

Elliptic anisotropy measurement of the $f_0(980)$ hadron in proton-lead collisions and evidence for its quark-antiquark composition

The CMS Collaboration*

Abstract

Despite the $f_0(980)$ hadron having been discovered half a century ago, the question about its quark content has not been settled: it might be an ordinary quark-antiquark ($q\bar{q}$) meson, a tetraquark ($q\bar{q}q\bar{q}$) exotic state, a kaon-antikaon ($K\bar{K}$) molecule, or a quark-antiquark-gluon ($q\bar{q}g$) hybrid. This paper reports strong evidence that the $f_0(980)$ state is an ordinary $q\bar{q}$ meson, inferred from the scaling of elliptic anisotropies (v_2) with the number of constituent quarks (n_q), as empirically established using conventional hadrons in relativistic heavy ion collisions. The $f_0(980)$ state is reconstructed via its dominant decay channel $f_0(980) \rightarrow \pi^+\pi^-$, in proton-lead collisions recorded by the CMS experiment at the LHC, and its v_2 is measured as a function of transverse momentum (p_T). It is found that the $n_q = 2$ ($q\bar{q}$ state) hypothesis is favored over $n_q = 4$ ($q\bar{q}q\bar{q}$ or $K\bar{K}$ states) by 7.7, 6.3, or 3.1 standard deviations in the $p_T < 10, 8, \text{ or } 6 \text{ GeV}/c$ ranges, respectively, and over $n_q = 3$ ($q\bar{q}g$ hybrid state) by 3.5 standard deviations in the $p_T < 8 \text{ GeV}/c$ range. This result represents the first determination of the quark content of the $f_0(980)$ state, made possible by using a novel approach, and paves the way for similar studies of other exotic hadron candidates.

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1 The $f_0(980)$ puzzle and relativistic heavy ion collisions

One of the most intriguing puzzles in quantum chromodynamics (QCD), the theory describing the strong interaction, is the phenomenon of confinement. Confinement is the peculiar feature of the QCD color charges that they cannot be separated and are fatefully confined in color-neutral bound states known as hadrons. The mechanism for the color confinement is still not well understood. A hadron can be the usual quark-antiquark ($q\bar{q}$) meson or three-quark (qqq) baryon, but it has been suggested that there also exist less conventional, “exotic” forms, such as tetraquarks or meson molecules ($q\bar{q}q\bar{q}$), pentaquarks ($q\bar{q}qqq$), and dibaryons ($qqqqqq$) [1–3], where q stands for a constituent quark of any flavor. Studies of these exotic states can significantly advance our understanding of how partons can form bound states and in which configurations. This knowledge is fundamental for a deeper understanding of QCD, especially in its nonperturbative regime [4].

Exotic hadrons are expected to be short-lived and decay into ordinary hadrons, making it challenging to decipher their original parton structure. The first evidence of a tetraquark or a molecular state, $X(3872)$, was reported by the Belle experiment at KEK [5]. Experiments at the CERN LHC, particularly LHCb, have recently observed several new candidates for tetraquarks and pentaquarks, as discussed, e.g., in Ref. [6]. Those candidates all involve heavy quarks, which implies that their properties can be calculated in nonrelativistic QCD [7, 8].

However, similar calculations are hard to perform for hadrons built of only light quarks, as one has to use relativistic QCD in its nonperturbative regime. In particular, the $f_0(980)$ hadron, discovered 50 years ago [9–11], has been hypothesized to be an ordinary $q\bar{q}$ meson, a tetraquark state, a $K\bar{K}$ molecule, or a $q\bar{q}$ -gluon hybrid state [12–17]. The suggestion that the $f_0(980)$ hadron can be a tetraquark extends beyond the ground-state constituent quark model, and studies of such states would impact our understanding of QCD and color confinement. Despite a multitude of experimental and theoretical work, the nature of the $f_0(980)$ state has not yet been established, as is evident from Ref. [18] and references therein.

This is where high-energy nuclear collisions may come to the rescue. The collisions of lead-lead (PbPb) ions at the LHC aim to recreate the quark-gluon plasma (QGP), widely believed to be the state of matter prevailing in the early universe, when the temperature and energy density were too high to allow for the formation of hadrons. They offer a universal laboratory to study various aspects of QCD, such as the formation of hadrons from the QGP hadronization. A large number of hadron species, presumably including exotic ones, are abundantly produced during and following the phase transition from the QGP to hadronic matter. Indeed, evidence for the production of the $X(3872)$ exotic state in PbPb collisions was reported by the CMS experiment [19]. The QGP phase transition (hadronization), intimately connected to color confinement, is being extensively studied, both experimentally and theoretically. A viable way to describe hadronization is via the coalescence of quarks, now dressed with gluons over the phase transition, into hadrons. The coalescence model was initially proposed to describe the formation of deuterons in targets exposed to proton beams [20] and is now commonly used to model hadronization in relativistic nuclear collisions [21–25].

In heavy ion collisions, the azimuthal distribution of produced particles is anisotropic. The anisotropy is believed to result from the interactions among quarks and gluons created in these collisions, converting the initial approximately elliptical (“almond-like”) overlap region of the colliding nuclei with a nonzero impact parameter into the anisotropy of particle momenta [26]. It is noteworthy that the collision geometry anisotropy is generic and also present in head-on heavy ion collisions, as well as in proton-proton (pp) and proton-nucleus collisions, arising from fluctuations in the distribution of constituents inside the colliding objects. While

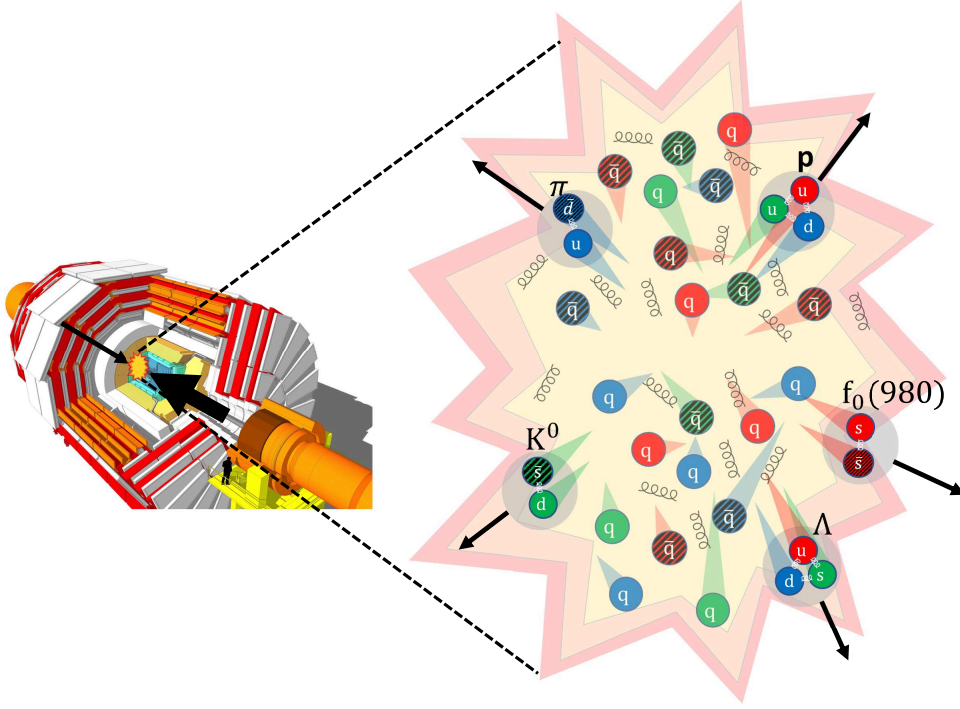


Figure 1: **Coalescence hadronization.** This picture illustrates the formation of hadrons in heavy ion collisions in the coalescence model. Hadrons tend to form when the constituent quarks have similar positions and momenta.

it initially came as a surprise when momentum anisotropy was first observed in pp [27–30] and proton-lead (pPb) [31–38] collisions, it is by now a well-established fact. This momentum anisotropy of quarks is then inherited by the formed hadrons, thus providing information that can be used to experimentally determine the quark content of the hadrons [39], as explained below. Since the anisotropy has been established at the LHC energies in PbPb, pPb, and even pp collisions with high multiplicity of particles produced, any of these colliding systems can be used for this type of measurements.

Azimuthal distributions of particles are often described by a Fourier series [40],

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi_n)], \quad (1)$$

where ϕ is the azimuthal angle of the particle momentum vector and ψ_n is the azimuthal angle of the n th harmonic plane, defined in each event such that $\sum_i \sin[n(\phi_i - \psi_n)] = 0$, where the index i runs over all particles in an event. Details on the reconstruction of the harmonic planes using event observables are given in the Methods section. The coefficients v_n , called anisotropic flow parameters, generally depend on the particle transverse momentum (p_T) and rapidity (y). The v_2 coefficient, called the elliptic flow, describes the dominant anisotropic component. The second-order harmonic plane angle ψ_2 is an approximation of the azimuthal angle of the reaction plane, which is defined by the line connecting the centers of the colliding nuclei and the beam line.

In the coalescence picture, illustrated in Fig. 1, quarks with close spatial positions and momenta are more likely to combine and, therefore, the anisotropic flow coefficients v_n of the formed hadron inherit those of the parent quarks ($v_{n,q}$). If n_q quarks with approximately equal

momenta combine to form a hadron, the resulting azimuthal distribution is then given by

$$\frac{dN_h}{d\phi} \propto \left(\frac{dN_q}{d\phi} \right)^{n_q} \propto \left[1 + \sum_{n=1}^{\infty} 2v_{n,q}(p_T^q) \cos(n[\phi - \psi_n]) \right]^{n_q}, \quad (2)$$

where $p_T^q = p_T/n_q$, and N_h (N_q) is the multiplicity of hadrons (quarks). For small values of v_n , relevant for the measurement reported in this paper, one can simplify Eq. (2) as

$$v_n(p_T) \approx n_q v_{n,q}(p_T/n_q).$$

This expression is commonly referred to as the number of constituent quarks (NCQ) scaling of the anisotropic flow [41]. The anisotropic flow of hadrons formed in heavy ion collisions can therefore reveal the number of constituent quarks n_q contained in a hadron, conventional or exotic [39]. Alternatively, such information can also be extracted by measuring the yields and p_T spectra (or their ratios) of these hadrons in heavy ion collisions, albeit in a more model-dependent way [42–45].

The NCQ scaling has been observed to approximately hold for common hadrons in heavy ion collisions at the BNL RHIC [46, 47] and at the CERN LHC [36, 48, 49]. It has also been established in pPb collisions at the LHC by the CMS experiment for K_S^0 , Λ , Ξ^- , and Ω hadrons [36, 50]. These observations of the NCQ scaling support the validity of the coalescence hadronization model, at least at low p_T . We note that the NCQ scaling may additionally arise from other mechanisms in the same or an extended p_T range. The empirical observations of the NCQ scaling do not depend, however, on a particular underlying physics mechanism.

This paper presents the first measurement of the elliptic flow of the $f_0(980)$ state. Data from pPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 8.16$ TeV are used. The choice of pPb collisions used in this measurement is driven by the smaller combinatorial background than in PbPb collisions, which simplifies the $f_0(980)$ signal extraction. The elliptic flow coefficient v_2 of the $f_0(980)$ state is determined as a function of p_T . The NCQ scaling of the $f_0(980)$ hadron v_2 coefficient is tested, under the $n_q = 2$ and 4 hypotheses, as well as under the $n_q = 3$ hypothesis, which is expected to be characteristic of a hybrid state. The numeric values from various figures presented in this paper can be found in the HEPData database [51].

2 The CMS detector and data analysis

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For nonisolated particles of $1 < p_T < 10$ GeV/c and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [52]. The procedure followed for aligning the detector is described in Ref. [53].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [54]. The second level, known as the high-level trigger, consists of a farm of processors running a version of

the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [55]. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [56, 57].

In this paper, the $f_0(980)$ state is measured in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV using a high-multiplicity data sample collected in 2016, corresponding to an integrated luminosity of 186 nb^{-1} [55]. The charged-particle multiplicity range is chosen to be $185 \leq N_{\text{trk}} < 250$. The N_{trk} multiplicity observable is defined in Ref. [50] and its range is chosen to be identical to the one used in that measurement, where significant anisotropic flow has been observed and to which we compare the NCQ scaling of the $f_0(980)$ measurement. The triggers and event selections are identical to those in Ref. [58], as discussed in more detail in the Methods section. The $f_0(980)$ state is reconstructed within the rapidity $|y| \lesssim 2.4$ via its dominant decay channel, $f_0(980) \rightarrow \pi^+ \pi^-$ [18]. The pion mass is assigned to all charged-particle tracks. The combinatorial background is modeled via same-charge-sign pion track pairs and subtracted from the opposite-charge-sign dipion mass spectrum. The resulting distribution is then fit to extract the $f_0(980)$ yield, as shown in Fig. 5, in the Methods section, along with the χ^2 of the fit per degree of freedom (dof). The fit model includes a sum of three Breit–Wigner functions [59–62] corresponding to the $f_0(980)$, $\rho(770)^0$, and $f_2(1270)$ resonances, and a third-order polynomial for the residual background. The observed elliptic flow v_2 of the $f_0(980)$ state is extracted by fitting the yield as a function of ϕ . The contamination from nonflow correlations—those unrelated to the nuclear collision geometry—is subtracted. After nonflow-contamination subtraction, the elliptic flow coefficient is denoted by v_2^{sub} . More details can be found in the Methods section.

In order to compare the $f_0(980)$ v_2^{sub} values to the established NCQ scaling for other hadrons, the $v_{n,q}$ of K_S^0 , Λ , Ξ^- , and Ω states measured in the same high-multiplicity range are fit with the following function:

$$f(KE_T/n_q) = KE_T/n_q \left(p_0 + p_1 KE_T/n_q \right) e^{-p_2 KE_T/n_q}. \quad (3)$$

The argument of the function, KE_T/n_q , is related to the kinetic energy per constituent quark, where $KE_T = \sqrt{m^2 + \langle p_T \rangle^2} - m$, $\langle p_T \rangle$ is the average p_T of the corresponding bound state, and m is its invariant mass. The $f_0(980)$ $\langle p_T \rangle$ value is obtained from an exponential fit to the $f_0(980)$ candidate dN/dp_T distribution. The NCQ scaling fit is based on the minimization of the χ^2 , assuming that the bin-by-bin uncertainties are uncorrelated, with the coefficients p_i ($i = 0, 1, 2$) being free parameters of the fit. Details about the n_q extraction and about testing of various quark content hypotheses can be found in the Methods section.

3 Systematic uncertainties

Systematic uncertainties in the $f_0(980)$ v_2 and v_2^{sub} are detailed in the Methods section. The correlation of systematic uncertainties between different p_T bins is taken into account by using a covariance matrix in the χ^2 calculation when extracting n_q . The statistical uncertainty in the $f(KE_T/n_q)$ fit is also included as a systematic uncertainty component in the extracted n_q . The n_q extraction procedure is repeated for variations in the functional form of $f(KE_T/n_q)$, as well as by using p_T instead of E_T in the NCQ scaling expression given by Eq. (3). The resulting difference in n_q from the default value is taken as the corresponding systematic uncertainty. The systematic uncertainties are listed in Table 1. The uncertainty in the $\langle p_T \rangle$ of the $f_0(980)$ state has a negligible impact on n_q .

Table 1: Sources and magnitudes of the uncertainties in the extracted n_q of the $f_0(980)$ state in the range $p_T < 10 \text{ GeV}/c$.

Source	n_q uncertainty
Statistical	0.16
$f_0(980)$ v_2 systematic uncertainty	0.13
Nonflow effects in v_2^{sub}	0.04
NCQ scaling fit parameters	0.02
NCQ scaling fit function	0.04
NCQ scaling using p_T/n_q	0.06

4 Elliptic anisotropy results and the $f_0(980)$ quark content

Figure 2 shows the v_2^{sub} of the $f_0(980)$ state, which is significantly above zero and exhibits a clear trend of rising and then falling with p_T , reaching a maximum in the $4 < p_T < 6 \text{ GeV}/c$ range. Such a trend in p_T has been also observed for other hadrons and is generally considered to come from an interplay between the hydrodynamic expansion at low p_T and partonic energy loss at high p_T .

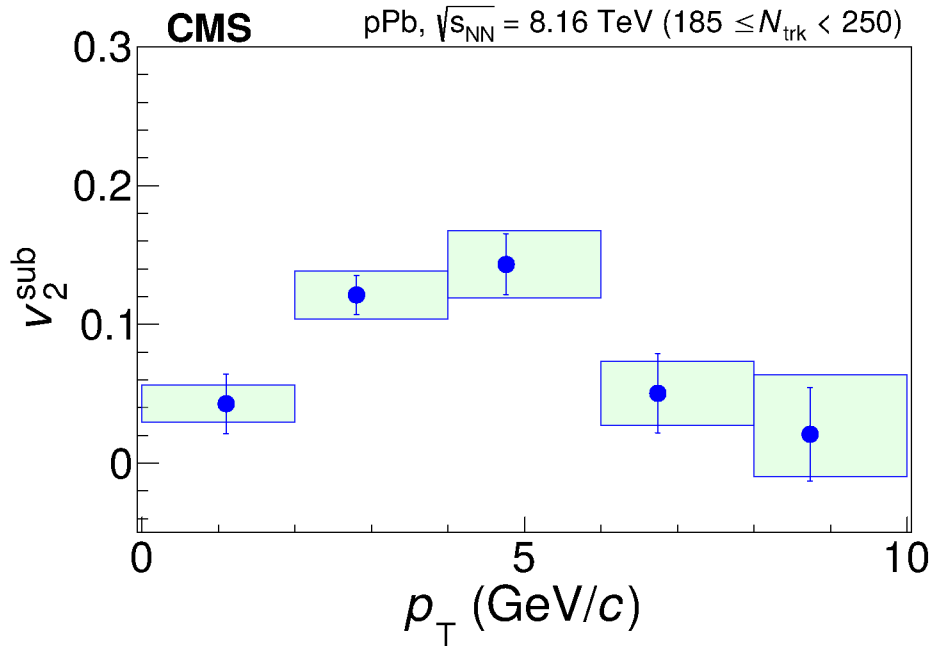


Figure 2: **Elliptic anisotropy results.** The nonflow-effect-subtracted elliptic anisotropy v_2^{sub} of the $f_0(980)$ is shown as a function of p_T within $|y| \lesssim 2.4$ in high-multiplicity pPb collisions. The error bars show statistical uncertainties while the shaded areas represent systematic uncertainties.

Figure 3 shows a comparison of v_2^{sub}/n_q for the $f_0(980)$ state with those of K_S^0 , Λ , Ξ^- , and Ω hadrons [50] as a function of KE_T/n_q . (A similar comparison for $v_{2,q}$ as a function of p_T/n_q can be found in the Methods section.) The two sets of the $f_0(980)$ data points correspond to the $n_q = 2$ and 4 hypotheses. The red curve shows the NCQ scaling parameterization of the v_2^{sub} data for these other hadrons (whose n_q values are fixed by their known quark content).

To assess the significance of the result, the log-likelihood ratio $-2 \ln(L_{n_q=4}/L_{n_q=2})$ is calculated using the v_2^{sub}/n_q data and the NCQ scaling expectation between the $n_q = 2$ and 4 assump-

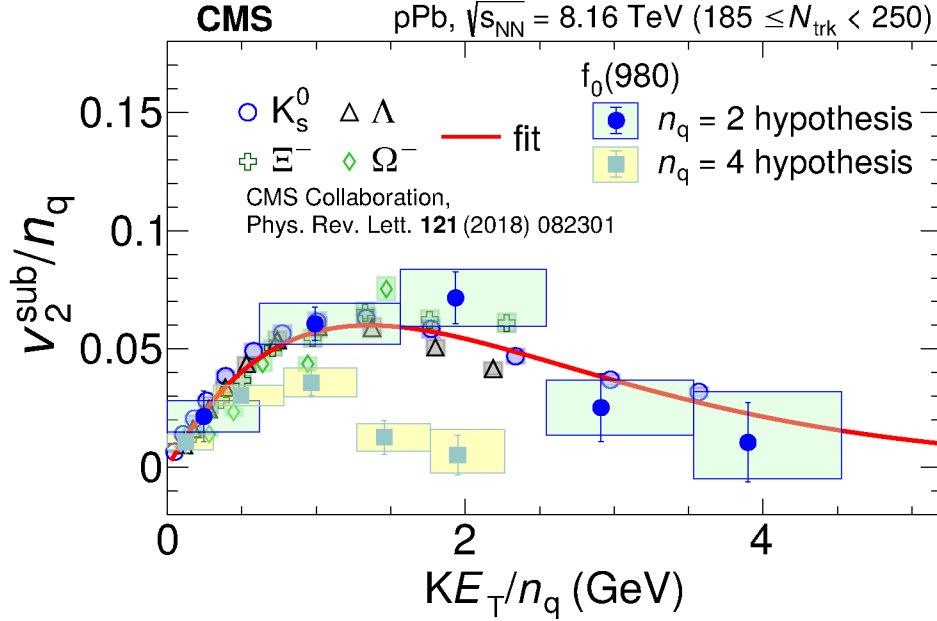


Figure 3: **NCQ scaling of elliptic anisotropy.** The v_2^{sub}/n_q of the $f_0(980)$ state (for the $n_q = 2$ and 4 hypotheses) as a function of KE_T/n_q , compared with those of K_S^0 , Λ , Ξ^- , and Ω^- strange hadrons [50] in high-multiplicity pPb collisions. The error bars show statistical uncertainties while the shaded areas represent systematic uncertainties. The red curve is the NCQ scaling parameterization of the data for K_S^0 , Λ , Ξ^- , and Ω^- hadrons given by Eq. (3).

tions. Details about the log-likelihood ratio can be found in the Methods section. The measured value is shown by the red arrow in Fig. 4, together with the distributions of the log-likelihood ratio from pseudo-experiments. The $f_0(980)$ v_2^{sub} values are generated according to the NCQ scaling under the $n_q = 2$ and 4 hypotheses, with a Gaussian smearing to account for the uncertainties. The extracted significance of the $n_q = 2$ hypothesis over the $n_q = 4$ hypothesis is 7.7σ in the $p_T < 10$ GeV/c range. As shown in Fig. 3, the NCQ scaling range as delineated by the K_S^0 data extends up to p_T/n_q of 4 GeV/c, whereas for the baryons it is restricted to about 2.5 GeV/c. For the $n_q = 2$ hypothesis, our high- p_T data start falling out of the measured NCQ scaling p_T/n_q range; for the $n_q = 4$ hypothesis, however, our data are within that range. Consequently, we extract significance values also for two restricted- p_T ranges: $p_T < 8$ and 6 GeV/c. The exclusion significances of the $n_q = 4$ vs. 2 hypotheses in these ranges are 6.3 and 3.1σ , respectively.

The $K\bar{K}$ molecule, if produced by the coalescence of two kaons, would possess the same v_2 as that of a tetraquark, and is thus practically also ruled out. It is unclear what v_2 a hybrid $q\bar{q}g$ state would attain in pPb collisions because the NCQ scaling has been tested only with ordinary hadrons. If the constituent gluon behaves just like the constituent (anti)quarks, the v_2 of a hybrid $q\bar{q}g$ state would scale as $n_q = 3$. Such a state would be ruled out with a 3.5σ significance using the $p_T < 8$ GeV/c range, in which the NCQ scaling is adequately measured for the $n_q = 3$ case.

The χ^2 quantity is calculated between the v_{n_q} data of the $f_0(980)$, with floating n_q , and the NCQ curve in KE_T/n_q in Fig. 3, with the covariance matrix taking into account correlations among uncertainties. Scans of χ^2 versus n_q are performed, as detailed in the Methods section. Using $f_0(980)$ data within the $p_T < 6$ GeV/c range (a conservative choice, which ensures that the NCQ scaling holds for the $n_q = 2$ hypothesis, given that $p_T/n_q < 3$ GeV/c), the preferred

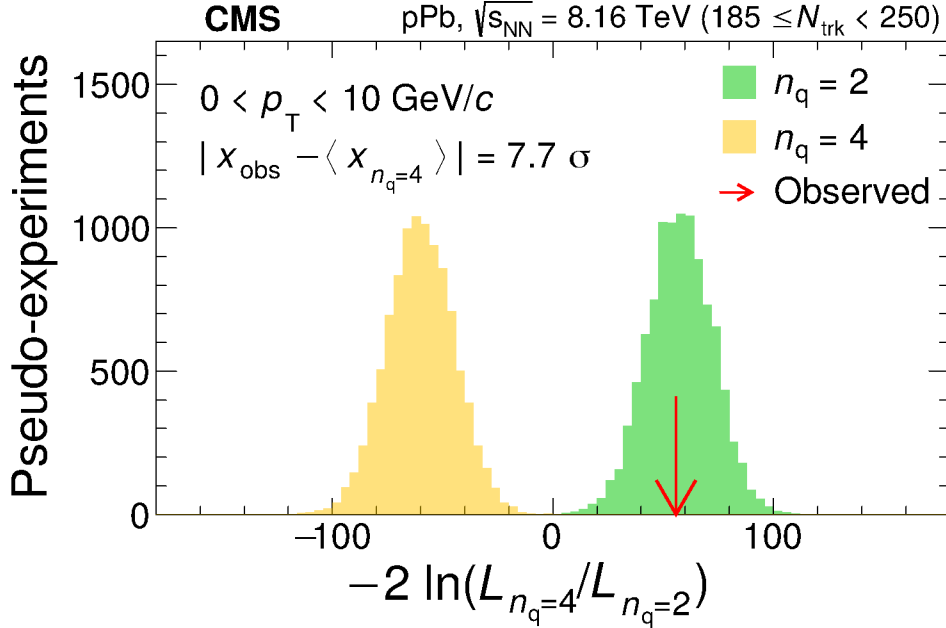


Figure 4: **Exclusion significance from $n_q = 4$.** The log-likelihood ratio distributions for the $n_q = 2$ and 4 hypotheses from pseudo-experiments, together with the measured value for the $f_0(980)$ state in the $0 < p_T < 10 \text{ GeV}/c$ range.

n_q value of the $f_0(980)$ is found to be $n_q = 2.40 \pm 0.40$. Assuming the NCQ scaling extends beyond $p_T/n_q \sim 3 \text{ GeV}/c$, the preferred n_q values of 2.10 ± 0.24 and 2.07 ± 0.21 are extracted in the $p_T < 8$ and $10 \text{ GeV}/c$ ranges, respectively. Indeed, the $n_q = 2$ hypothesis for $f_0(980)$ is consistent with the NCQ scaling from the other hadrons, with $\chi^2 = 4.7$ for the 5 data points. Contrary to that, the $n_q = 4$ hypothesis is inconsistent with the data, as evident from the corresponding $\chi^2 = 58$, with a Gaussian p -value of 3×10^{-11} . Consequently, we report a strong evidence for the $q\bar{q}$ quark content of the $f_0(980)$ state.

5 Summary

The $f_0(980)$ state is observed in the $\pi^+\pi^-$ invariant mass distribution of high-multiplicity proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$, using data collected by the CMS experiment in 2016 and corresponding to an integrated luminosity of 186 nb^{-1} . The elliptic flow anisotropy v_2 of the $f_0(980)$ state is measured as a function of p_T up to $10 \text{ GeV}/c$, with respect to the second-order harmonic plane reconstructed from forward/backward energy flow. After subtracting the non-flow contamination, evaluated from K_S^0 measurements, we obtain the corrected v_2^{sub} observable. By comparing the $f_0(980)$ v_2^{sub} to those of K_S^0 , Λ , Ξ^- , and Ω under the number-of-constituent-quarks scaling hypothesis, we rule out the hypotheses that the $f_0(980)$ is a tetraquark state or a $K\bar{K}$ molecule, in favor of an ordinary $q\bar{q}$ meson hypothesis, at 7.7 standard deviations (6.3 or 3.1 standard deviations, respectively, if only a restricted range of $p_T < 8$ or $6 \text{ GeV}/c$ is considered). The $f_0(980)$ data in the $p_T < 8 \text{ GeV}/c$ range are found to disfavor a quark-antiquark-gluon hybrid state at 3.5 standard deviations. The number of constituent quarks of the $f_0(980)$ state, as extracted from a fit to the v_2^{sub} data, is consistent with the value of 2, characteristic of an ordinary meson. Consequently, we find strong evidence that the $f_0(980)$ hadron is a normal quark-antiquark state. We believe that the results reported in this paper present a clear solution to a half-a-century-old puzzle.

The experimental determination of the quark content of the $f_0(980)$ state with high confidence, using this novel approach, is expected to stimulate further experimental investigations as well as theoretical studies. It paves the way for studies of other exotic hadron candidates using the collective flow scaling approach in high-multiplicity proton-nucleus and heavy ion collisions.

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A Methods

In this section we provide experimental details of various steps used in the analysis presented in this paper.

A.1 Trigger

Events of interest were selected using a suite of triggers based on particle multiplicity. At level-1, where tracking information is not available, the events were seeded using a tower count in the ECAL and HCAL barrel calorimeters, by selecting events passing a minimum threshold on the number of active towers. An active tower is defined as a trigger tower with a transverse energy exceeding 0.5 GeV. Trigger towers are built by summing energy deposits in the ECAL and HCAL cells in $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ regions (matching the size of one HCAL cell in the

barrel region). The trigger required the tower count to exceed either 115 or 120, depending on the data-taking period.

Several high-level triggers based on the multiplicity of tracks reconstructed either in the pixel detector layers or the full tracker were used for the analysis. The events were first selected requiring more than 125 tracks with $p_T > 0.4 \text{ GeV}/c$, $|\eta| < 2.4$, and the distance of closest approach along the beam axis between the track and the interaction vertex of less than 0.12 cm, reconstructed using only the pixel detector. Further, the events were required to have more than 185 tracks reconstructed in the full tracker with the same p_T and $|\eta|$ requirements, and with the distance of closest approach less than 0.15 cm. The interaction vertex is required to be within 15 cm of the detector center along the beam direction. Offline, we require the number of reconstructed tracks, N_{trk} , to be between 185 and 250. The trigger turn-on effect has been shown to have a negligible impact on the result.

A.2 Event selection and reconstruction of the $f_0(980)$ signal

The $f_0(980)$ candidates are reconstructed through the dominant decay channel, $f_0(980) \rightarrow \pi^+\pi^-$ [18]. All charged-particle tracks with $p_T > 0.4 \text{ GeV}/c$ and $|\eta| < 2.4$ passing standard high-purity requirements [52], and with a distance of closest approach to the interaction vertex divided by its uncertainty of less than 3 in both the direction along the beams and in the plane perpendicular to it, are considered as pion candidates. To improve the mass resolution, we only consider tracks with a relative uncertainty in p_T of less than 10%. The $f_0(980)$ candidates are formed from pairs of tracks of opposite-charge-sign, with the charged pion mass assigned to both. The combinatorial background is estimated from same-charge-sign track pairs and is subtracted from the invariant mass spectrum of the $f_0(980)$ candidates. The spectrum is further corrected for the tracking efficiency as a function of the track p_T and η , as obtained via a HIJING v1.0 simulation [63] followed by the CMS detector response simulation with GEANT4 [64]. The analysis is performed in bins of $\phi - \psi_2$, the azimuthal angle of the $f_0(980)$ candidate relative to that of the second harmonic plane. The latter is reconstructed from the energy deposition in the HF calorimeter in the Pb-going direction (resulting in a better resolution compared to that using the opposite HF calorimeter) and corrected for the nonuniform detector performance by using the procedure described in Ref. [40]. Figure 5 shows an example of the invariant mass spectrum of the $f_0(980)$ candidates within a p_T range of 4–6 GeV/ c and a $\phi - \psi_2$ range of $0-\pi/12$ (where the $\phi - \psi_2$ value is first folded from the full range into the $0-\pi/2$ range to decrease the statistical uncertainty per $\phi - \psi_2$ bin).

Several resonances are evident in the mass spectrum shown in Fig. 5, including a significant $f_0(980)$ peak at $\sim 0.98 \text{ GeV}/c^2$. The mass spectrum is fit with a template composed of three Breit–Wigner functions corresponding to the $\rho(770)^0$, $f_0(980)$, and $f_2(1270)$ resonances, and a third-order polynomial to model the residual background. The fit mass range is chosen to be 0.8–1.7 GeV/ c^2 in order to exclude the contribution from a $\rho(1700)$ peak at high masses and to avoid the low-mass region ($< 0.8 \text{ GeV}/c^2$) exhibiting a nontrivial turn-on behavior. Since only the right tail of the $\rho(770)^0$ resonance is included in the fit, the extrapolated peak into the lower mass region does not necessarily represent the true shape of the $\rho(770)^0$ resonance. The ϕ -integrated mass spectrum is fit in each p_T interval to obtain the $f_0(980)$ yield and the line-shapes of the three resonances present within the fit window. The resonant line-shapes are then fixed and the fit of the mass spectrum is repeated in six individual $\phi - \psi_2$ bins in the corresponding p_T interval, treating the resonance yields as free parameters.

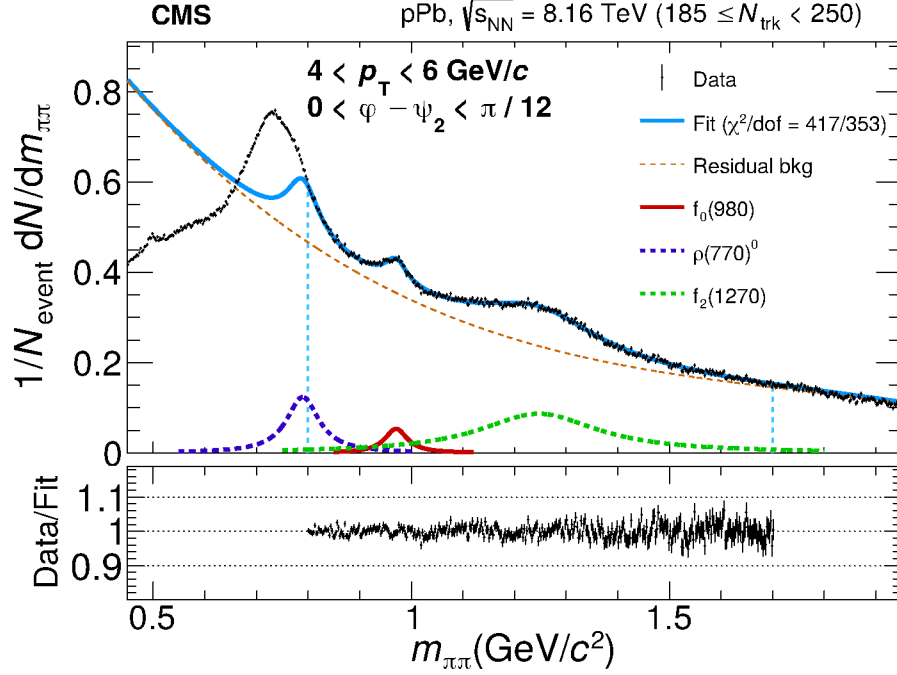


Figure 5: **Invariant mass fit.** The invariant mass spectrum of opposite-sign pion pairs after the combinatorial background subtraction, for the pair transverse momentum $4 < p_T < 6 \text{ GeV}/c$ and the azimuthal angle $0 < \phi - \psi_2 < \pi/12$, in high-multiplicity pPb collisions. The solid blue curve is the fit result within the fit range marked with vertical blue dashed lines; the orange dashed curve represents the residual background. The solid red curve represents the $f_0(980)$ signal, while the dashed dark-violet and light-green curves correspond to the background contributions from the $\rho(770)^0$ and $f_2(1270)$ resonances, respectively. The ratio between data and the fit result is shown in the lower panel, with the error bars representing statistical uncertainties only. The low-mass region exhibits a nontrivial turn-on behavior and is not included in the fit.

A.3 Extraction of $f_0(980)$ elliptic anisotropy v_2 values

Figure 6 shows the $f_0(980)$ yield as a function of $\phi - \psi_2$ in the $4 < p_T < 6 \text{ GeV}/c$ bin as an example. The $f_0(980)$ yield as a function of $\phi - \psi_2$ is fit with Eq. (1) with only the $n = 2$ term to extract the v_2 parameter. The fitted v_2 values are corrected for the harmonic plane resolution, which represents the precision of the reconstructed ψ_2 . The resolution is obtained by the subevent method [40] and evaluated in each fine multiplicity interval, and an average resolution is obtained weighted by the corresponding ϕ -integrated yield of $f_0(980)$. Figure 7 shows the corrected v_2 of the $f_0(980)$ as a function of p_T .

The v_2 measurement is contaminated by nonflow correlations, such as back-to-back jet pairs, where an $f_0(980)$ candidate is found within a jet and the harmonic plane is reconstructed from hadrons that include the other fragments of the dijet system. Since $f_0(980)$ is a hadron known to likely contain strange quarks, the relative nonflow contribution $(v_2 - v_2^{\text{sub}})/v_2$ to the $f_0(980)$ v_2 is assumed to be the same as that for the K_S^0 meson, in each p_T bin, where v_2^{sub} represents the elliptic flow after nonflow-effect subtraction. The latter, evaluated using events with low track multiplicity [50], is fit with a second-order polynomial as a function of p_T . The relative nonflow contribution to the $f_0(980)$ v_2 is evaluated from the fit function at the $\langle p_T \rangle$ in each p_T bin and ranges 9–64% for different p_T bins. The nonflow effects are subtracted to obtain the final v_2^{sub} of the $f_0(980)$ state. The v_2^{sub} of the $f_0(980)$ is shown in Fig. 2 as a function of p_T .

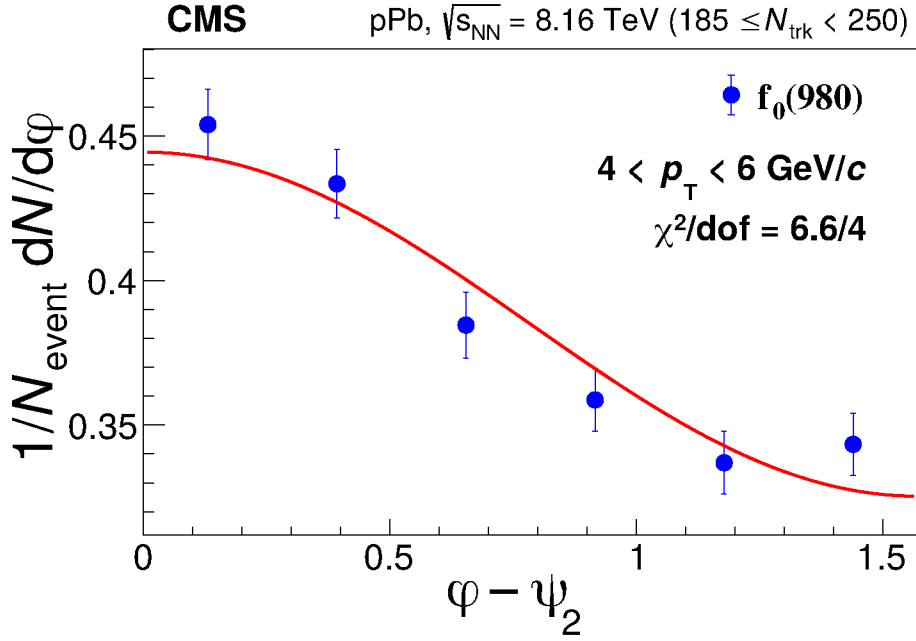


Figure 6: **Extraction of the elliptic anisotropy v_2 parameter.** The $f_0(980)$ yield in the $4 < p_T < 6$ GeV/c range as a function of $\phi - \psi_2$ in high-multiplicity pPb collisions. Error bars show statistical uncertainties. The red curve is a fit to Eq. (1) with only the $n = 2$ term.

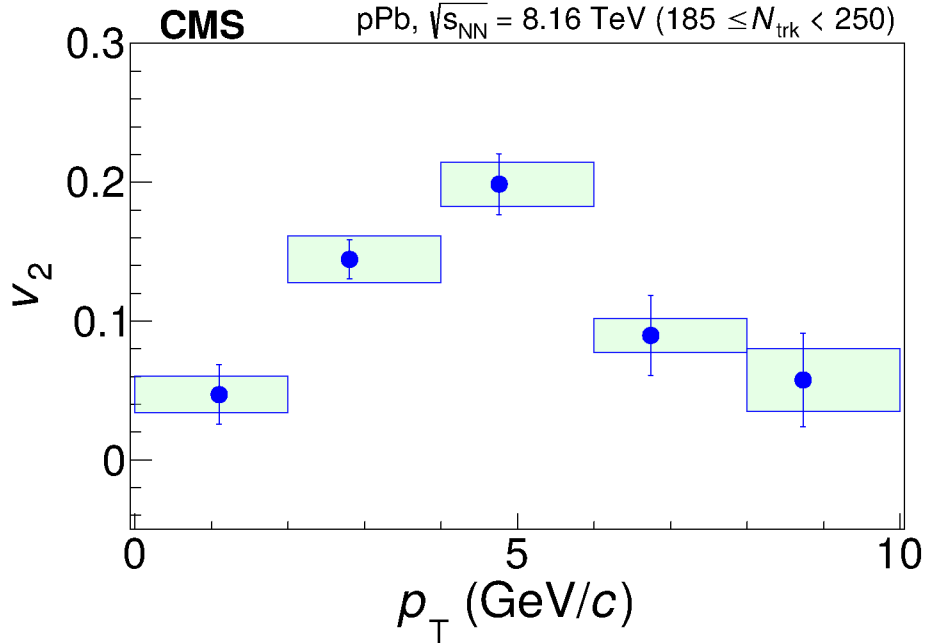


Figure 7: **Elliptic anisotropy before the nonflow effect subtraction.** The elliptic anisotropy v_2 of the $f_0(980)$ state is shown as a function of p_T within rapidity $|y| \lesssim 2.4$ in high-multiplicity pPb collisions. The error bars show statistical uncertainties while the shaded areas represent systematic uncertainties.

The NCQ-scaled v_2^{sub}/n_q as a function of p_T/n_q is shown in Fig. 8 for the $f_0(980)$ state together with those of the K_S^0 , Λ , Ξ^- , and Ω hadrons [50].

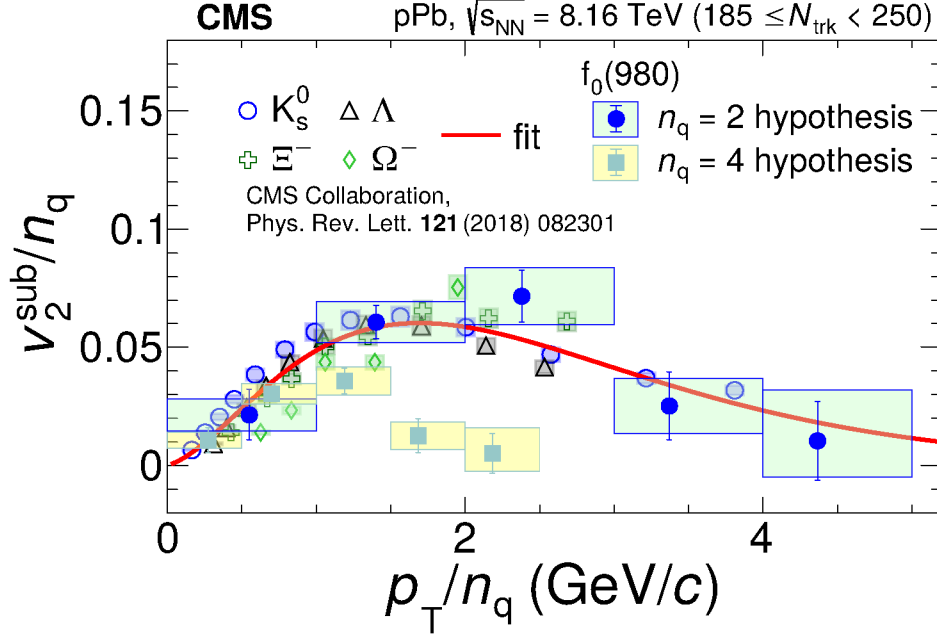


Figure 8: **NCQ scaling of elliptic anisotropy in p_T/n_q .** The v_2^{sub}/n_q of the $f_0(980)$ state (for the $n_q = 2$ and 4 hypotheses) as a function of p_T/n_q is compared with those of the K_S^0 , Λ , Ξ^- , and Ω strange hadrons [50] in high-multiplicity pPb collisions. Error bars show the statistical uncertainties while the shaded areas represent systematic uncertainties. The red curve is the NCQ scaling parameterization of the data for the K_S^0 , Λ , Ξ^- , and Ω hadrons.

A.4 Systematic uncertainties in $f_0(980)$ v_2 values

The systematic uncertainties in the $f_0(980)$ yield, and consequently those in the $f_0(980)$ v_2 values, include those from track selection, track efficiency correction, combinatorial background subtraction, residual background parameterization, resonance line-shape modeling, fit range choice, and the harmonic plane resolution. They are summarized in Table 1 and are evaluated as follows.

- Looser and tighter criteria of track selection are applied and the obtained $f_0(980)$ v_2 results are compared to the default ones, all of which are not corrected for track efficiencies. The uncertainty is 3–22% in the $f_0(980)$ v_2 value, depending on p_T .
- There could be a difference in the detector response between the same-charge-sign and opposite-charge-sign pairs in the same event. To assess this systematic uncertainty, the default combinatorial background spectrum from same-sign pairs is scaled by the ratio of opposite- to same-sign spectra from mixed events (i.e., when the two tracks forming a pair are taken from different events). The effect on the $f_0(980)$ v_2 values is smaller than 3%.
- The residual background is parameterized by second-, fourth-, and fifth-order polynomials besides the default third-order one. The corresponding systematic uncertainty in v_2 is found to be less than 5%.
- The resonance mass peaks are alternatively modeled via a relativistic Breit-Wigner function [65] and a relativistic Voigt function [66], which yields a systematic uncer-

tainty in v_2 of less than 2%, except in the highest measured p_T interval, where it reaches 25%. The default fit range (0.8–1.7 GeV/ c^2) is varied by 0.02 GeV/ c^2 on each side and gives a systematic uncertainty in v_2 of less than 8%.

- The statistical uncertainty in the harmonic plane angle extraction is propagated to the $f_0(980)$ v_2 and treated as a systematic uncertainty, of approximately 6%.
- An alternative way to estimate the nonflow contribution to the $f_0(980)$ v_2 is by assuming that the absolute nonflow contribution $v_2 - v_2^{\text{sub}}$, instead of the relative $(v_2 - v_2^{\text{sub}})/v_2$ contribution, at a given p_T , is the same as that of the K_S^0 meson. The difference between the $f_0(980)$ v_2^{sub} estimates obtained with the alternative and default methods is treated as the systematic uncertainty in the nonflow-effect subtraction, which is further symmetrized using the larger of the negative and positive variations. The resultant systematic uncertainty band in v_2^{sub} is then capped between the measured v_2 value and zero, ranging from 1% to 33%, depending on p_T .
- We have also examined the nonflow contribution using D^0 and Λ data instead of K_S^0 data. Moreover, we have compared the uncorrected v_2 distribution of the $f_0(980)$ to those of the K_S^0 , Λ , Ξ^- , and Ω hadrons. The variations observed in these cross-checks are shown to be fully covered by the systematic uncertainty detailed in the previous item.

These various sources of systematic uncertainties are assumed to be independent of each other. The statistical uncertainty is treated as uncorrelated for different p_T bins. The systematic uncertainty arising from the event plane resolution is assumed to be fully correlated between the p_T bins. For each of the other systematic uncertainties, the v_2^{sub} covariance matrix element for the i th and j th p_T bins is calculated as

$$\sigma_{i,j} = \frac{1}{N_{\text{alt}}} \sum_{k=1}^{N_{\text{alt}}} \left(v_{2,k}^{\text{sub}}(p_{T,i}) - v_{2,\text{default}}^{\text{sub}}(p_{T,i}) \right) \left(v_{2,k}^{\text{sub}}(p_{T,j}) - v_{2,\text{default}}^{\text{sub}}(p_{T,j}) \right), \quad (4)$$

where N_{alt} is the number of alternative methods to extract this systematic uncertainty and $v_{2,\text{default}}^{\text{sub}}$ is the default value. The overall covariance matrix of the v_2^{sub} is the sum of the covariance matrices corresponding to the various systematic uncertainties. The uncertainty in the $\langle p_T \rangle$ evaluation is estimated using pseudo-experiments and is found to be negligible.

A.5 Cross-checks of the NCQ scaling assumption

The uncertainty used in the parametrization of Eq. (3) of the v_2^{sub}/n_q data for the K_S^0 , Λ , Ξ^- , and Ω hadrons is the combined statistical and systematic uncertainties of the fit added in quadrature. The resulting best fit parameters are: $p_0 = 0.111 \pm 0.004$, $p_1 = 0.045 \pm 0.017$, and $p_2 = -1.00 \pm 0.08$. The fit yields a relatively large $\chi^2/\text{dof} = 80/34$, which indicates that the NCQ scaling is not perfect. To accommodate for this, we increased the uncertainties to achieve the χ^2/dof of 1 and found the effect on the n_q result to be negligible.

To extract the n_q of $f_0(980)$, the χ^2 of the $f_0(980)$ v_2^{sub}/n_q data (denoted by \vec{y}) with respect to the NCQ scaling curve (denoted by \vec{f}) is calculated by $\chi^2 = (\vec{y} - \vec{f})^T (C_y + C_f)^{-1} (\vec{y} - \vec{f})$, where C_y is the $f_0(980)$ v_2^{sub} covariance matrix scaled by $1/n_q^2$ and C_f is the covariance matrix of the NCQ scaling function from the fit to the $f_0(980)$ v_2^{sub}/n_q data. The latter is given by $C_f = J \cdot C_p \cdot J^T$, where C_p is the covariance matrix of the fit parameters and $J = \partial f / \partial \vec{p}$ is the Jacobian matrix that describes how the fit function value changes with the fit parameters \vec{p} .

Scans of χ^2 as a function of n_q , treated as a continuous parameter, between the $f_0(980)$ v_2^{sub}/n_q data and the NCQ scaling curve, are shown in Fig. 9. The three curves correspond to the $f_0(980)$

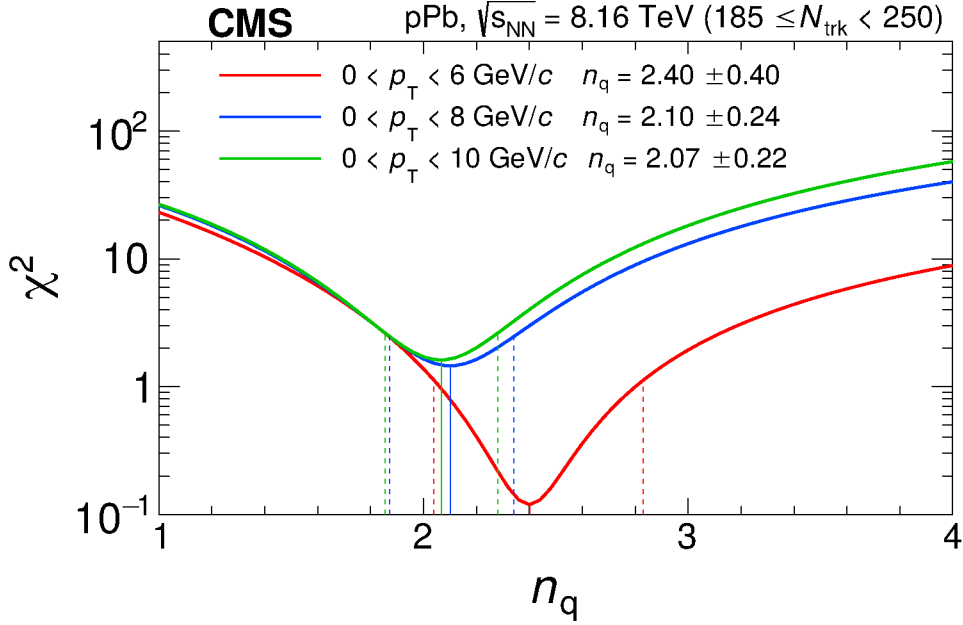


Figure 9: **The χ^2 scan.** The χ^2 of the $f_0(980)$ elliptic flow data with respect to the NCQ scaling parameterization, scanned in steps of n_q . The three curves correspond to using $f_0(980)$ data for $p_T < 6, 8,$ and 10 GeV/c, respectively.

data for $p_T < 6, 8,$ and 10 GeV/c, respectively. The statistical and systematic uncertainties are included in the χ^2 calculation with the covariance matrix. The optimal n_q value is determined at the minimum χ^2 , denoted by χ_{\min}^2 , with the uncertainty bracketed by the $\chi_{\min}^2 + 1$ level. The corresponding n_q values are listed in Fig. 9, with the uncertainties accounting for the effects of variations in the NCQ fit functional forms and from using p_T/n_q instead of KE_T/n_q , which are relatively small (as detailed in Table 1).

Lead-lead collision data from ALICE suggest that the NCQ scaling holds within a precision of 20% [48, 49]. We vary the overall fit curve of the NCQ scaling by $\pm 10\%$ and obtain $n_q = 1.95 \pm 0.22$ and 2.19 ± 0.24 , respectively for the positive and negative variations, by using $f_0(980)$ data for $p_T < 10$ GeV/c. Both these values agree well with the nominal result of $n_q = 2.07 \pm 0.22$, demonstrating the robustness of our result with respect to variations in the NCQ scaling assumption.

To examine the effects of imperfect NCQ scaling, we carry out further cross-checks as follows. We fit only the $K_S^0 v_2^{\text{sub}}$ data to obtain an alternative NCQ scaling curve and repeat the analysis. The $f_0(980)$ n_q extracted this way is 2.03 ± 0.22 . When we use the nominal NCQ scaling curve with Λv_2^{sub} data, the extracted Λ n_q value is 2.73 ± 0.14 . The 2σ deviation from the nominal value of 3 indicates degree of the validity of the NCQ scaling between the K_S^0 and Λ hadrons. Similarly, when we use only the Λv_2^{sub} data to obtain the NCQ scaling curve, the extracted n_q is 2.30 ± 0.22 for the $f_0(980)$ and 2.29 ± 0.18 for the K_S^0 states. We have also tested the NCQ scaling validity on Ω data by using the $K_S^0, \Lambda,$ and Ξ^- data for the NCQ scaling fit; the extracted n_q value for Ω is 3.21 ± 0.69 .

A.6 Exclusion significance determination

The log-likelihood ratio $-2 \ln(L_{n_q=4}/L_{n_q=2})$, evaluated as the χ^2 difference between the $n_q = 2$ and 4 hypotheses, is calculated for the $f_0(980) v_2^{\text{sub}}$ data. We also generate pseudo-data of

$f_0(980)$ v_2^{sub} according to the NCQ scaling curve for a given n_q hypothesis. The v_2^{sub} uncertainties are taken into account by smearing v_2^{sub} with a Gaussian distribution according to the covariance matrix given by Eq (4). The corresponding log-likelihood ratio is calculated for the pseudo-data in the same way as for pPb data. The pseudo-experiments yield an expected distribution of the log-likelihood ratio for the two given $f_0(980)$ n_q hypotheses. Each of these distributions is fit with a Gaussian function and the significance of the main hypothesis over the alternative one is extracted as the distance between the Gaussian mean of the alternative distribution (the yellow histogram in, e.g., Fig. 4) and the measured value in data (the red arrow in the same figure), divided by the width of the Gaussian function. The consistency with the main hypothesis can be inferred in a similar way by comparing the value obtained in data with the Gaussian mean and width of the main distribution (the green histogram in the same figure).

The log-likelihood ratio distributions for the $n_q = 2$ vs. 4 hypotheses for the two restricted p_T ranges are shown in Fig. 10. The log-likelihood ratio distributions for the $n_q = 2$ vs. 3 hypotheses in the $p_T < 8 \text{ GeV}/c$ range are shown in Fig. 11.

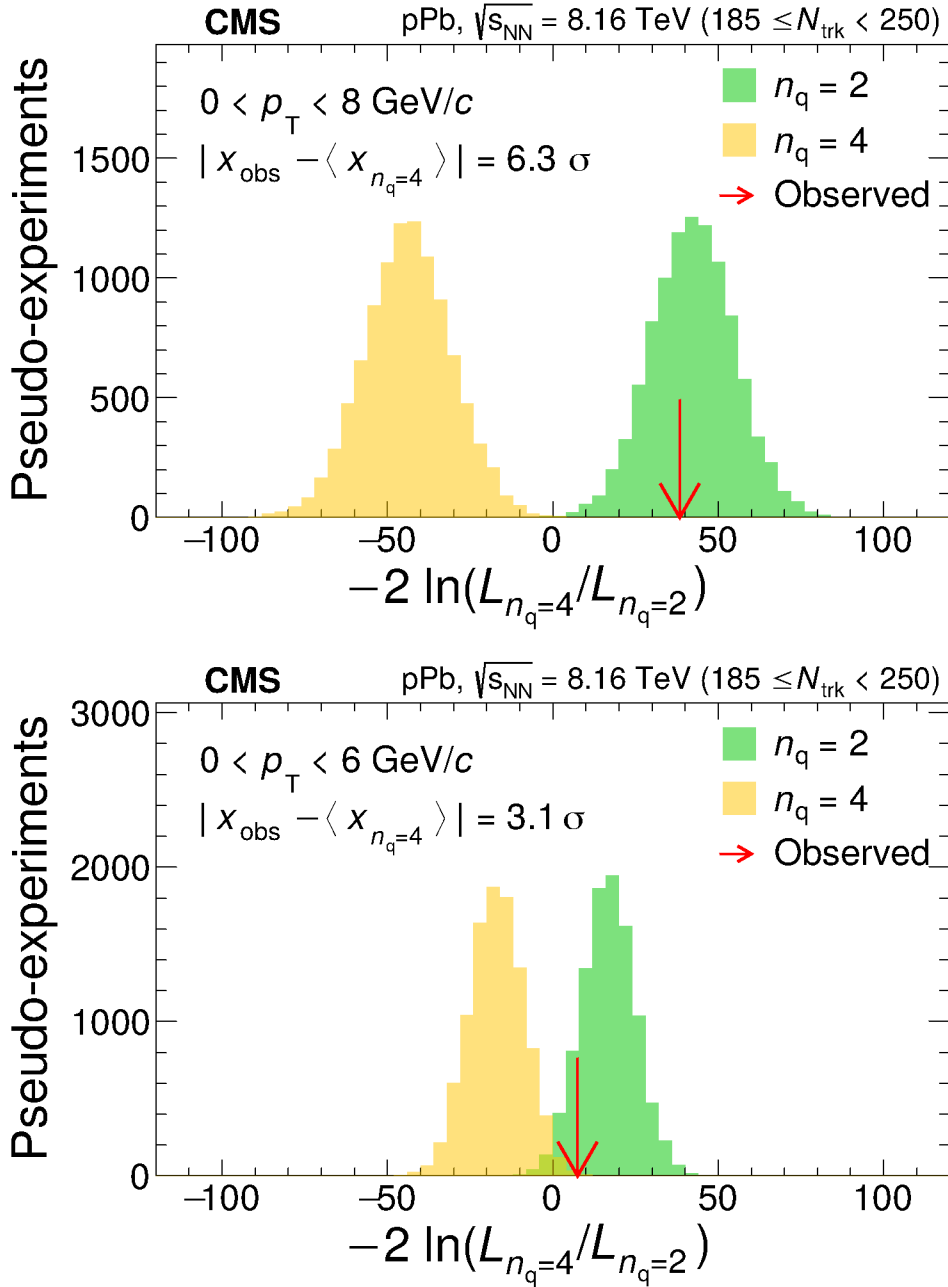


Figure 10: Exclusion significances for $n_q = 4$. Same as Fig. 4 but using $f_0(980)$ v_2^{sub} data within the restricted ranges $p_{\text{T}} < 8$ GeV/c (upper) and $p_{\text{T}} < 6$ GeV/c (lower).

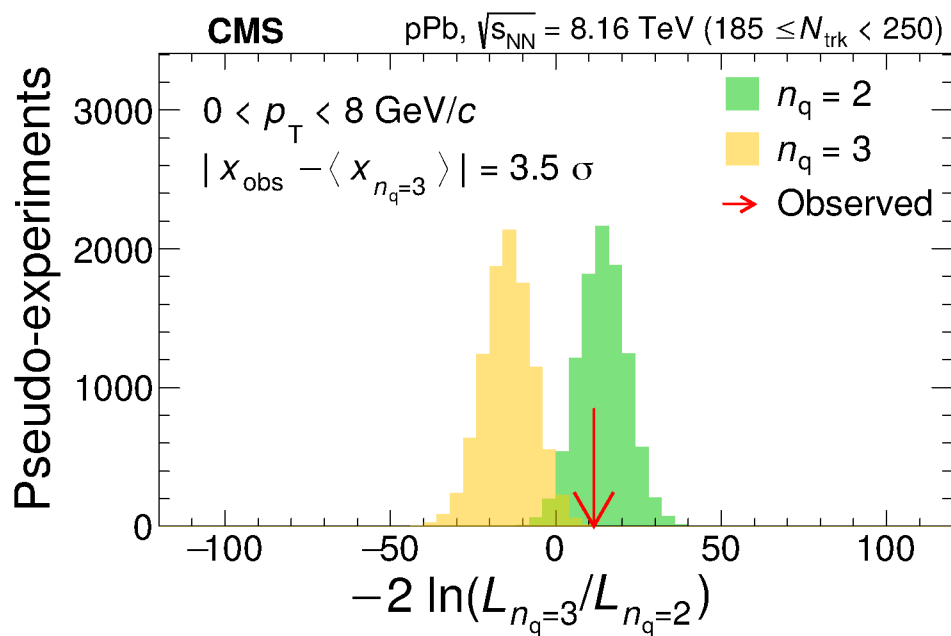





















Figure 11: **Exclusion significance for $n_q = 3$.** The expected log-likelihood ratio distributions for $n_q = 2$ vs. 3 hypotheses from the pseudo-experiments and the observed value for the $f_0(980)$ in data in the $p_{\text{T}} < 8$ GeV/c range.

B The CMS Collaboration




Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

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

















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , P. Van Mechelen 











Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat⁴ , G.P. Van Onsem , S. Van Putte , D. Vannerom 














Université Libre de Bruxelles, Bruxelles, Belgium

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






Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , Y. Hong , J. Knolle , L. Lambrecht , G. Mestdach, K. Mota Amarilo , C. Rendón, A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 



















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , C. Delaere , I.S. Donertas , A. Giammanco , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , K. Mondal , T.T. Tran , S. Wertz 









Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , T. Menezes De Oliveira, A. Moraes , P. Rebello Teles , M. Soeiro

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, J. Martins⁷ , C. Mora Herrera , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , A. Vilela Pereira 

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

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

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

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




University of Sofia, Sofia, Bulgaria

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

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

S. Keshri , S. Thakur 












Beihang University, Beijing, China

T. Cheng , T. Javaid , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

Z. Hu , J. Liu, K. Yi^{8,9} 

Institute of High Energy Physics, Beijing, China

G.M. Chen¹⁰ , H.S. Chen¹⁰ , M. Chen¹⁰ , F. Iemmi , C.H. Jiang, A. Kapoor¹¹ , H. Liao , Z.-A. Liu¹² , R. Sharma¹³ , J.N. Song¹², J. Tao , C. Wang¹⁰, J. Wang , Z. Wang¹⁰, H. Zhang 

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

A. Agapitos , Y. Ban , A. Levin , C. Li , Q. Li , Y. Mao, S.J. Qian , X. Sun , D. Wang , H. Yang, L. Zhang , C. Zhou 

Sun Yat-Sen University, Guangzhou, China

Z. You 

University of Science and Technology of China, Hefei, China

K. Jaffel , N. Lu 

Nanjing Normal University, Nanjing, China

G. Bauer¹⁴

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

X. Gao¹⁵ , D. Leggat, H. Okawa 

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 





Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

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

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









University of Split, Faculty of Science, Split, Croatia






























































































M. Kovac , T. Sculac 





































































































Institute Rudjer Boskovic, Zagreb, Croatia




P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, S. Mishra , A. Starodumov¹⁶ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

Charles University, Prague, Czech RepublicM. Finger , M. Finger Jr. , A. Kveton **Escuela Politecnica Nacional, Quito, Ecuador**E. Ayala **Universidad San Francisco de Quito, Quito, Ecuador**E. Carrera Jarrin **Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**A.A. Abdelalim^{17,18} , E. Salama^{19,20} **Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M.A. Mahmoud , Y. Mohammed **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , E. Brücken , F. Garcia , K.T.S. Kallonen , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow **IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro²¹ , P. Simkina , M. Titov , M. Tornago **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram²² , J. Andrea , D. Apparau , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , C. Grimault, R. Haeberle , A.-C. Le Bihan , M. Meena , G. Saha , M.A. Sessini , P. Van Hove **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen²³ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 

Georgian Technical University, Tbilisi, GeorgiaG. Adamov, I. Lomidze , Z. Tsamalaidze¹⁶ **RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Rówert , M. Teroerde **RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann, M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , U. Sarkar , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo²⁴ , L. Vigilante, S. Wiedenbeck , S. Zaleski**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**C. Dziwok , G. Flügge , W. Haj Ahmad²⁵ , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz **Deutsches Elektronen-Synchrotron, Hamburg, Germany**H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman²⁶ , K. Borras²⁷ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁶ , A. Geiser , A. Giraldi , V. Guglielmi , M. Guthoff , A. Hinzmann , A. Jafari²⁸ , L. Jeppe , N.Z. Jomhari , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁹ , W. Lohmann³⁰ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , A. Mussgiller , L.P. Nair , A. Nürnberg , Y. Otariid, J. Park , D. Pérez Adán , E. Ranken , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , M. Scham^{31,27} , S. Schnake²⁷ , P. Schütze , C. Schwanenberger²⁶ , D. Selivanova , K. Sharko , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁷ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos **University of Hamburg, Hamburg, Germany**A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , M. Eich, K. El Morabit , Y. Fischer , C. Garbers , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , 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, M. Wolf **Karlsruher Institut fuer Technologie, Karlsruhe, Germany**S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann³² , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer 

S. Wieland , F. Wittig, R. Wolf , X. Zuo 





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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos³², A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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



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

M. Bartók³³ , C. Hajdu , D. Horvath^{34,35} , K. Márton, F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , M.M.A. Gadallah³⁶ , Á. Kadlecik , P. Major , K. Mandal , G. Pásztor , A.J. Rádl³⁷ , G.I. Veres 



Faculty of Informatics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari , G. Zilizi 















Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

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

T. Csorgo³⁷ , F. Nemes³⁷ , T. Novak 




Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁸ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 














University of Delhi, Delhi, India

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



Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁹ , S. Bhattacharya , S. Dutta , S. Dutta, S. Sarkar






Indian Institute of Technology Madras, Madras, India







M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , P. Jana , P. Kalbhor , J.R. Komaragiri⁴⁰ , D. Kumar⁴⁰ , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 

Tata Institute of Fundamental Research-A, Mumbai, India













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

Tata Institute of Fundamental Research-B, Mumbai, India


A. Bala , S. Banerjee , R.M. Chatterjee, R.K. Dewanjee⁴¹ , M. Guchait , Sh. Jain 

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


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

S. Bahinipati⁴² , C. Kar , D. Maity⁴³ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴³ , K. Naskar⁴³ , A. Nayak⁴³ , P. Sadangi, P. Saha , S.K. Swain ,
S. Varghese⁴³ , D. Vats⁴³ 

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

S. Acharya⁴⁴ , A. Alpana , S. Dube , B. Gomber⁴⁴ , B. Kansal , A. Laha , B. Sahu⁴⁴ ,
S. Sharma , K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁵ , E. Khazaie⁴⁶ , M. Zeinali⁴⁷ 
































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

S. Chenarani⁴⁸ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 





INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

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


















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

C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borghonovi^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} ,
A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} ,
F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} ,
C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,49} , L. Lunerti^{a,b} , S. Marcellini^a ,
G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} ,
T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,50} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,50} , C. Tuve^{a,b} 

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

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
















INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵¹ , D. Piccolo 










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

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


















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

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












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

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,52} , P. Paolucci^{a,32} , B. Rossi^a , C. Sciacca^{a,b} 













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

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,53} , A. Bergnoli^a , M. Biasotto^{a,54} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , E. Lusiani^a , M. Margoni^{a,b} , F. Marini^a , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , G. Strong^a , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b}


















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

S. Abu Zeid^{a,20} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 


















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

S. Ajmal^{a,b} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,55} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 



















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


P. 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} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a

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

P. Barria^a , C. Basile^{a,b} , M. Campana^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , F. Errico^{a,b} , E. Longo^{a,b} , P. Meridiani^a , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a

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












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

E. Vlasov^{a,b} 


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

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





Kyungpook National University, Daegu, Korea

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

Department of Mathematics and Physics - GWNNU, Gangneung, Korea

M.S. Kim 

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

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

Hanyang University, Seoul, Korea

E. Asilar , D. Kim , T.J. Kim , J.A. Merlin

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 








Sejong University, Seoul, Korea

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



Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

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


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

T. Beyrouthy

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns⁵⁶ 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 



Vilnius University, Vilnius, Lithuania

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



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

N. Bin Norjoharuddeen , I. Yusuff⁵⁷ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁸ , R. Lopez-Fernandez , C.A. Mondragon Herrera, A. Sánchez Hernández 


Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , M. Ramírez García 


Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

University of Montenegro, Podgorica, Montenegro

I. Bubanja, N. Raicevic 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

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

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







AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeleper , P. Zalewski 

















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

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



Warsaw University of Technology, Warsaw, Poland

K. Pozniak , W. Zabolotny 

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

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























Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , P. Milenovic 

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

M. Dordevic , J. Milosevic , V. Rekovic

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














M. Aguilar-Benitez, J. Alcaraz Maestre , Cristina F. Bedoya , 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 , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo 

I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , L. Urda Gómez , J. Vazquez Escobar , C. Willmott



















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 





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

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasasosa García , 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 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁹ , D.U.J. Sonnadara , D.D.C. Wickramarathna 













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

W.G.D. Dharmaratna⁶⁰ , K. Liyanage , N. Perera , N. Wickramage 



CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , L. Forthomme , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , M. Matthewman, 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 , D. Piparo , H. Qu , D. Rabady , G. Reales Gutiérrez, M. Rovere , H. Sakulin , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶¹ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsirou, D. Walter , J. Wanczyk⁶² , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner























Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua⁶³ , L. Caminada⁶³ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶³ , L. Noehte⁶³ , T. Rohe 








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

T.K. Aarrestad , K. Androsova⁶² , M. Backhaus , A. Calandri , C. Cazzaniga , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani⁶² , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶² , D. Valsecchi , R. Wallny 



















Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁴ , P. Bäertschi , D. Brzhechko , M.F. Canelli , K. Cormier , J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , U. Molinatti , A. Reimers , P. Robmann , S. Sanchez Cruz , M. Senger , F. Stäger , Y. Takahashi , R. Tramontano 




National Central University, Chung-Li, Taiwan

C. Adloff⁶⁵ , D. Bhowmik , C.M. Kuo , W. Lin , P.K. Rout , P.C. Tiwari⁴⁰ , S.S. Yu 




















National Taiwan University (NTU), Taipei, Taiwan

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


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

C. Asawatrangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁶ , E. Eskut , Y. Guler⁶⁷ , E. Gurpinar Guler⁶⁷ , C. Isik , O. Kara , A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁸ , A. Polatoz , B. Tali⁶⁹ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

M. Yalvac⁷⁰ 





Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷¹ , O. Kaya⁷² , S. Tekten⁷³ 



Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{66,74} , Y. Komurcu , S. Sen⁷⁵ 

Istanbul University, Istanbul, Turkey

O. Aydilek²⁵ , S. Cerci⁶⁹ , V. Epshteyn , B. Hacisahinoglu , I. Hos⁷⁶ , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey

B. Isildak⁷⁷ , D. Sunar Cerci⁶⁹ 









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

A. Boyaryntsev , B. Grynyov 









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

L. Levchuk 

University of Bristol, Bristol, United Kingdom

































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

Rutherford Appleton Laboratory, Didcot, United Kingdom




A.H. Ball , K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis , K. Harder , S. Harper , M.-L. Holmberg⁸⁰ , 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 , T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Malik, M. Mieskolainen , J. Nash⁸² , M. Pesaresi, B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva, C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee³² , M. Vojinovic , N. Wardle , D. Winterbottom 



Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

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





















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 


















The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸³ , E. Usai , R. Yi 




















Boston University, Boston, Massachusetts, USA

A. Akpınar , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan , A.G. Zecchinelli 




Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²⁷, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , S. Sagir⁸⁵ , F. Simpson , M. Stamenkovic , X. Yan , W. Zhang






University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , 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 , D. Pellett , W. Wei , Y. Yao , F. Zhang 
























University of California, Los Angeles, California, USA

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

















University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si , S. Wimpenny[†] 










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

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

















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

A. Barzdukas , L. Brennan , C. Campagnari , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vami , S. Wang 















California Institute of Technology, Pasadena, California, USA

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



















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , M. Cremonesi , V. Dutta , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , P. Palit , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 












































































University of Colorado Boulder, Boulder, Colorado, USA

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





















Cornell University, Ithaca, New York, USA

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

















Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , 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 , A. Whitbeck , I. Zoi 









University of Florida, Gainesville, Florida, USA

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





















Florida State University, Tallahassee, Florida, USA

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












Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , M.M. Baarmand , S. Butalla , T. Elkafrawy²⁰ , M. Hohlmann , R. Kumar Verma , M. Rahmani , E. Yanes 





University of Illinois Chicago, Chicago, USA, Chicago, USA

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














The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend, K. Dilsiz⁸⁸ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁹ , J. Nachtman , O. Neogi, H. Ogul⁹⁰ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹¹ 








Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , N. Minafra , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹² , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson














Kansas State University, Manhattan, Kansas, USA

B. Allmond , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , J. Natoli , D. Roy , G. Sorrentino

















Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 














University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranje, L. Wang


Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , I.A. Cali , 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 , A. Novak , C. Paus , D. Rankin , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang













University of Minnesota, Minneapolis, Minnesota, USA

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

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 

















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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






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

H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams



























Northeastern University, Boston, Massachusetts, USA

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









Northwestern University, Evanston, Illinois, USA

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



















University of Notre Dame, Notre Dame, Indiana, USA

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

The Ohio State University, Columbus, Ohio, USA

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





















Princeton University, Princeton, New Jersey, USA

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




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 












Purdue University, West Lafayette, Indiana, USA

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

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, Texas, USA

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


















University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin⁹³ , E. Popova⁹³ , R. Taus 

The Rockefeller University, New York, New York, USA

K. Goulianos 














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

B. Chiarito, J.P. Chou , S.V. Clark , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , O. Karacheban³⁰ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 










University of Tennessee, Knoxville, Tennessee, USA

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












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

D. Aebi , M. Ahmad , O. Bouhali⁹⁴ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁵ , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 








Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

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























University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA

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

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

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁹⁶, E. Boos , V. Borshch , D. Budkouski , V. Chekhovsky, R. Chistov⁹⁶ , M. Danilov⁹⁶ , A. Dermenev , T. Dimova⁹⁶ , D. Druzhkin⁹⁷ , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov , V. Kachanov , A. Kaminskiy , V. Karjavine , A. Karneyev , L. Khein, V. Kim⁹⁶ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , O. Kodolova⁹⁸ , D. Konstantinov , V. Korenkov , V. Korotkikh, A. Kozyrev⁹⁶ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁹ , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁶ , V. Murzin , A. Nikitenko^{100,98} , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , S. Petrushanko , S. Polikarpov⁹⁶ , V. Popov , O. Radchenko⁹⁶ , M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁶ , S. Slabospitskii , V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tisova , A. Toropin , L. Uvarov , A. Uzunian , I. Vardanyan , A. Vorobyev[†], N. Voytishin , B.S. Yuldashev¹⁰¹, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

-
- ⁴Also at Ghent University, Ghent, Belgium
- ⁵Also at Universidade Estadual de Campinas, Campinas, Brazil
- ⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- ⁷Also at UFMS, Nova Andradina, Brazil
- ⁸Also at Nanjing Normal University, Nanjing, China
- ⁹Now at The University of Iowa, Iowa City, Iowa, USA
- ¹⁰Also at University of Chinese Academy of Sciences, Beijing, China
- ¹¹Also at China Center of Advanced Science and Technology, Beijing, China
- ¹²Also at University of Chinese Academy of Sciences, Beijing, China
- ¹³Also at China Spallation Neutron Source, Guangdong, China
- ¹⁴Now at Henan Normal University, Xinxiang, China
- ¹⁵Also at Université Libre de Bruxelles, Bruxelles, Belgium
- ¹⁶Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- ¹⁷Also at Helwan University, Cairo, Egypt
- ¹⁸Now at Zewail City of Science and Technology, Zewail, Egypt
- ¹⁹Also at British University in Egypt, Cairo, Egypt
- ²⁰Now at Ain Shams University, Cairo, Egypt
- ²¹Also at Purdue University, West Lafayette, Indiana, USA
- ²²Also at Université de Haute Alsace, Mulhouse, France
- ²³Also at Department of Physics, Tsinghua University, Beijing, China
- ²⁴Also at The University of the State of Amazonas, Manaus, Brazil
- ²⁵Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ²⁶Also at University of Hamburg, Hamburg, Germany
- ²⁷Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁸Also at Isfahan University of Technology, Isfahan, Iran
- ²⁹Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ³⁰Also at Brandenburg University of Technology, Cottbus, Germany
- ³¹Also at Forschungszentrum Jülich, Juelich, Germany
- ³²Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³³Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³⁴Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³⁵Now at Universitatea Babeş-Bolyai - Facultatea de Fizică, Cluj-Napoca, Romania
- ³⁶Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁷Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³⁸Also at Punjab Agricultural University, Ludhiana, India
- ³⁹Also at University of Visva-Bharati, Santiniketan, India
- ⁴⁰Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴¹Also at Birla Institute of Technology, Mesra, Mesra, India
- ⁴²Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴³Also at Institute of Physics, Bhubaneswar, India
- ⁴⁴Also at University of Hyderabad, Hyderabad, India
- ⁴⁵Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁶Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁷Also at Sharif University of Technology, Tehran, Iran
- ⁴⁸Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁹Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy

- ⁵⁰ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵¹ Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵² Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵³ Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁴ Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- ⁵⁵ Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁶ Also at Riga Technical University, Riga, Latvia
- ⁵⁷ Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁸ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁹ Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁶⁰ Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶¹ Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶² Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶³ Also at Universität Zürich, Zurich, Switzerland
- ⁶⁴ Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁵ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁶ Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁷ Also at Konya Technical University, Konya, Turkey
- ⁶⁸ Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁹ Also at Adiyaman University, Adiyaman, Turkey
- ⁷⁰ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷¹ Also at Marmara University, Istanbul, Turkey
- ⁷² Also at Milli Savunma University, Istanbul, Turkey
- ⁷³ Also at Kafkas University, Kars, Turkey
- ⁷⁴ Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁵ Also at Hacettepe University, Ankara, Turkey
- ⁷⁶ Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷ Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸ Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸⁰ Also at University of Bristol, Bristol, United Kingdom
- ⁸¹ Also at IPPP Durham University, Durham, United Kingdom
- ⁸² Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸³ Also at Università di Torino, Torino, Italy
- ⁸⁴ Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁵ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁶ Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁷ Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁸ Also at Bingol University, Bingol, Turkey
- ⁸⁹ Also at Georgian Technical University, Tbilisi, Georgia
- ⁹⁰ Also at Sinop University, Sinop, Turkey
- ⁹¹ Also at Erciyes University, Kayseri, Turkey
- ⁹² Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁹³ Now at an institute or an international laboratory covered by a cooperation agreement with

CERN

⁹⁴Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁵Also at Kyungpook National University, Daegu, Korea

⁹⁶Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁷Also at Universiteit Antwerpen, Antwerpen, Belgium

⁹⁸Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁹Also at Northeastern University, Boston, Massachusetts, USA

¹⁰⁰Also at Imperial College, London, United Kingdom

¹⁰¹Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan