c, m_b and f_s are set as in the QCD interpretation [5] of the CMS inclusive jet measurement at $\sqrt{s} = 13$ TeV, the minimum Q^2 cut for HERA data is increased from 7.5 to $10\,\mathrm{GeV}^2$. This adjustment aligns with the original HERA publication [13], which features tensions between low-Q^2 ($< 15\,\mathrm{GeV}^2$) and high-Q^2 ($> 150\,\mathrm{GeV}^2$) data. The published DIS cross sections are already corrected for the dominant EW effects.

The PDFs for the gluon, valence u- and d-quark, and $\bar{u}$ and $\bar{d}$ quark densities are parametrized at a starting (evolution) scale of $Q_0^2 = 1.9\,\mathrm{GeV}^2$, varied by $0.2\,\mathrm{GeV}^2$ [5]. The Q^2 dependence of the PDFs and of α_S is obtained by solving the DGLAP evolution equations at NNLO in pQCD as implemented in QCDNUM. The functional form of the PDFs for each parton i at the starting scale is

$$xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x), \tag{1}$$

where the A_i are normalization parameters and $P_i(x) = (1 + D_i x + E_i x^2)$ are polynomials that interpolate between the small- and large-x behaviour given by the B_i and C_i parameters. The D_i and E_i terms in the polynomial expansion are only included following the results of an optimization procedure. In such a "parametrization scan", all D_i and E_i parameters are set to zero and then included in the fit, one at a time. The process is monitored through the resulting change in χ^2 and the scan is terminated when no further improvement is observed. The parameters A_{u_v} and A_{d_v} are determined during the fit from the valence-quark number sum rule and the value of A_g is obtained from the momentum sum rule. In the present work, the parametrization scan led to the same parameters as the most recent NNLO QCD analysis [5] of the CMS measurement of inclusive jet production at 13 TeV, using the same assumptions for the PDF parameters. This parametrization includes 15 free parameters for the PDFs. Additional terms in the polynomial expansion proportional to D_i and E_i are added to estimate the parametrization uncertainty as discussed in Section 6.

The fit is performed using the xFITTER [30,31] program. The values of the PDF parameters and of α_S are obtained in the minimization procedure using MINUIT [44] with a χ^2 goodness-of-fit function that includes experimental uncertainties as nuisance parameters $b_{i,\mathrm{exp}}$. The χ^2 definition is the same as defined in xFITTER [30,31] and used in most recent analyses [5],

$$\chi^2(\mathbf{T}, \mathbf{b}_{\mathrm{exp}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left[M_i - T_i(1 - \sum_j \gamma_{ij}^{\mathrm{exp}} b_{j,\mathrm{exp}})\right]^2}{\delta_{i,\mathrm{uncor}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 M_i T_i (1 - \sum_j \gamma_{ij}^{\mathrm{exp}} b_{j,\mathrm{exp}})} + \sum_{j=1}^{N_{\mathrm{exp.sys}}} b_{j,\mathrm{exp}}^2. \tag{2}$$

The index i runs over all $N_{\mathrm{data}} = 1469$ data points of the inclusive jet and HERA measurements. Here, M_i and T_i are the measurements and theory predictions, respectively. Further, $\delta_{i,\mathrm{uncor}}$ and $\delta_{i,\mathrm{stat}}$ denote the statistical and uncorrelated systematic uncertainties of the measurement i. The experimental correlated uncertainty sources are included using the set of parameters $b_{j,\mathrm{exp}}$, with the impact of each source on the theory point T_i described by the matrices $\gamma_{ij}^{\mathrm{exp}}$. Asymmetric uncertainties in the PDF parameters are obtained from a $\Delta\chi^2 = 1$ criterion using an iterative Hessian approach, following the prescription of Ref. [45]. The uncertainties quoted in the following correspond to 68% confidence level (CL).

6. Results

In Fig. 1, the measurements divided by the NNLO LC QCD predictions are shown, corrected for NP and EW effects. In general, a very good agreement between the theory predictions and the data is observed. The consistency of all the experimental data is quantified by the goodness

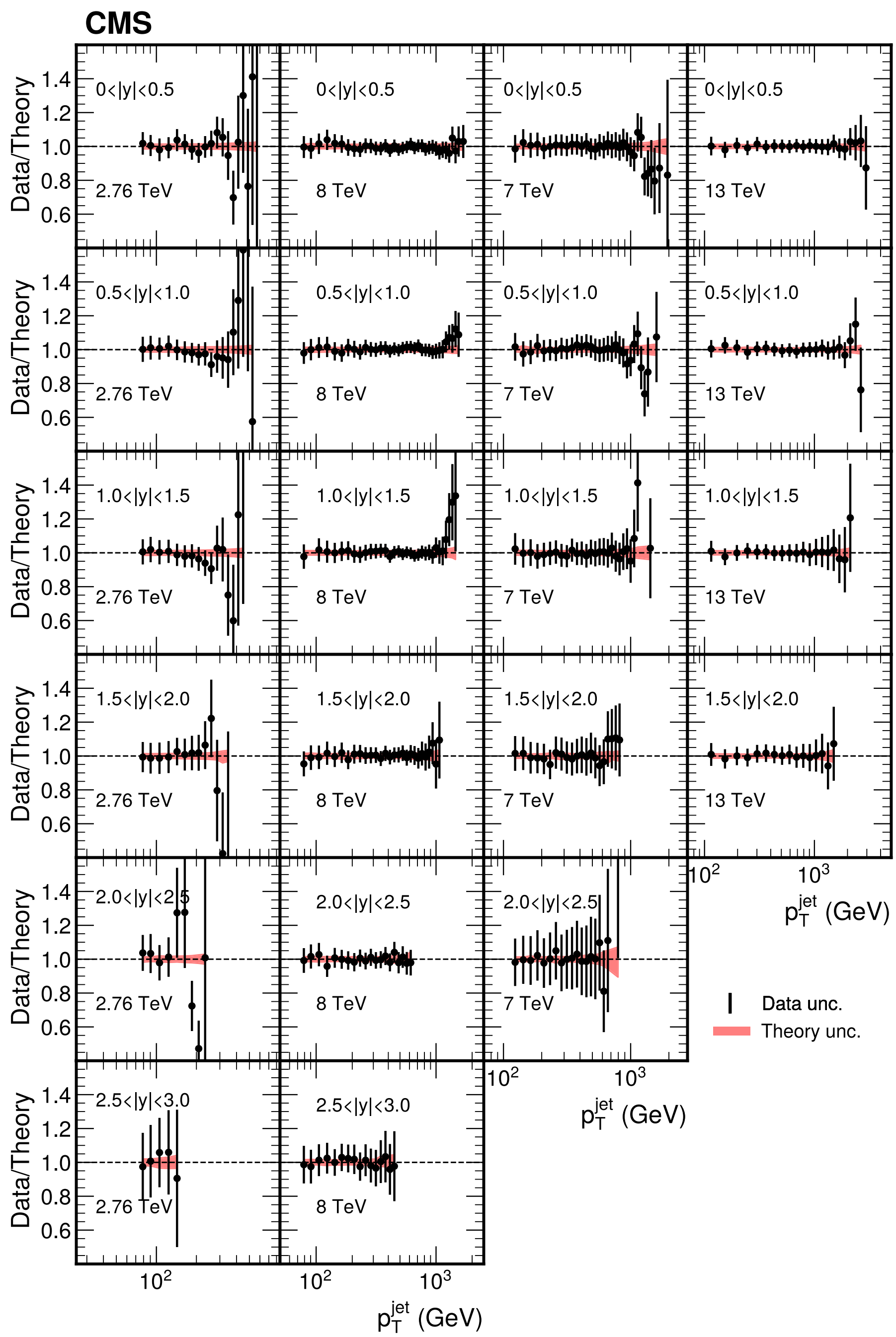

Fig. 1. Cross section ratios between data and theory for inclusive jet production in pp collisions as measured by CMS at $\sqrt{s}$ of 2.76, 8, 7, and 13 TeV, using the anti-k_T clustering algorithm with $R = 0.7$, as functions of individual jet p_T in intervals of absolute rapidity $|y|$. Shown is the total uncertainty of every data point (vertical bar). Predictions correspond to the NNLO LC QCD calculations corrected for NP and EW effects. The PDFs obtained in this work are used. The total theory uncertainty (red shaded band) includes the PDF and scale variation uncertainties.

of the fit χ^2 from Eq. (2). The values of χ^2 per N_p are reported for the individual data sets (partial χ^2/N_p) in Table 2, together with the total χ^2 per number of degrees of freedom N_{dof}, which is 1680/1453. A somewhat higher partial χ^2/N_p for the HERA DIS data is investigated in detail in the original work [13], where tensions between the measurements at low Q^2 (<15 GeV^2) and high Q^2 (>150 GeV^2) were identified. The sum of partial χ^2/N_p for all CMS jet measurements, including their correlation, is 496/453.

In Fig. 2, the impact of the CMS jet data on the PDF determination (*HERA+CMS* fit) is illustrated, considering the Hessian fit uncertainties. The uncertainties in the PDFs resulting from the present QCD analysis are shown in comparison with the results of an alternative fit, which includes only HERA DIS data (*HERA-only* fit). In the HERA-only fit, due to poor sensitivity of the DIS data to $\alpha_S(m_Z)$, its value is fixed to that of the HERA+CMS fit. The PDFs are shown at the factorization scale $Q^2 = m_t^2$, where m_t is the top quark mass. This particular scale is chosen for enabling comparisons with previous results [5]. Significant improvement in the uncertainties of all PDFs is observed once CMS jet measurements are included in the analysis. Whereas improvements in the precision of the gluon PDF have been reported in earlier QCD analyses using individual inclusive jet measurements, the inclusion of all available CMS inclusive jet measurements at different $\sqrt{s}$ provides additional constraints on the d_v distribution.

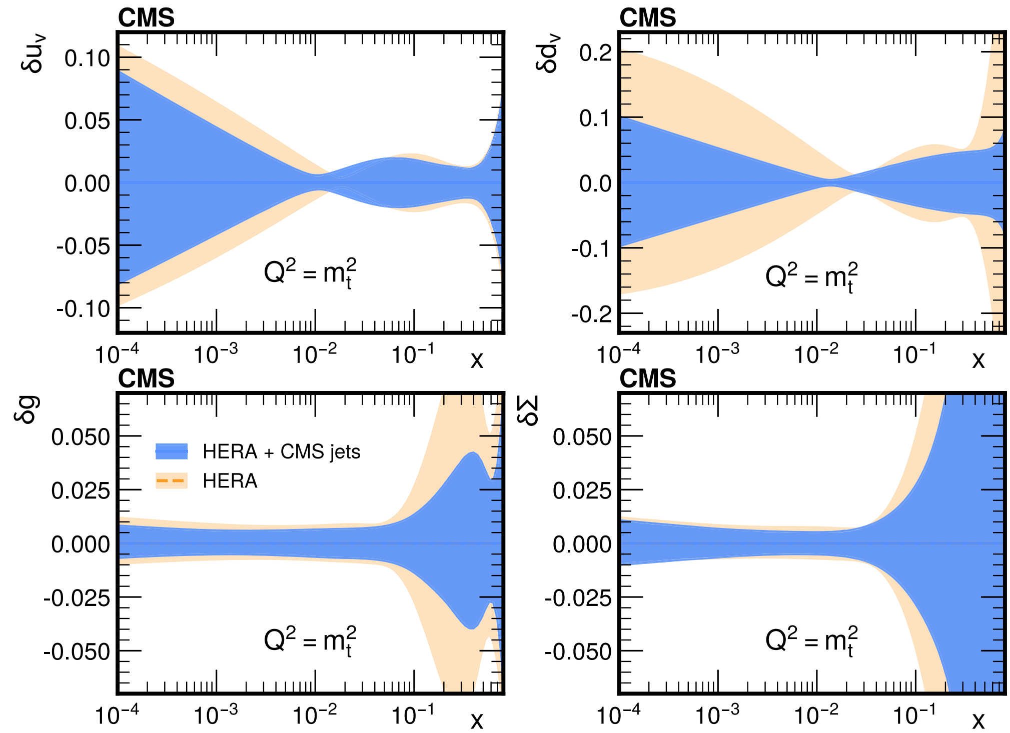

Fig. 2. The fit uncertainties in the valence u quark (u_v) (upper left), valence d quark (d_v) (upper right), gluon g (lower left), and sea quark Σ (lower right) distributions, shown as a function of x at the factorization scale $Q^2 = m_t^2$. The results of the HERA+CMS fit (blue shaded area) are compared with the results of the HERA-only fit (orange shaded area). In the HERA-only fit, due to poor sensitivity of the DIS data to $\alpha_S(m_Z)$, its value is fixed to that of the HERA+CMS fit. The uncertainties are given at 68% CL.

Table 2
The values of χ^2 per N_p for each individual data set as obtained in the fit to HERA and CMS jet data, together with the contribution to the χ^2 from correlated uncertainty sources. In the last line, the total χ^2 per number of degrees of freedom, N_{dof}, is reported.

Data set	Partial χ^2/N_p
HERA I+II neutral current	1036/935
HERA I+II charged current	112/81
CMS jets 2.76 TeV	63/80
CMS jets 7 TeV	81/130
CMS jets 8 TeV	206/165
CMS jets 13 TeV	77/78
Correlated χ^2 HERA	56
Correlated χ^2 Jets	69
Total χ^2/N_{dof}	1680/1453

In Fig. 3, the PDFs obtained in the HERA+CMS fit are compared with those obtained by the global fitting groups HERAPDF20 [13], NNPDF40 [46], CT18NNLO [47], and MSHT20 [48]. These global PDFs are based on inclusive HERA DIS data and use some of the CMS jet measurements included in the present work, except for the HERAPDF20 PDF set. In general, the PDFs determined in this analysis are in resonable agreement with the global PDF sets, particularly in the x range probed by the CMS jet data. By adding these data, the valence quark PDF, in particular the valence d quark (d_v) distribution, is observed to agree better with the global PDFs NNPDF40 and MSHT20 than HERAPDF20. In the HERA+CMS fit, the value of $\alpha_S(m_Z)$ is determined together with the PDFs, resulting in $\alpha_S(m_Z) = 0.1176 \pm 0.0009$, where the uncertainty denotes the Hessian fit uncertainties.

Additional uncertainties are included in the QCD analysis following the strategy of Ref. [5]. These uncertainties are the model uncertainty, obtained from variations of the fit input parameters, such as m_b, m_c, f_s, the minimum Q^2 for DIS data Q_0^2, the uncertainty originating from missing higher-order corrections, and the parametrization uncertainty, accounting for alternative PDF parametrizations. For each variation, an alternative fit is performed. The contributions to the model uncertainty are added in quadrature, resulting in $\delta\alpha_S(m_Z) = {}^{+0.0006}_{-0.0004}$ (model). The uncertainty from missing higher orders in the calculation of the jet cross sections is evaluated by varying the scales μ_r and μ_f (scale uncertainty) independently by a factor of two up and down, avoiding cases with $\mu_f/\mu_r = 4$ or $1/4$. For each scale choice, an individual fit is performed, and the maximum difference to the central result is included as an uncertainty of $\delta\alpha_S(m_Z) = {}^{+0.0009}_{-0.0012}$ (scale). The parametrization uncertainty is estimated by extending the functional form of the PDFs by additional parameters D and E, added one at a time. An uncertainty $\delta\alpha_S(m_Z) = {}^{+0}_{-0.00004}$ (param.) is obtained from an envelope of the results of the corresponding fits and is added linearly to the aforementioned uncertainties.

Summarizing the findings above, the value of $\alpha_S(m_Z)$ is obtained as

$$\alpha_S(m_Z) = 0.1176\,{}^{+0.0009}_{-0.0009}\,(\text{fit})\,{}^{+0.0006}_{-0.0004}\,(\text{model})\,{}^{+0.0009}_{-0.0012}\,(\text{scale})\,{}^{+0.}_{<(-0.0001)}\,(\text{param.}), \quad (3)$$

corresponding to the total uncertainty of ${}^{+0.0014}_{-0.0016}$ (tot). This value is in good agreement with the PDG world average of $\alpha_S(m_Z) = 0.1180 \pm 0.0009$ [49] and with previous CMS results obtained at NNLO [5,50–53], as shown in Fig. 4. The inclusion of data from multiple centre-of-mass energies improves the precision by significantly reducing the fit uncertainty. The dominant contribution to the uncertainty originates from missing higher order corrections.

The value of α_S in five different ranges of $\mu_r = p_T$ is determined, following the previous approach, which illustrates the running of the strong coupling, $\alpha_S(\mu_r)$ at NNLO. For this purpose, the CMS measurements of inclusive jet production are split into exclusive ranges of individual jet p_T. For each p_T range, a simultaneous fit of PDFs and $\alpha_S(m_Z)$ is performed individually. The values of $\alpha_S(m_Z)$ obtained in each individ-

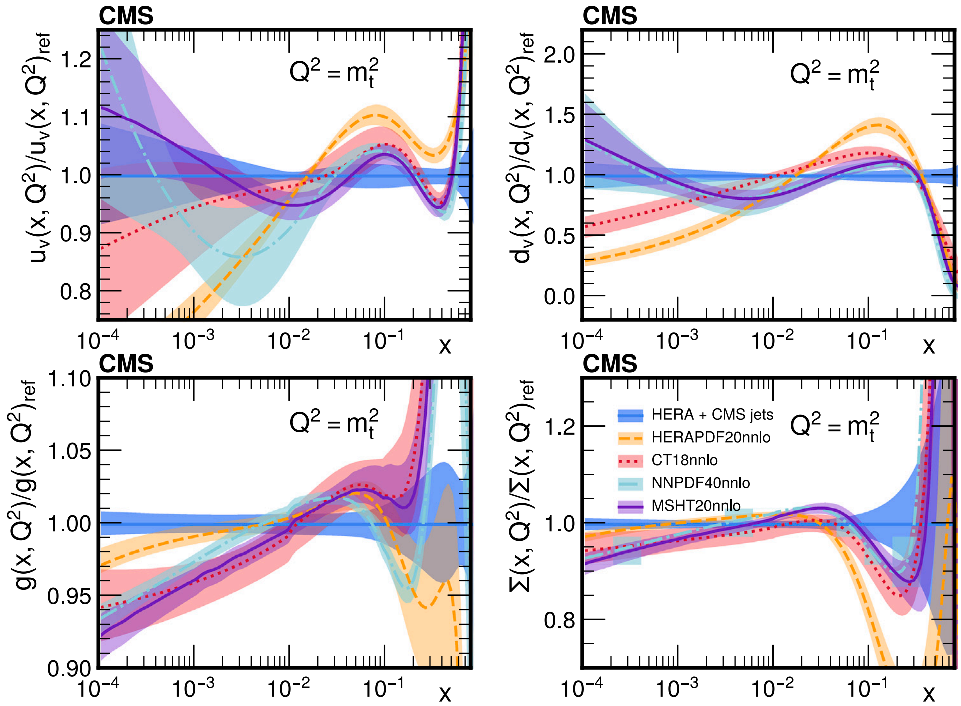

Fig. 3. Ratios of different global PDF sets at NNLO, namely HERAPDF20 [13], CT18 [47], NNPDF4 [46], and MSHT20 [48], to the result of the present study. The valence u quark (u_v) (upper left), valence d quark (d_v) (upper right), gluon g (lower left), and sea quark Σ (lower right) distributions are shown as functions of x at the factorization scale $Q^2 = m_t^2$. The Hessian PDF uncertainties at 68% CL are shown, where the width of the band represents the uncertainty in the numerator by keeping the denominator constant.

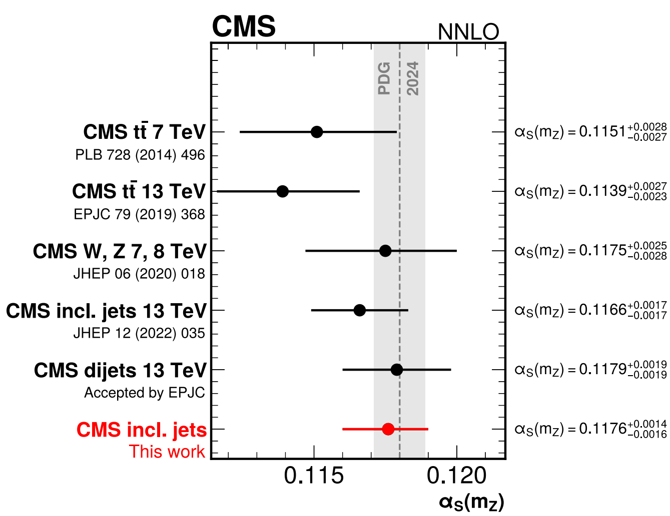

Fig. 4. The value of $\alpha_S(m_Z)$ obtained in this analysis (red marker), compared with all CMS results obtained at NNLO by using different methods (black markers) with their total uncertainties (horizontal error bars). The PDG world average (dashed line) together with its uncertainty (shaded band) is also shown.

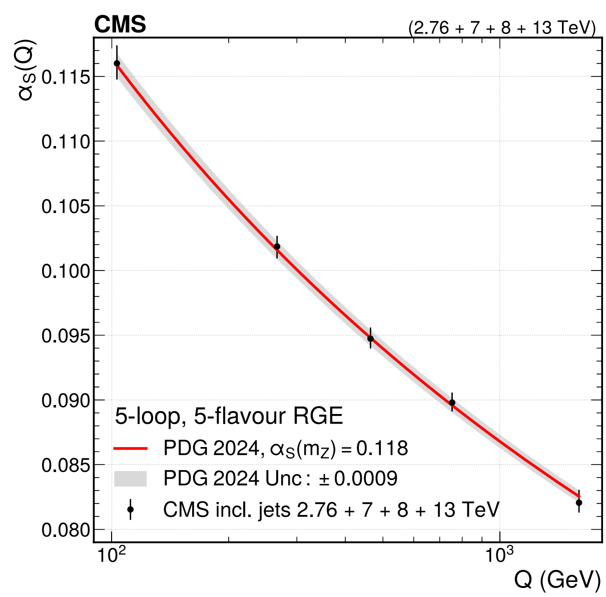

Fig. 5. Values of α_S as extracted from different jet transverse momentum ranges in the present QCD analysis at NNLO, each translated to a single scale $\langle Q \rangle$, as indicated in Table 3. The results (black markers) are shown with their total uncertainties (vertical error bars). For comparison, the RGE at 5 loops is shown using the current world-average value $\alpha_S(m_Z) = 0.1180 \pm 0.0009$ [49] (red line) together with its associated total uncertainty (shaded band).

ual fit are evolved as $\alpha_S(\mu_r)$ using the five-loop five-flavour renormalization group equation (RGE) encoded in CRunDec [54] version 0.5.2. The same RGE is used to obtain the corresponding uncertainties. The fit, model, scale, and parametrization uncertainties are computed as in the case of Eq. (3). In each p_T range, μ_r is calculated at NNLO QCD as a cross section-weighted average $\langle p_T \rangle$. Results are summarised in Table 3 and shown in Fig. 5, where the values of $\alpha_S(\mu_r)$ are compared with the evolution of the world average of $\alpha_S(m_Z)$ performed at five-loop order in QCD using CRunDec.

7. Summary

The value of the strong coupling constant at the scale of the mass of the Z boson, $\alpha_S(m_Z)$, is extracted together with the parton distribution functions (PDFs) of the proton in an analysis at next-to-next-to-leading order (NNLO) accuracy in quantum chromodynamics (QCD). The simultaneous extraction of $\alpha_S(m_Z)$ and PDFs mitigates a possible bias from

Table 3
The determined $\alpha_S(m_Z)$ and the corresponding $\alpha_S(Q)$ values for each p_T range with their total uncertainties. For $\alpha_S(Q)$, the individual uncertainty contributions (fit, scale, model, parametrization) are listed. Values reported as 0.0 indicate uncertainties smaller than 0.0001, while "–" indicates that the corresponding upper or lower uncertainty does not exist since it is one-sided.

p_T (GeV)	$\langle Q \rangle$	$\alpha_S(m_Z)$ (tot)	$\alpha_S(Q)$	(fit)	(scale)	(model)	(param.)	(tot)
74–220	103.06	$0.1182^{+0.0014}_{-0.0013}$	0.1160	$^{+0.0011}_{-0.0011}$	$^{+0.0007}_{-0.0005}$	$^{+0.0006}_{-0.0004}$	$^{+0.0}_{-}$	$^{+0.0014}_{-0.0012}$
220–395	266.63	$0.1184^{+0.0011}_{-0.0012}$	0.1019	$^{+0.0007}_{-0.0007}$	$^{+0.0}_{-0.0004}$	$^{+0.0004}_{-0.0003}$	$^{-}_{-0.0}$	$^{+0.0008}_{-0.0009}$
395–638	464.31	$0.1179^{+0.0013}_{-0.0012}$	0.0947	$^{+0.0007}_{-0.0007}$	$^{+0.0003}_{-0.0}$	$^{+0.0004}_{-0.0003}$	$^{-}_{-0.0}$	$^{+0.0009}_{-0.0008}$
638–1410	753.66	$0.1184^{+0.0014}_{-0.0012}$	0.0898	$^{+0.0006}_{-0.0006}$	$^{+0.0003}_{-0.0}$	$^{+0.0004}_{-0.0003}$	$^{+0.0}_{-}$	$^{+0.0008}_{-0.0007}$
1410–3103	1600.5	$0.1170^{+0.0021}_{-0.0016}$	0.0821	$^{+0.0007}_{-0.0007}$	$^{+0.0004}_{-}$	$^{+0.0005}_{-0.0003}$	$^{+0.0}_{-}$	$^{+0.0010}_{-0.0008}$

their correlations. The analysis includes electroweak effects at next-to-leading order and nonperturbative corrections. The CMS measurements of inclusive jet production in proton-proton collisions at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV, using the anti-k_T clustering algorithm with a distance parameter of 0.7, are used together with the inclusive deep inelastic scattering cross sections from HERA. The correlations among the systematic uncertainties of each individual jet cross section measurement, as well as across all centre-of-mass energies, are reevaluated. These correlations should be included in future global QCD analyses of these data. By using the CMS jet data in the fit, the value of $\alpha_S(m_Z) = 0.1176^{+0.0014}_{-0.0016}$ is obtained, in good agreement with the world average. It is the most precise result for $\alpha_S(m_Z)$ from jet cross sections to date. At the same time, this analysis demonstrates that improved PDFs can be extracted by using these data. Furthermore, by extracting the value of α_S in different intervals of jet p_T, the running of α_S is tested at NNLO in QCD up to energy scales of 1.6 TeV. The observed running of α_S is in agreement with the prediction of the QCD renormalization group equation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. JES correlation of inclusive jet measurements

The JES correlation scheme as illustrated in Fig. A.1 has been applied in the QCD analysis of the CMS inclusive jet measurements at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV. A filled black box indicates that the corresponding two measurements are treated as fully correlated for the specific source of uncertainty.

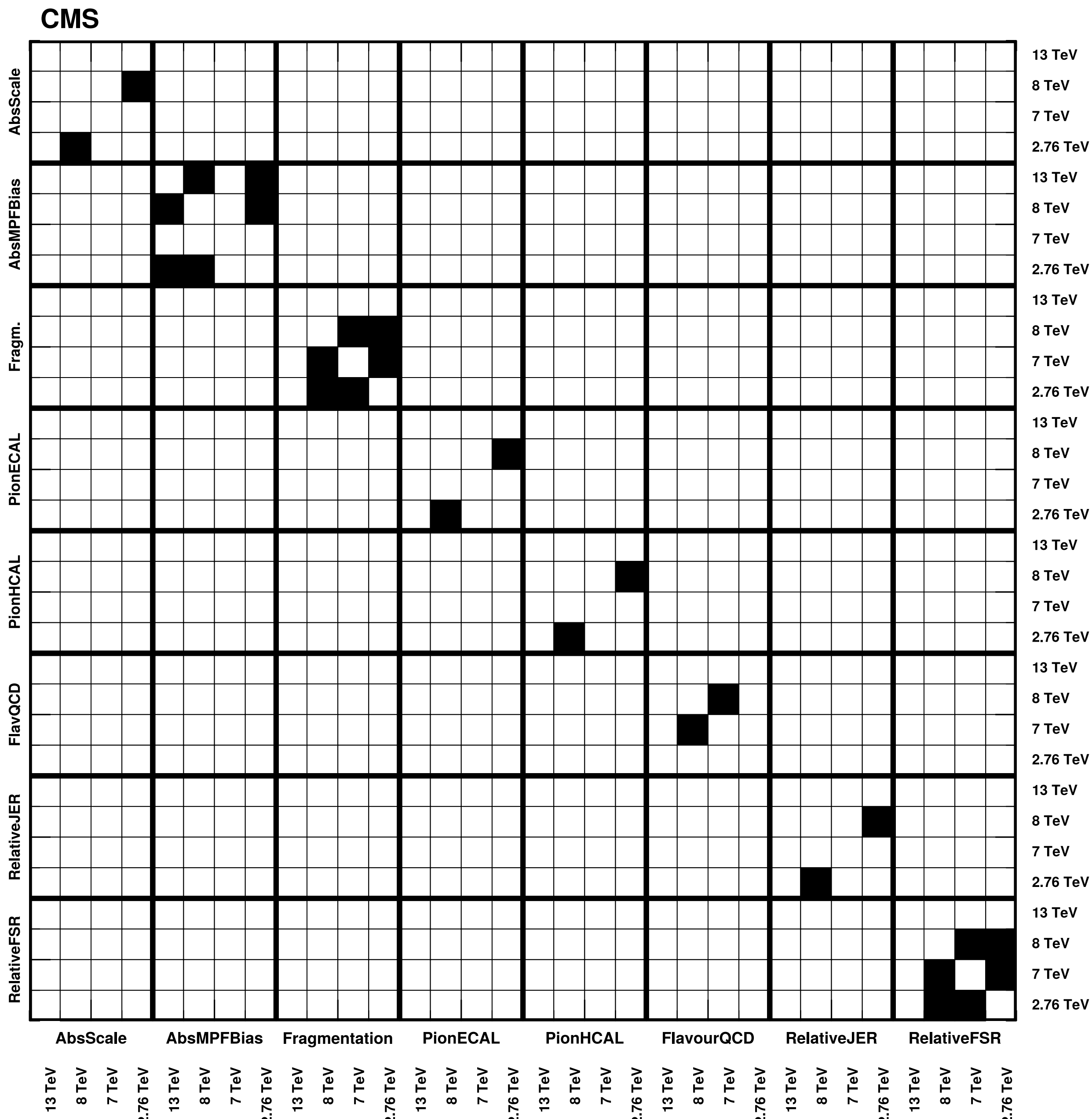

Fig. A.1. Sketch of the treatment of JES sources of uncertainty among the measurements at different $\sqrt{s}$. A filled black box indicates that the corresponding two uncertainty sources are treated as correlated.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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The CMS collaboration

V. Chekhovsky, A. Hayrapetyan, V. Makarenko, A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck[2], D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Institut für Hochenergiephysik, Vienna, Austria

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

Universiteit Antwerpen, Antwerpen, Belgium

N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

G.A. Alves, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, T. Laux Kuhn[7], M. Macedo, J. Martins, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

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

C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Keshri, D. Laroze, S. Thakur

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

T. Cheng, T. Javaid, L. Yuan

Beihang University, Beijing, China

Z. Hu, Z. Liang, J. Liu

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen[8], H.S. Chen[8], M. Chen[8], F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], J. Wang, Z. Wang[8], H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, Y. Zhao, C. Zhou

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

S. Yang

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

Z. You

Sun Yat-Sen University, Guangzhou, China

K. Jaffel, N. Lu

University of Science and Technology of China, Hefei, China

G. Bauer[12], B. Li[13], H. Wang, K. Yi[14], J. Zhang

Nanjing Normal University, Nanjing, China

Y. Li

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

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Los Andes, Bogota, Colombia

J. Jaramillo, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

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

M. Kovac, A. Petkovic, T. Sculac

University of Split, Faculty of Science, Split, Croatia

P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov[15], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla[16], Y. Assran[17,18], B. El-mahdy

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

M. Abdullah Al-Mashad, M.A. Mahmoud

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

H. Kirschenmann, P. Luukka, H. Petrow

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[19], P. Simkina, M. Titov, M. Tornago

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

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

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

J.-L. Agram[20], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

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

A. Di Florio

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

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[21], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

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

A. Khvedelidze[22], I. Lomidze, Z. Tsamalaidze[22]

Georgian Technical University, Tbilisi, Georgia

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

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

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

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

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

H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, A. Cardini, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[26], W. Lohmann[27], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

S. Brommer, E. Butz, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[29], A. Stakia

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

C. Hajdu, D. Horvath [30,31], K. Márton, A.J. Rádl [32], F. Sikler, V. Veszpremi

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

M. Csanád, K. Farkas, A. Fehérkuti [33], M.M.A. Gadallah [34], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

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

B. Ujvari, G. Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

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

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

T. Csorgo [33], F. Nemes [33], T. Novak

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

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [35], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Baradia, S. Barman [36], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri [37], D. Kumar [37], T. Mishra, B. Parida [38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Indian Institute of Technology Madras, Madras, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [39], C. Kar, D. Maity [40], P. Mal, K. Naskar [40], A. Nayak [40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese [40], D. Vats [40]

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

S. Acharya [41], A. Alpana, S. Dube, B. Gomber [41], P. Hazarika, B. Kansal, A. Laha, B. Sahu [41], S. Sharma, K.Y. Vaish

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

H. Bakhshiansohi [42], A. Jafari [43], M. Zeinali [44]

Isfahan University of Technology, Isfahan, Iran

S. Bashiri, S. Chenarani [45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang [46]

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], A. Colaleo [a,b], D. Creanza [a,c], B. D'Anzi [a,b], N. De Filippis [a,c], M. De Palma [a,b], W. Elmetenawee [a,b,47], N. Ferrara [a,b], L. Fiore [a], G. Iaselli [a,c], L. Longo [a], M. Louka [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a], V. Mastrapasqua [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], D. Ramos [a], A. Ranieri [a], L. Silvestris [a], F.M. Simone [a,c], Ü. Sözbilir [a], A. Stamerra [a,b], D. Troiano [a,b], R. Venditti [a,b], P. Verwilligen [a], A. Zaza [a,b]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

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

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Costa [a,b,49], A. Di Mattia [a], A. Lapertosa [a], R. Potenza [a,b], A. Tricomi [a,b,49]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

P. Assiouras [a], G. Barbagli [a], G. Bardelli [a,b], B. Camaiani [a,b], A. Cassese [a], R. Ceccarelli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], T. Kello [a], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a], M. Meschini [a], S. Paoletti [a], A. Papanastassiou [a,b], G. Sguazzoni [a], L. Viliani [a]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Meola [50], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Alves Gallo Pereira [a], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

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

A. Benaglia [a], F. Brivio [a], F. Cetorelli [a,b], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a], G. Lavizzari [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], S. Palluotto [a,b], D. Pedrini [a], A. Perego [a,b], B.S. Pinolini [a], G. Pizzati [a,b], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

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

S. Buontempo [a], A. Cagnotta [a,b], F. Carnevali [a,b], N. Cavallo [a,c], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,51], P. Paolucci [a,29], B. Rossi [a]

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

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

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

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

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

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

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

C. Aimè [a], C.A. Alexe [a,c], P. Asenov [a,b], P. Azzurri [a], G. Bagliesi [a], R. Bhattacharya [a], L. Bianchini [a,b], T. Boccali [a], E. Bossini [a], D. Bruschini [a,c], R. Castaldi [a], M.A. Ciocci [a,b], M. Cipriani [a,b], V. D'Amante [a,d], R. Dell'Orso [a], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], A.C. Marini [a], D. Matos Figueiredo [a], A. Messineo [a,b], S. Mishra [a], V.K. Muraleedharan Nair Bindhu [a,b,40], M. Musich [a,b], S. Nandan [a], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], F. Vaselli [a,c], A. Venturi [a], P.G. Verdini [a]

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

P. Barria [a], C. Basile [a,b], F. Cavallari [a], L. Cunqueiro Mendez [a,b], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], F. Errico [a,b], R. Gargiulo [a,b], E. Longo [a,b], L. Martikainen [a,b], J. Mijuskovic [a,b], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a], V. Vladimirov [a,b]

[a] INFN Sezione di Roma, Roma, Italy
[b] Sapienza Università di Roma, Roma, Italy

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], C. Borca [a,b], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], L. Finco [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], F. Luongo [a,b], C. Mariotti [a], L. Markovic [a,b], S. Maselli [a],

A. Mecca [a,b], L. Menzio [a,b], P. Meridiani [a], E. Migliore [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], F. Siviero [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], C. Tarricone [a,b], D. Trocino [a], G. Umoret [a,b], R. White [a,b]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, Italy

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

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

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

Kyungpook National University, Daegu, Korea

M.S. Kim

Department of Mathematics and Physics – GWNU, Gangneung, Korea

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

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

E. Asilar, J. Choi [55], D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh, S. Yang

Kyung Hee University, Department of Physics, Seoul, Korea

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

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

S. Ha, K. Hwang, B. Kim, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Gharbia

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

F. Alazemi

Kuwait University – College of Science – Department of Physics, Safat, Kuwait

K. Dreimanis, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

Riga Technical University, Riga, Latvia

N.R. Strautnieks

University of Latvia (LU), Riga, Latvia

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

I. Yusuff [56], Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz [57], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

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

C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Universidad Iberoamericana, Mexico City, Mexico

I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, N. Raicevic

University of Montenegro, Podgorica, Montenegro

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

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

V. Avati, A. Bellora, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

AGH University of Krakow, Krakow, Poland

H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

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

P. Fokow, K. Pozniak, W. Zabolotny

Warsaw University of Technology, Warsaw, Poland

M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

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

P. Adzic, P. Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

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

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

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

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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

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

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

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

B. Kailasapathy[58], D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna[59], K. Liyanage, N. Perera

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

D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C.E. Brown, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, M. Magherini, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[61], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua[62], L. Caminada[62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[62], L. Noehte[62], T. Rohe, A. Samalan

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[61], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

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

C. Amsler[63], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

Universität Zürich, Zurich, Switzerland

C. Adloff[64], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[37]

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

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

Y. Maghrbi

Tunis El Manar University, Tunis, Tunisia

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[65], E. Eskut, Y. Guler[66], E. Gurpinar Guler[66], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[67], A. Polatoz, B. Tali[68], U.G. Tok, E. Uslan, I.S. Zorbakir

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

M. Yalvac[69]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], S. Tekten[72]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak[65,73], S. Sen[74]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek[75], B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Istanbul University, Istanbul, Turkey

S. Cerci, B. Isildak[77], D. Sunar Cerci, T. Yetkin

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev, B. Grynyov

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

L. Levchuk

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

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

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, TX, USA

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

Catholic University of America, Washington, DC, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[81], E. Usai, R. Yi

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Barone, G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[83], X. Shen, M. Stamenkovic, N. Venkatasubramanian

Brown University, Providence, RI, USA

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

University of California, Davis, Davis, CA, USA

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

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, G. Hanson

University of California, Riverside, Riverside, CA, USA

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

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

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

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

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

California Institute of Technology, Pasadena, CA, USA

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

Carnegie Mellon University, Pittsburgh, PA, USA

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

University of Colorado Boulder, Boulder, CO, USA

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

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

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

University of Florida, Gainesville, FL, USA

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

Florida State University, Tallahassee, FL, USA

B. Alsufyani, S. Butalla, S. Das, T. Elkafrawy[86], M. Hohlmann, E. Yanes

Florida Institute of Technology, Melbourne, FL, USA

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

University of Illinois Chicago, Chicago, IL, USA

M. Alhusseini, D. Blend, K. Dilsiz[87], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

The University of Iowa, Iowa City, IA, USA

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

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[91], C. Rogan, C. Royon, S. Sanders, C. Smith, G. Wilson

The University of Kansas, Lawrence, KS, USA

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

Kansas State University, Manhattan, KS, USA

A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[92], A. Shevelev, L. Wang, L. Zhang

University of Maryland, College Park, MD, USA

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

Massachusetts Institute of Technology, Cambridge, MA, USA

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

University of Minnesota, Minneapolis, MN, USA

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

University of Nebraska-Lincoln, Lincoln, NE, USA

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

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

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

Northeastern University, Boston, MA, USA

S. Dittmer, K.A. Hahn, D. Li, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

Northwestern University, Evanston, IL, USA

G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[22], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

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

The Ohio State University, Columbus, OH, USA

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

Princeton University, Princeton, NJ, USA

S. Malik, R. Sharma

University of Puerto Rico, Mayaguez, PR, USA

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

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar, A. Pathak

Purdue University Northwest, Hammond, IN, USA

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

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[92], R. Taus

University of Rochester, Rochester, NY, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash,

J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

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

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

University of Tennessee, Knoxville, TN, USA

D. Aebi, M. Ahmad, T. Akhter, K. Androsov[61], O. Bouhali[93], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, R. Mueller, D. Overton, A. Safonov

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

N. Akchurin, J. Damgov, Y. Feng, N. Gogate, Y. Kazhykarim, K. Lamichhane, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Texas Tech University, Lubbock, TX, USA

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

Vanderbilt University, Nashville, TN, USA

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

University of Virginia, Charlottesville, VA, USA

S. Bhattacharya, P.E. Karchin

Wayne State University, Detroit, MI, USA

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

University of Wisconsin – Madison, Madison, WI, USA

S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, O. Kodolova[95,92], V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[96], A. Nikitenko[97,95], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[†,98], A. Zarubin, I. Zhizhin, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin

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

G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[99], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†], T. Aushev, K. Ivanov, V. Gavrilov, N. Lychkovskaya, V. Popov, A. Zhokin, M. Chadeeva[99], R. Chistov[99], S. Polikarpov[99], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[84], L. Dudko, A. Gribushin, V. Klyukhin, O. Lukina, S. Petrushanko, V. Savrin, A. Snigirev, V. Blinov[99], T. Dimova[99], A. Kozyrev[99], O. Radchenko[99], Y. Skovpen[99], V. Kachanov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin

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

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Ghent University, Ghent, Belgium.
[4] Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[5] Also at FACAMP – Faculdades de Campinas, Sao Paulo, Brazil.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[8] Also at University of Chinese Academy of Sciences, Beijing, China.
[9] Also at China Center of Advanced Science and Technology, Beijing, China.
[10] Also at University of Chinese Academy of Sciences, Beijing, China.
[11] Also at China Spallation Neutron Source, Guangdong, China.
[12] Now at Henan Normal University, Xinxiang, China.
[13] Also at University of Shanghai for Science and Technology, Shanghai, China.
[14] Now at The University of Iowa, Iowa City, Iowa, USA.
[15] Also at an institute formerly covered by a cooperation agreement with CERN.
[16] Also at Cairo University, Cairo, Egypt.
[17] Also at Suez University, Suez, Egypt.
[18] Now at British University in Egypt, Cairo, Egypt.
[19] Also at Purdue University, West Lafayette, Indiana, USA.
[20] Also at Université de Haute Alsace, Mulhouse, France.
[21] Also at Istinye University, Istanbul, Turkey.
[22] Also at an international laboratory covered by a cooperation agreement with CERN.
[23] Also at The University of the State of Amazonas, Manaus, Brazil.
[24] Also at University of Hamburg, Hamburg, Germany.
[25] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[26] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[27] Also at Brandenburg University of Technology, Cottbus, Germany.
[28] Also at Forschungszentrum Jülich, Juelich, Germany.
[29] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[30] Also at HUN-REN ATOMKI – Institute of Nuclear Research, Debrecen, Hungary.
[31] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[32] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[33] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[34] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[35] Also at Punjab Agricultural University, Ludhiana, India.
[36] Also at University of Visva-Bharati, Santiniketan, India.
[37] Also at Indian Institute of Science (IISc), Bangalore, India.
[38] Also at Amity University Uttar Pradesh, Noida, India.
[39] Also at IIT Bhubaneswar, Bhubaneswar, India.
[40] Also at Institute of Physics, Bhubaneswar, India.
[41] Also at University of Hyderabad, Hyderabad, India.
[42] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[43] Also at Isfahan University of Technology, Isfahan, Iran.
[44] Also at Sharif University of Technology, Tehran, Iran.
[45] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[46] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[47] Also at Helwan University, Cairo, Egypt.
[48] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[49] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[50] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[51] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[52] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[53] Also at Lulea University of Technology, Lulea, Sweden.
[54] Also at Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy.
[55] Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[56] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[57] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[58] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[59] Also at Saegis Campus, Nugegoda, Sri Lanka.
[60] Also at National and Kapodistrian University of Athens, Athens, Greece.
[61] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[62] Also at Universität Zürich, Zurich, Switzerland.
[63] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[64] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[65] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[66] Also at Konya Technical University, Konya, Turkey.
[67] Also at Izmir Bakircay University, Izmir, Turkey.
[68] Also at Adiyaman University, Adiyaman, Turkey.
[69] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[70] Also at Marmara University, Istanbul, Turkey.
[71] Also at Milli Savunma University, Istanbul, Turkey.
[72] Also at Kafkas University, Kars, Turkey.
[73] Now at Istanbul Okan University, Istanbul, Turkey.
[74] Also at Hacettepe University, Ankara, Turkey.
[75] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[76] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[77] Also at Yildiz Technical University, Istanbul, Turkey.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at IPPP Durham University, Durham, United Kingdom.

[80] Also at Monash University, Faculty of Science, Clayton, Australia.
[81] Also at Università di Torino, Torino, Italy.
[82] Also at Bethel University, St. Paul, Minnesota, USA.
[83] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[84] Also at California Institute of Technology, Pasadena, California, USA.
[85] Also at United States Naval Academy, Annapolis, Maryland, USA.
[86] Also at Ain Shams University, Cairo, Egypt.
[87] Also at Bingol University, Bingol, Turkey.
[88] Also at Georgian Technical University, Tbilisi, Georgia.
[89] Also at Sinop University, Sinop, Turkey.
[90] Also at Erciyes University, Kayseri, Turkey.
[91] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[92] Now at another institute formerly covered by a cooperation agreement with CERN.
[93] Also at Texas A&M University at Qatar, Doha, Qatar.
[94] Also at Kyungpook National University, Daegu, Korea.
[95] Also at Yerevan Physics Institute, Yerevan, Armenia.
[96] Also at another international laboratory covered by a cooperation agreement with CERN.
[97] Also at Imperial College, London, United Kingdom.
[98] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[99] Also at another institute formerly covered by a cooperation agreement with CERN.