



Letter

System-size dependence of charged-particle suppression in ultrarelativistic nucleus-nucleus collisions

The CMS Collaboration¹

CERN, Geneva, Switzerland

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ABSTRACT

High-energy partons lose energy while propagating through the hot, strongly interacting medium produced in ultrarelativistic nucleus-nucleus collisions, leading to a suppression of particle production at high transverse momentum (p_T). The dependence of this energy loss on the size of the colliding nuclear system has yet to be firmly established experimentally. This Letter presents a systematic study of charged-particle suppression across four different nucleus-nucleus collision systems using nuclear modification factors (R_{AA}) measured by the CMS Collaboration at the CERN LHC. Previous CMS measurements of R_{AA} in oxygen-oxygen, xenon-xenon, and lead-lead collisions are recast with identical p_T intervals and are complemented by the first measurement of the charged-particle R_{AA} in neon-neon collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The neon-neon data correspond to an integrated luminosity of 0.76 nb^{-1} . The R_{AA} in all collision systems examined show similar qualitative trends as a function of p_T , but have a magnitude which is ordered with the nucleon number A . The R_{AA} feature a downward slope at low p_T , a local minimum at around 5–7 GeV, and an upward slope with increasing p_T . The R_{AA} are also compared in terms of $A^{1/3}$, which is proportional to the nuclear radius. Models including only initial-state nuclear effects fail to reproduce the observed trends, whereas energy loss models reproduce the trends in the region $p_T > 9.6$ GeV.

1. Introduction

In ultrarelativistic heavy ion collisions, a hot and deconfined state of strongly interacting matter, known as quark-gluon plasma (QGP), is formed [1,2]. High-energy partons produced in initial hard scatterings traverse the QGP and probe its short-distance structure [3–5]. As a consequence of their interactions with the surrounding medium, partons lose energy while propagating through it [6,7]. A characteristic experimental signature of parton energy loss in heavy ion collisions is the suppression of high transverse momentum (p_T) particle yields relative to those measured in a reference proton-proton (pp) collision system.

The magnitude of parton energy loss depends on the presence or absence of QGP formation and, if such a medium is formed, on its properties, including the temperature and transport properties characterizing parton-medium interactions. In the presence of the QGP, the amount of parton energy loss is expected to depend primarily on the in-medium path length traversed by the parton, which is strongly influenced by the size of the colliding nuclear system. In this context, the system size refers to the spatial extent of the nuclear overlap region, which is largely determined by the radii of the colliding nuclei. Energy loss proceeds via a combination of different mechanisms, e.g., collisional or radiative processes, which have different path-length dependences. Variations in

the local temperature, the density, and the dynamic expansion of the medium also affect the path-length dependence of energy loss. Thus, the exact scaling of parton energy loss with system size is a theoretically challenging topic, and experimental input is needed to provide additional constraints. To date, studies of the system-size dependence have largely relied on centrality-selected observables in heavy ion collisions [8–14]. Centrality is used to quantify the geometric overlap of the two colliding nuclei and is based on the percentile of the total inelastic nucleus-nucleus (AA) cross section, with lower (higher) percentiles corresponding to more central (more peripheral) collisions. These measurements predominantly explore variations in collision geometry within a single nuclear system, rather than comparisons across different systems. They are affected by selection and geometry biases inherent to the centrality determination, particularly in peripheral events [9,15,16]. As a result, a quantitative and unbiased characterization of the system-size dependence of parton energy loss remains an open challenge, limiting the development of a unified theoretical description of nuclear suppression phenomena.

A characterization of nuclear suppression effects based instead on the nucleon number A provides a model-independent measure of the overall system size and a less biased approach to study the system-size dependence of parton energy loss. Recent light ion collision data, i.e.,

Contact: cms-publication-committee-chair@cern.ch.

¹ Authors are listed at the end of this paper.

from oxygen-oxygen (OO) and neon-neon (NeNe) collisions [17–19], have provided a new avenue to probe the onset of parton energy loss effects in small nuclear collision systems. These data circumvent the aforementioned issues of event selection and geometric biases and complement the existing measurements in xenon-xenon (XeXe) and lead-lead (PbPb) collisions. In addition, high- p_T particle production preferentially selects more head-on central collisions, further reducing the range of collision geometries sampled by the measurement within a given collision system.

Nuclear suppression effects from parton energy loss can be quantified using the charged-particle nuclear modification factor, R_{AA} . For centrality-integrated (minimum bias) AA collisions, this factor can be defined as

$$R_{AA} = \frac{1}{A^2} \left[\left(\frac{d\sigma^{AA}}{dp_T} \right) / \left(\frac{d\sigma^{pp}}{dp_T} \right) \right], \quad (1)$$

where σ^{AA} (σ^{pp}) denotes the charged-particle production cross section in nucleus-nucleus (pp) collisions. The A^2 normalization originates from having A nucleons in each nucleus and therefore constitutes an exact quantity, avoiding model-dependent estimates of the nuclear overlap [20,21]. Deviations of R_{AA} from unity indicate modifications of particle production arising from nuclear effects, including both initial- and final-state interactions. Owing to the steeply falling p_T spectrum, even modest amounts of energy loss can lead to a sizable suppression of the observed particle yields, making R_{AA} a particularly sensitive probe of medium-induced energy loss.

Recently, the CMS Collaboration reported the discovery of suppressed charged-particle production in inclusive OO collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.36$ TeV by measuring the charged-particle R_{AA} [22]. When combined with existing centrality-integrated PbPb measurements at $\sqrt{s_{NN}} = 5.02$ TeV [12] and XeXe measurements at 5.44 TeV [9], these data provide a unique opportunity for an experimental constraint of parton energy loss effects versus the nuclear system size. The XeXe measurement uses the 80% most central collisions and is therefore expected to provide a close approximation to the inclusive R_{AA} .

Motivated by these developments, this Letter investigates the system-size dependence of high- p_T charged-particle production in AA collisions at the CERN LHC. In addition to existing charged-particle R_{AA} measurements, this analysis presents the first measurement of the charged-particle R_{AA} in NeNe collisions at $\sqrt{s_{NN}} = 5.36$ TeV, adding an additional nuclear system having a size between that of OO and XeXe collisions. The four collision systems are presented in identical charged-particle p_T intervals to facilitate the systematic evaluation of the charged-particle R_{AA} as functions of p_T and A . Tabulated results are provided in the HEP-Data record for this analysis [23].

2. Detector description

The CMS apparatus [24,25] is a multipurpose, nearly hermetic detector, designed to trigger on [26–28] and identify electrons, muons, photons, and hadrons [29–31]. A global “particle-flow” algorithm [32] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The silicon tracker [33] measures charged particles up to pseudorapidity $|\eta| = 3.0$ with typical resolutions of 2.0% in p_T and 10–75 μm in the transverse impact parameter [34] for nonisolated particles of $1 < p_T < 100$ GeV. The measurement is restricted to $|\eta| < 1$, in order to be able to compare with previous measurements. This is also a η interval where the p_T resolution and track reconstruction have optimal performance. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end from

the interaction region, and together they provide coverage in the range $3.0 < |\eta| < 5.2$.

3. Charged-particle R_{AA} in NeNe collisions

In general, the NeNe measurement strategy follows the one devised for the charged-particle R_{AA} measurement in OO collisions in ref. [22]. The same pp reference from ref. [22] is used to evaluate the charged-particle R_{AA} in NeNe collisions.

The NeNe data were collected in 2025 using the same online selection as that employed in the OO analysis, based on energy deposits in the HF calorimeters in coincidence with colliding bunches. The average number of interactions per bunch crossing, typically referred to as pileup, was approximately 0.13. The total integrated luminosity used in this analysis is $0.76 \pm 0.04 \text{ nb}^{-1}$. This value is obtained by combining two independent luminosity measurements. The first method is based on a preliminary analysis of van der Meer scan data [35,36]. An independent luminosity determination was performed by comparing the observed Z boson yields to a well-calibrated reference data set [37]. The luminosities obtained with the two approaches are in good agreement; their central values differ by only 4.1%.

The NeNe R_{AA} analysis is reported for primary charged particles, defined as charged particles with a proper decay length $c\tau > 1$ cm. Particles that result from secondary decays are not considered primary if the parent particle is classified as primary. Charged particles are reconstructed in the silicon tracker. To reduce the contributions from secondary tracks, tracks are required to have a distance of closest approach (DCA) to any primary vertex smaller than three times the corresponding DCA uncertainty in both the transverse and longitudinal directions. Track reconstruction, selection criteria, and kinematic requirements ($|\eta| < 1$ and $3.0 < p_T < 103.6$ GeV) are the same as those used in the OO measurement and in the corresponding pp reference analysis [22]. These selections ensure minimal bias from online and offline event requirements and maximize the cancellation of reconstruction-related uncertainties in the R_{AA} ratio. Restricting the measurement to $p_T < 103.6$ GeV improves control over contributions from misreconstructed tracks, which become increasingly challenging to constrain in the dense track environment of high- p_T jet showers.

Event selection requirements are chosen to efficiently select minimum bias NeNe collisions, while suppressing backgrounds from ultra-peripheral [38] and beam-related interactions. Offline event selections follow exactly those of the OO analysis [22], and rely on coincidence signals that produce energy deposits above 13 GeV in one or more detector elements on each half of the HF. The presence of at least one reconstructed primary vertex [31] is also required. The resulting inefficiency arising from the event selection requirements for minimum bias events is below 1% for the fiducial region of the charged particles considered in this analysis. This inefficiency, particularly its impact on the charged particle p_T spectrum, is taken into account with the corrections to the primary charged-particle level p_T spectrum. Ion beam contamination, such as that from transmutation from the electromagnetic dissociation of ^{20}Ne [39], was found to be negligible based on the time dependence of distributions characterizing the event activity [40].

Simulated Monte Carlo events are employed to determine tracking efficiency and acceptance corrections, to assess the impact of momentum resolution and residual background contamination, and to validate the stability of the correction procedures. Minimum bias NeNe collisions are simulated using the HIJING v1.383 generator [41]. High- p_T charged-particle production is modeled by embedding PYTHIA v8.311 [42] events with the CP5 tune [43] into HIJING events, forming composite events that combine a hard scattering process with particle production from the underlying event [22]. Potential contamination from ultra-peripheral collisions [38] is studied using the STARLIGHT v3.3.0 generator [44] and is found to be negligible for the phase-space region reported in this measurement. The detector response is simulated using GEANT4 [45]. After event generation, simulated events are weighted on

an event-by-event basis such that the distribution of the position along the beam axis of reconstructed primary interaction vertices matches the one observed in data. Differences between data and simulation in the charged-particle species composition, such as the fractional composition of charged pions, kaons, protons, and strange hadrons, are corrected using the same procedure as in the OO analysis [22]. The procedure uses as input the p_T -dependent species fractions measured by the ALICE experiment in pp collisions [46,47], which are further rescaled guided by the measured hadrochemistry evolution with the average charged-particle density ($dN_{ch}/d\eta$) [48,49] in order to match the expected composition for the NeNe collision system. The measurements in refs. [48,49] indicate that the particle species composition is governed by particle activity, independently of the collision system. For this correction, we assume a reference value of $dN_{ch}/d\eta = 50$ for NeNe collisions, determined from the measured $dN_{ch}/d\eta = 40$ in minimum bias OO collisions [50] scaled to the NeNe system using the Glauber calculations in Ref. [51] as input. The p_T -dependent correction factors are similar, to the per-mille level, to the ones from OO, as expected from the observed evolution of the particle species for those values of $dN_{ch}/d\eta$ [48,49].

Systematic uncertainties are evaluated through dedicated variations of the relevant correction inputs, following the same procedures as in the OO R_{AA} measurement [22]. The uncertainty on the particle species inputs from pp collisions is obtained by propagating the experimental uncertainties [46,47] on the measured species fractions versus p_T ; this effect cancels in the R_{AA} ratio but affects the charged-particle p_T spectrum. The particle species extrapolation uncertainty is determined by varying the assumed particle composition resulting from variations in the $dN_{ch}/d\eta$ -based extrapolation for central NeNe collisions. This uncertainty affects the spectrum and is propagated directly to the R_{AA} . The charged-particle p_T resolution uncertainty is propagated by applying an additional Gaussian smearing of 1% to the data; this uncertainty affects the charged-particle p_T spectrum but cancels in the R_{AA} . The luminosity uncertainty for NeNe collisions, 4.8%, is assumed to be uncorrelated from the luminosity uncertainty of 3.0% for pp collisions [22], amounting to a global normalization uncertainty of 5.7% in the R_{AA} observable. The tracking efficiency uncertainty is taken as a 2.1% p_T -independent uncertainty [52], fully correlated across p_T bins. This contribution cancels in the R_{AA} ratio but is present for the charged-particle p_T spectrum. Data-simulation differences in the rejection of secondary tracks are evaluated by varying the rejection selections, deriving new tracking efficiency tables for each variation, and taking the spread of the corrected yields as the corresponding systematic uncertainty. The DCA significance requirement is varied between two and five times its uncertainty. The resulting uncertainty on the spectrum cancels partially in the R_{AA} , and is under 3.5% because of partial cancellations. The systematic uncertainties are combined in quadrature. The corrected charged-particle p_T spectrum can be found in supplementary material Section 1. The resulting R_{AA} for NeNe collisions is presented in Fig. 1 together with other systems, following the p_T binning scheme discussed next.

4. Charged-particle R_{AA} dependence on p_T and A

To enable a consistent system-size comparison, the R_{AA} measurements in OO, NeNe, XeXe, and PbPb collisions ($A = 16, 20, 129$, and 208) are computed using a common p_T binning scheme corresponding to that of the published XeXe measurement [9], which has the coarsest binning. The study includes CMS results from minimum bias OO collisions at 5.36 TeV [22], minimum bias NeNe collisions at 5.36 TeV, XeXe collisions at 5.44 TeV in the 0–80% centrality range [9], and minimum bias PbPb collisions at 5.02 TeV [12]. The minor differences in collision energy are not expected to strongly affect the overall conclusions that can be drawn in the comparison of different systems, since comparisons of charged-particle R_{AA} measurements at 2.76 and 5.02 TeV show no strong dependence on collision energy at the TeV scale [12]. To recompute the PbPb R_{AA} from the published data, the PbPb and 5.02 TeV pp spectra are rebinned by merging adjacent p_T intervals using

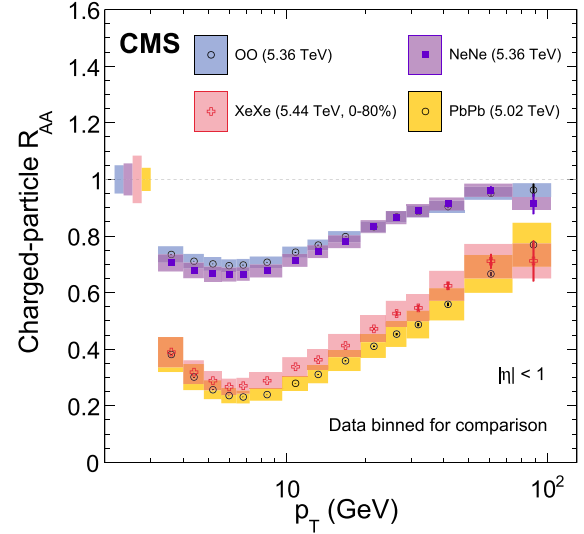


Fig. 1. Charged-particle R_{AA} values versus p_T measured in NeNe collisions at 5.36 TeV compared to previous measurements in centrality-integrated OO collisions at 5.36 TeV [22], 0–80% centrality XeXe at 5.44 TeV [9], and minimum bias PbPb collisions at 5.02 TeV [12]. The vertical error bars represent statistical uncertainties and the boxes represent systematic uncertainties. Global normalization uncertainties are not included directly in the data markers error bands, but they are instead represented by the various boxes on the left around unity. For this compilation plot, a uniform p_T binning scheme is adopted to ensure a consistent comparison across collision systems, as described in the text. The same results with finer binning can be found in supplementary material Section 3.

p_T -weighted averages to preserve the underlying spectral shapes, with statistical uncertainties combined in quadrature and systematic uncertainties combined linearly assuming full bin-to-bin correlation, while normalization uncertainties remain unchanged. The same procedure is applied consistently to the 5.02 TeV pp reference. The OO and NeNe R_{AA} measurements are repeated with the same binning scheme using the original data sets—no assumptions are needed regarding the combination of adjacent p_T intervals for these data. Further details of the binning procedure are provided in supplementary material Section 2, and the R_{AA} results with the high-granularity binning format can be found in supplementary material Section 3.

Fig. 1 shows the measured charged-particle R_{AA} dependence on p_T for particles with $|\eta| < 1$. The NeNe results are compared to previous CMS measurements [9,12,22]. The NeNe and OO measurements display a similar p_T dependence, with NeNe exhibiting a stronger suppression below $p_T \approx 20$ GeV, while converging to comparable R_{AA} values at higher p_T . The NeNe measurement provides additional leverage to quantify how rapidly nuclear suppression effects change with the system size relative to OO. Different models initially predicted varying degrees of separation between these two systems [53]. The observed splitting between NeNe and OO hints at a smooth transition with system size. Owing to the current luminosity uncertainties affecting both light ion measurements, particularly the extent to which they are correlated, a definitive statement on their relative suppression magnitude is not yet possible. Data from the larger XeXe and PbPb systems show a substantially stronger suppression and a steeper increase of R_{AA} with p_T . Together with the light ion systems results, this highlights the systematic evolution of the p_T -dependent suppression pattern with collision system size. Overall, the shape of the R_{AA} as a function of p_T is similar across all systems, with a minimum around 5–7 GeV, a decreasing trend at low p_T , and a rising trend toward higher p_T . In heavy ion systems, the low- p_T behavior is typically attributed to the interplay of p_T -dependent effects such as Cronin enhancement [54] and radial flow [55,56], while the

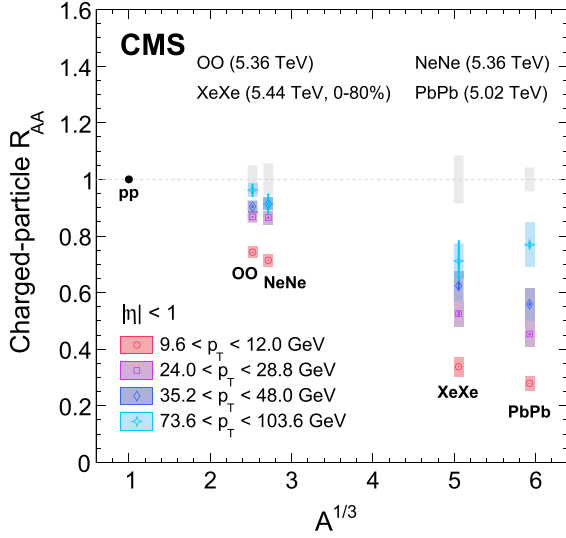


Fig. 2. Charged-particle R_{AA} values, in intervals of p_T , versus $A^{1/3}$ of the AA colliding system. The open markers represent the measured R_{AA} , with the vertical bars representing the statistical uncertainty, and the vertical band representing the experimental uncertainty. Global normalization uncertainties for each data set are shown in the light-gray boxes around unity. For visualization purposes, a subset of four out of the fifteen p_T intervals is presented. A point for pp collisions at $A = 1$, in which the R_{AA} is unity by definition, is also included in the upper left.

magnitude and evolution of the suppression at high p_T are generally associated with parton energy loss in the medium.

Fig. 2 presents the evolution of the charged-particle R_{AA} with $A^{1/3}$ for different AA collision systems and for four representative p_T intervals spanning 9.6–103.6 GeV. Since the nuclear volume grows approximately with A , $A^{1/3}$ is proportional to the nuclear radius. Presenting the evolution of the R_{AA} with $A^{1/3}$ and in a fixed p_T interval enables a direct model-independent comparison of nuclear suppression effects with the system size. The level of suppression exhibits a monotonic dependence on the system size, with R_{AA} decreasing as A (or $A^{1/3}$) increases.

The measured charged-particle R_{AA} across systems are compared to a set of theoretical calculations that span baseline nuclear initial-state effects and different implementations of parton energy loss in hot, strongly interacting matter. This cross-system comparison provides more stringent constraints than studies of R_{AA} versus p_T for individual collision systems, as it reduces the freedom for models to independently describe light and heavy ion collision systems. The calculations discussed here were provided following the first charged-particle R_{AA} measurement in OO collisions. A comparison is presented over four representative p_T intervals. A set of theoretical predictions for NeNe and OO collisions provided prior to the release of the OO results is presented in supplementary material Section 6 and, for the OO system, in ref. [22], respectively. A comparison with the more recent calculations illustrates the difficulty in describing these data with the knowledge available before the OO experimental results.

Fig. 3 compares the measured R_{AA} to baseline calculations that include only initial-state nuclear effects and no final-state energy loss [57, 58]. These calculations are based on next-to-leading order (NLO) perturbative quantum chromodynamics (pQCD) calculations interfaced with modern nuclear parton distribution functions (nPDFs). Calculations using the EPPS21 [59] and nNNPDF3.0 [60] nPDF sets include the full propagation of nPDF uncertainties, as well as variations of the renormalization and factorization scales. These models predict a modest suppression at low p_T that is largely independent of A and arises from initial-state nuclear effects alone. As such, these baseline calculations establish

a reference against which genuine final-state suppression effects can be isolated. Future analysis of recent pO data sets may further constrain the A dependence of nPDFs [70].

A comparison of theoretical calculations that include parton energy loss versus the data is presented in Fig. 4. The regime of validity of these begins at approximately $p_T > 10$ GeV. The Faraday–Horowitz calculation [61,62] employs medium-induced radiative energy loss based on the Djordjevic–Gyulassy–Levai–Vitev (DGLV) formalism [63,64], supplemented by collisional energy loss contributions and a short path-length correction (SPLC) designed for small collision systems. In this framework, the system-size dependence of R_{AA} emerges from the interplay between the in-medium path length traversed by hard partons and the evolving temperature profile of the medium. The predicted suppression increases smoothly with increasing A , and is compatible with the measurements within uncertainties for all collision systems, although some tension is present for the OO and NeNe data points. The calculations from DGLV + SPLC use the same parametrization as in the preliminary results, but they are presented according to the binning employed in this analysis. The measurements are also compared to predictions from the CUJET/CIBJET framework [67,68], which is another DGLV-based description of parton energy loss coupled with viscous hydrodynamic modeling of the medium. These calculations incorporate an updated characterization of the medium properties based on a recent Bayesian analysis of the R_{AA} versus the high- p_T elliptic flow coefficient v_2 of heavy ion collisions at RHIC and the LHC [69]. This Bayesian analysis constrained the temperature-dependent chromoelectric and chromomagnetic composition of the QGP, particularly the abundance of chromomagnetic monopoles. The Bayesian analysis does not include light ion collision data. These theoretical calculations are compatible with the data within the uncertainties for these p_T intervals.

Calculations based on the light-cone path integral (LCPI) formalism [65] include medium-induced radiative energy loss applied to a pQCD baseline with nPDFs. The calculation shown in Fig. 4 corresponds to model scenarios with or without the formation of a “mini QGP” (mQGP) droplet in pp collisions, leading to different extrapolations toward small A . The resulting R_{AA} calculation without QGP formation in pp exhibits some tension at low p_T with respect to the measured R_{AA} in light ion collisions, but is compatible for all p_T . The prediction with a QGP formation in pp is in agreement with the data within the uncertainties.

A complementary approach is provided by calculations that determine the jet transport coefficient $\hat{q}$ using Bayesian inference constrained by heavy ion data [71]. The variable $\hat{q}$ characterizes the average p_T broadening per unit path length experienced by a high-energy parton traversing the deconfined nuclear medium. In this framework, the space–time evolution of the medium is described using 3 + 1 dimensional relativistic hydrodynamics [72], and energy loss is implemented consistently across collision systems by scaling the temperature and path length distributions experienced by propagating partons. The resulting calculations reproduce the rise of R_{AA} toward smaller A , and are compatible with the measurement within the uncertainties.

The results are compared to a model that provides an empirical description of high- p_T hadron suppression in heavy ion collisions [66] based on scaling properties. In this approach, the magnitude and system-size dependence of R_{AA} are governed by an effective parton energy loss scale inferred from the observed scaling of suppression with collision geometry and particle multiplicity. The scaling parametrization is inspired by the expected relationship between parton energy loss and in-medium path length at leading order in pQCD. Fits of this scaling model to RHIC and LHC data yield an average parton energy loss with an approximately linear dependence of the in-medium path length; light ion collision data are not included in this fit. These scaling-based calculations are in agreement with the data within the uncertainties.

The LCPI and CUJET/CIBJET calculations use charged-particle p_T spectra from pp collisions calculated at leading order in perturbation

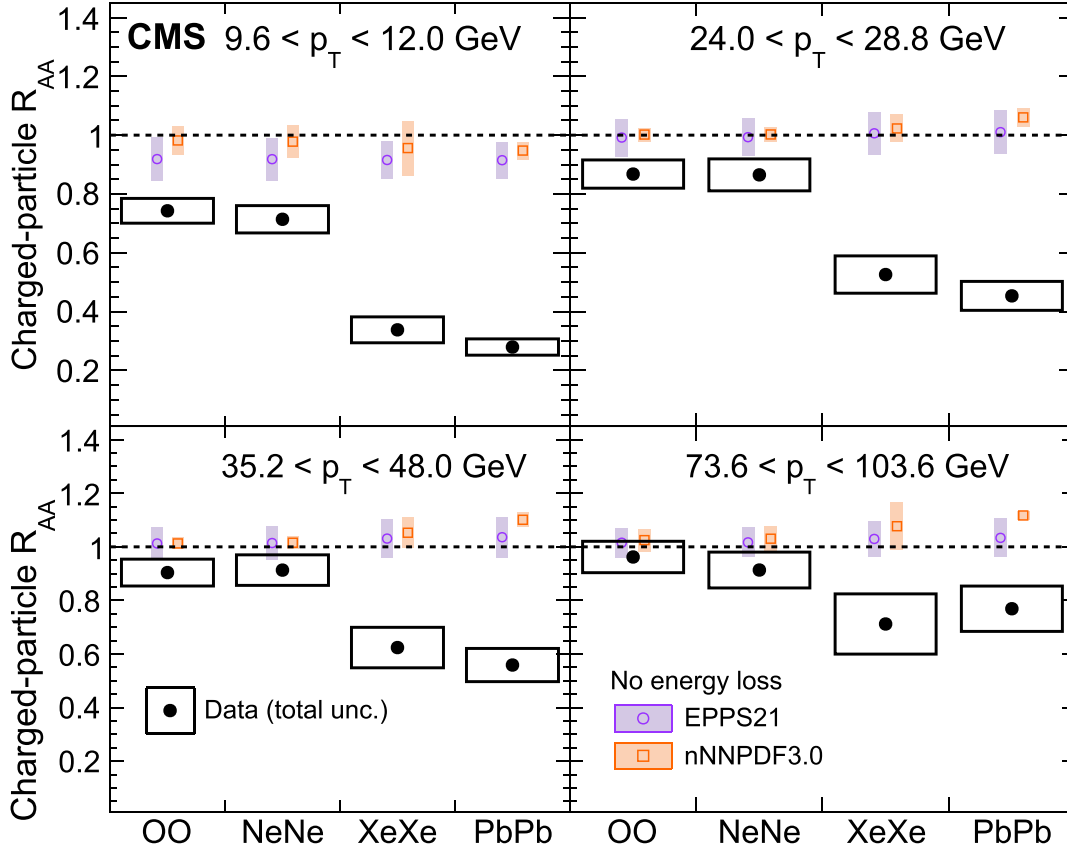


Fig. 3. Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with NLO pQCD calculations that incorporate only initial-state effects through nPDFs and do not include parton energy loss [57,58]. The open boxes with black circular markers represent the data. The box height represents the total experimental uncertainty obtained from the quadratic combination of statistical, systematic, and global normalization uncertainties. The purple markers correspond to calculations using the EPPS21 nPDF set [59], while the orange markers represent calculations based on the nNNPDF3.0 nPDF set [60]. The vertical uncertainty bands reflect the combined scale-variation and nPDF uncertainties, with the latter providing the dominant contribution.

theory, whereas DGLV + SPLC and Bayesian use NLO pQCD calculations. Differences in the fragmentation function parametrizations do not substantially change the slope of the predicted charged-particle p_T spectrum in pp collisions, as summarized in refs. [73,74]. The R_{AA} observable benefits from substantial cancellations of the renormalization and factorization scale uncertainties and fragmentation function fit uncertainties in the ratio, while remaining sensitive to modifications of particle production arising from nuclear effects.

Overall, models that include parton energy loss naturally generate a monotonic decrease of R_{AA} with increasing A , qualitatively consistent with the data. The magnitude and detailed A dependence vary among models, reflecting differences in the assumptions about medium formation in small and large systems, the path-length dependence of energy loss, and the temperature scaling of the jet transport coefficient $\hat{q}$. Although still compatible within the combined experimental and theoretical uncertainties, a subset of the models tend to slightly underestimate the central value of the data, as seen in Fig. 4. Therefore, the CMS R_{AA} measurements offer enhanced sensitivity to key aspects of energy loss modeling when considered in aggregate as opposed to individually. This is further supported by the comparison to the theoretical predictions presented prior to the release of the preliminary results, which is described in supplementary material Section 6. A comparison of the theoretical calculations of R_{AA} as a function of p_T can be found in supplementary material Section 5.

5. Summary

This Letter presents a systematic study of the system-size dependence of the charged-particle nuclear modification factor (R_{AA}) versus transverse momentum (p_T). The study is based on a cross-system comparison that minimizes centrality selection biases. For this purpose, the analysis reports the first measurement of the charged-particle R_{AA} in minimum bias neon-neon (NeNe) collisions at a center-of-mass energy per nucleon pair of 5.36 TeV, based on data collected in 2025 and corresponding to an integrated luminosity of 0.76 nb^{-1} . By comparing existing CMS measurements in oxygen-oxygen, xenon-xenon, and lead-lead collisions with the new NeNe results, this analysis samples nuclear systems across a broad range of nucleon number values (A). This enables an evaluation of the role that the system size has on energy loss. The R_{AA} is measured for charged particles with pseudorapidity $|\eta| < 1$ using identical p_T intervals across all collision systems, which allows for a direct comparison of nuclear suppression effects with A , which characterizes the system size.

The R_{AA} at a given p_T value is found to monotonically decrease as a function of the cubic root of the nucleon number $A^{1/3}$, a quantity that is related to the nuclear radius. The p_T dependences of R_{AA} in all collision systems have similar qualitative shapes, with a local minimum at about 5–7 GeV. The inclusion of the NeNe system extends the coverage in system size and enables a more complete mapping of the evolution of suppression effects across collision systems.

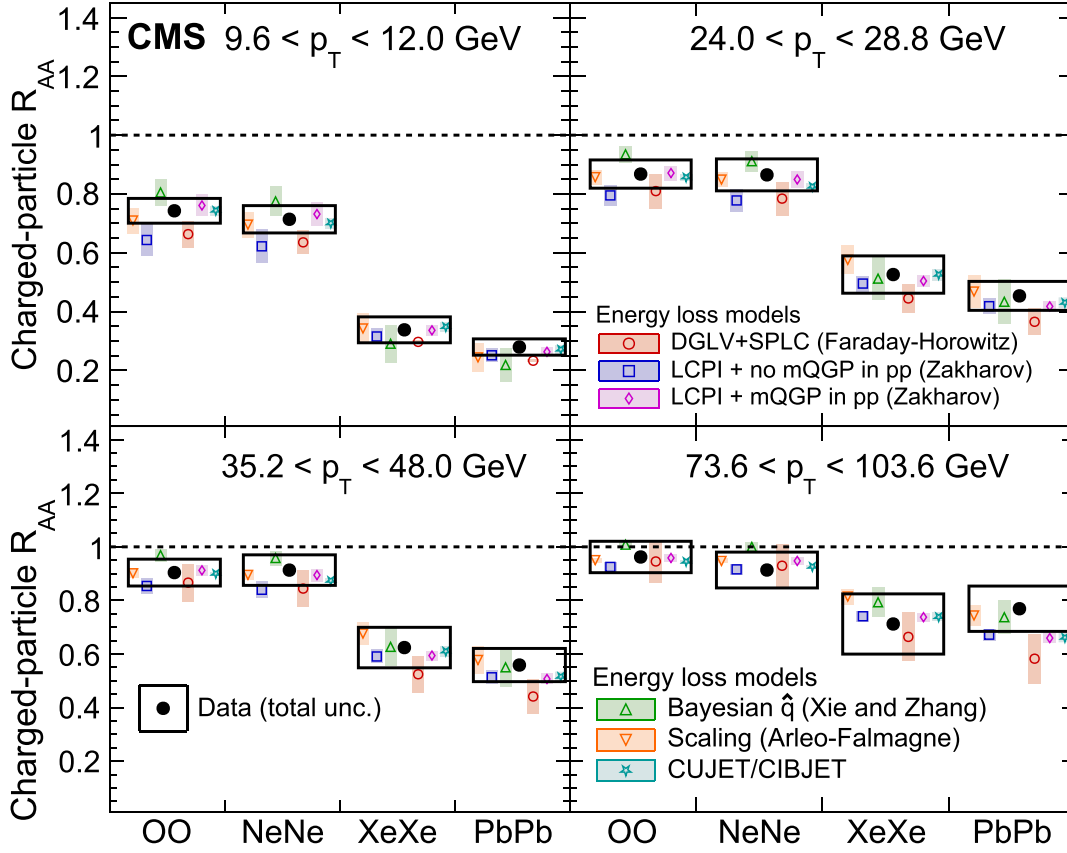


Fig. 4. Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with calculations that incorporate parton energy loss effects [61–69]. The open boxes with black circular markers represent the data, with the box height indicating the total experimental uncertainty obtained from the quadratic combination of statistical, systematic, and global normalization uncertainties. The other colored markers represent theoretical predictions based on different approaches, as described in the text. The uncertainty band is smaller than the marker size for some of the calculations.

Comparisons with theoretical calculations show that baseline perturbative quantum chromodynamics predictions incorporating nuclear parton distribution functions predict only modest modifications relative to $R_{AA} = 1$, with a weak dependence on A . In contrast, models that also include parton energy loss reproduce the observed monotonic evolution of R_{AA} with increasing A . Differences among these calculations in the predicted R_{AA} value and its detailed system-size dependence reflect variations in the modeling of medium effects. Overall, models incorporating parton energy loss describe the measurements within experimental and theoretical uncertainties. This study constrains the existence and characteristics of any transition towards a deconfined, hot medium as the system size increases. Hence, this measurement offers guidance for the selection of ion species in future nuclear physics programs at the LHC.

Declaration of competing interest

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

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Data availability

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

Supplementary material

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The CMS Collaboration

A. Belyaev¹, A. Gevorgyan¹, A. Hayrapetyan¹, A. Tumasyan^{XXIII,1}, W. Adam¹, L. Benato¹, T. Bergauer¹, M. Dragicevic¹, S. Gundacker¹, A.K. Guven¹, P.S. Hussain¹, M. Jeitler^{XXIV,1}, N. Krammer¹, A. Li¹, D. Liko¹, M. Matthewman¹, J. Schieck^{XXIV,1}, R. Schöfbeck^{XXIV,1}, M. Shoshitari¹, M. Sonawane¹, N. Van Den Bossche¹, W. Waltenberger¹, C.-E. Wulz^{XXIV,1}, T. Janssen², H. Kwon², D. Ocampo Henao², T. Van Laer², P. Van Mechelen², D. Ahmadi³, J. Bierkens³, N. Breugelmans³, S. Dansana³, A. De Moor³, M. Delcourt³, C. Gupta³, F. Heyen³, Y. Hong³, K. Kang³, P. Kashko³, S. Lowette³, I. Makarenko³, S. Nandakumar³, S. Tavernier³, M. Tytgat^{II,3}, G.P. Van Onsem³, S. Van Putte³, D. Vannerom³, T. Wybouw³, A. Beshr⁴, B. Bilin⁴, F. Caviglia Roman⁴, B. Clerbaux⁴, A.K. Das⁴, I. De Bruyn⁴, G. De Lentdecker⁴, E. Ducarme⁴, H. Evard⁴, L. Favart⁴, I. Kalaitzidou⁴, A. Khalilzadeh⁴, A. Malara⁴, M.A. Shahzad⁴, L. Thomas⁴, M. Vanden Bemden⁴, C. Vander Velde⁴, P. Vanlaer⁴, C. Yuan⁴, F. Zhang⁴, A. Cauwels^{II}, M. De Coen^{II}, D. Dobur^{II}, C. Giordano^{II}, G. Gokbulut^{II}, K. Kaspar^{II}, D. Kavtaradze^{II}, D. Marckx^{II}, A. Mehta^{II}, K. Skovpen^{II}, A.M. Tomaru^{II}, J. van der Linden^{II}, J. Vandenbroeck^{II}, H. Aarup Petersen⁵, A. Benecke⁵, A. Bethani⁵, A. Cappati⁵, J. De Favereau De Jeneret⁵, C. Delaere⁵, F. Gameiro Casalinho⁵, A. Giammanco⁵, A.O. Guzel⁵, M. Hussain⁵, Z. Lawrence⁵, V. Lemaître⁵, J. Lidrych⁵, P. Malek⁵, S. Turkcapar⁵, G.A. Alves⁶, M. Barroso Ferreira Filho⁶, E. Coelho⁶, M.V. Gonçalves Sales⁶, C. Hensel⁶, D. Matos Figueiredo⁶, T. Menezes De Oliveira⁶, C. Mora Herrera⁶, P. Rebello Teles⁶, M. Soeiro⁶, E.J. Tonelli Manganote^{XXV,6}, A. Vilela Pereira⁶, W.L. Aldá Júnior⁷, H. Brandao Malbouisson⁷, W. Carvalho⁷, J. Chinellato^{XXVIII,7}, G. Correia Silva⁷, M. Costa Reis⁷, E.M. Da Costa⁷, D. Da Silva Dalto⁷, G.G. Da Silveira^{XXVII,7}, D. De Jesus Damiao⁷, S. Fonseca De Souza⁷, R. Gomes De Souza⁷, S. S. Jesus⁷, T. Laux Kuhn^{XXVII,7}, K. Maslova⁷, K. Mota Amarilo⁷, L. Mundim⁷, H. Nogima⁷, J.P. Pinheiro⁷, A. Santoro⁷, A. Sznajder⁷, M. Thiel⁷, F. Torres Da Silva De Araujo^{XXVI,7}, D. Torres Machado⁷, C.A. Bernardes⁸, L. Calligaris⁸, J. Carvalho Leite⁸, M. P. Coelho⁸, F. Damas⁸, T.R. Fernandez Perez Tomei⁸, E.M. Gregores⁸, B. Lopes Da Costa⁸, I. Maietto Silverio⁸, P.G. Mercadante⁸, S.F. Novaes⁸, Sandra S. Padula⁸, V. Scheurer⁸, A. Aleksandrov⁹, G. Antchev⁹, P. Danev⁹, R. Hadjiiska⁹, P. Iaydjiev⁹, M. Shopova⁹, G. Sultanov⁹, A. Dimitrov¹⁰, L. Litov¹⁰, B. Pavlov¹⁰, P. Petkov¹⁰, A. Petrov¹⁰, S. Keshri¹¹, D. Laroze¹¹, M. Meena¹¹, S. Thakur¹¹, W. Brooks¹², T. Cheng¹³, L. Wang¹³, L. Yuan¹³, J. Gu¹⁴, Z. Hu¹⁴, Z. Liang¹⁴, J. Liu¹⁴, X. Wang¹⁴, Y. Wang¹⁴, H. Yang¹⁴, S. Zhang¹⁴, Y. Zhao¹⁴, N. Bi¹⁵, G.M. Chen^{XXI,15}, H.S. Chen^{XXI,15}, M. Chen^{XXI,15}, Y. Chen¹⁵, B. Hou^{XXI,15}, Q. Hou¹⁵, F. Iemmi¹⁵, C.H. Jiang¹⁵, H. Liao¹⁵, G. Liu¹⁵, Z.-A. Liu^{XXIX,15}, S. Song¹⁵, J. Tao¹⁵, C. Wang^{XXI,15}, J. Wang¹⁵, A. Zada¹⁵, H. Zhang¹⁵, J. Zhao¹⁵, Y. Ban¹⁶, A. Carvalho Antunes De Oliveira¹⁶, S. Deng¹⁶, X. Geng¹⁶, B. Guo¹⁶, Q. Guo¹⁶, Z. He¹⁶, C. Jiang¹⁶, A. Levin¹⁶, C. Li¹⁶, Q. Li¹⁶, Y. Mao¹⁶, S. Qian¹⁶, S.J. Qian¹⁶, X. Qin¹⁶, C. Quaranta¹⁶, X. Sun¹⁶, D. Wang¹⁶, J. Wang¹⁶, T. Yang¹⁶, M. Zhang¹⁶, Y. Zhao¹⁶, C. Zhou¹⁶, X. Hua¹⁷, S. Yang¹⁷, Z. You¹⁸, N. Lu¹⁹, G. Bauer^{XXXIV,XXXII,III}, L. Chen^{III}, Z. Cui^{XXXII,III}, B. Li^{XXXIII,III}, H. Wang^{III}, K. Yi^{XX,III}, J. Zhang^{III}, F. Zhu^{III}, C. Li²⁰, Y. Li²¹, Y. Zhou^{III,21}, Z. Lin²², C. Lu²², M. Xiao^{XXX,22}, C. Avila²³, A. Cabrera²³, C. Florez²³, J.A. Reyes Vega²³, C. Rendón²⁴, M. Rodriguez²⁴, A.A. Ruales Barbosa²⁴, J.D. Ruiz Alvarez²⁴, N. Godinovic²⁵, D. Lelas²⁵, I. Puljak²⁵, A. Sculac²⁵, M. Kovac²⁶, A. Petkovic²⁶, T. Sculac²⁶, P. Bargassa²⁷, V. Brigljevic²⁷, D. Ferencek²⁷, K. Jakovcic²⁷, A. Starodumov²⁷, T. Susa²⁷, A. Attikis²⁸, S. Konstantinou²⁸, C. Leonidou²⁸, L. Paizanos²⁸, F. Ptochos²⁸, P.A. Razis²⁸, H. Rykaczewski²⁸, H. Saka²⁸, A. Stepenov²⁸, M. Finger^{LXXXIX,29}, M. Finger^{Jr,29}, E. Acurio³⁰, E. Carrera Jarrin³¹, A.A. Abdelalim^{XXXVI,XXXVII,32}, B. El-mahdy^{XXXV,32}, A. Hussein³³, M.A. Mahmoud³³, H. Mohammed³³, K. Jaffel³⁴, M. Kadastik³⁴, T. Lange³⁴, C. Nielsen³⁴, J. Pata³⁴,

M. Raidal³⁴, N. Seeba³⁴, L. Tani³⁴, E. Brücken³⁵, A. Milieva³⁵, K. Osterberg³⁵, M. Voutilainen³⁵, F. Garcia³⁶, T. Hilden³⁶, P. Inkaew³⁶, K.T.S. Kallonen³⁶, R. Kumar Verma³⁶, T. Lampén³⁶, K. Lassila-Perini³⁶, B. Lehtela³⁶, S. Lehti³⁶, T. Lindén³⁶, N.R. Mancilla Xinto³⁶, M. Myllymäki³⁶, M.m. Rantanen³⁶, S. Saariokari³⁶, N.T. Toikka³⁶, J. Tuominiemi³⁶, N. Bin Norjoharuddeen³⁷, H. Kirschenmann³⁷, P. Luukka³⁷, H. Petrow³⁷, M. Besancon³⁸, F. Couderc³⁸, M. Dejardin³⁸, D. Denegri³⁸, P. Devouge³⁸, J.L. Faure³⁸, F. Ferri³⁸, P. Gagne³⁸, S. Ganjour³⁸, P. Gras³⁸, F. Guilloux³⁸, G. Hamel de Monchenault³⁸, M. Kumar³⁸, V. Lohzeic³⁸, Y. Maidannyk³⁸, J. Malcles³⁸, F. Orlandi³⁸, L. Portales³⁸, S. Ronchi³⁸, M.Ö. Sahin³⁸, P. Simkina³⁸, M. Titov³⁸, M. Tornago³⁸, R. Amella Ranz³⁹, F. Beaudette³⁹, K. Biriukov³⁹, G. Boldrini³⁹, P. Busson³⁹, C. Charlot³⁹, M. Chiusi³⁹, T.D. Cuisset³⁹, O. Davignon³⁹, A. De Wit³⁹, T. Debnath³⁹, I.T. Ehle³⁹, S. Ghosh³⁹, A. Gilbert³⁹, R. Granier de Cassagnac³⁹, M. Manoni³⁹, M. Nguyen³⁹, S. Obraztsov³⁹, C. Ochando³⁹, R. Salerno³⁹, J.B. Sauvan³⁹, Y. Sirois³⁹, G. Sokmen³⁹, Y. Song³⁹, L. Urda Gómez³⁹, B. Voirin³⁹, A. Zabi³⁹, A. Zghiche³⁹, J.-L. Agram^{XXXVIII,40}, J. Andrea⁴⁰, D. Bloch⁴⁰, J.-M. Brom⁴⁰, E.C. Chabert⁴⁰, C. Collard⁴⁰, G. Coulon⁴⁰, C. Eschenlauer⁴⁰, S. Falke⁴⁰, U. Goerlach⁴⁰, A.-C. Le Bihan⁴⁰, G. Saha⁴⁰, A. Savoy-Navarro^{XXII,40}, P. Vaucelle⁴⁰, A. Di Florio⁴¹, B. Orzari⁴¹, D. Amram^{IV}, S. Beauceron^{IV}, B. Blancon^{IV}, G. Boudoul^{IV}, N. Chanon^{IV}, D. Contardo^{IV}, P. Depasse^{IV}, H. El Mamouni^{IV}, J. Fay^{IV}, E. Fillaudeau^{IV}, S. Gascon^{IV}, M. Gouzevitch^{IV}, C. Greenberg^{IV}, B. Ille^{IV}, E. Jourdhuy^{IV}, M. Lethuillier^{IV}, K. Long^{IV}, B. MassotEAU^{IV}, L. Mirabito^{IV}, A. Purohit^{IV}, M. Vander Donckt^{IV}, C. Verollet^{IV}, G. Adamov^V, I. Lomidze^V, Z. Tsamalaidze^{LXXXVII,V}, K.F. Adamowicz⁴², V. Botta⁴², S. Consuegra Rodríguez⁴², L. Feld⁴², K. Klein⁴², M. Lipinski⁴², P. Nattland⁴², V. Oppenländer⁴², A. Pauls⁴², D. Pérez Adán⁴², C. Daumann^{VI}, S. Diekmann^{VI}, N. Eich^{VI}, D. Eliseev^{VI}, F. Engelke^{VI}, J. Erdmann^{VI}, M. Erdmann^{VI}, M.Z. Farkas^{VI}, B. Fischer^{VI}, T. Hebbeker^{VI}, K. Hoepfner^{VI}, A. Jung^{VI}, N. Kumar^{VI}, M.y. Lee^{VI}, F. Mausolf^{VI}, M. Merschmeyer^{VI}, A. Meyer^{VI}, A. Pozdnyakov^{VI}, W. Redjeb^{VI}, H. Reithler^{VI}, U. Sarkar^{VI}, V. Sarkisovi^{VI}, A. Schmidt^{VI}, J.G. Schulz^{VI}, C. Seth^{VI}, A. Sharma^{VI}, J.L. Spah^{VI}, V. Vaulin^{VI}, U. Willemsen^{VI}, S. Zaleski^{VI}, F.P. Zinn^{VI}, M.R. Beckers⁴³, G. Flügge⁴³, N. Hoeflich⁴³, T. Kress⁴³, A. Nowack⁴³, O. Pooth⁴³, A. Stahl⁴³, A. Abel^{VII}, M. Aldaya Martin^{VII}, J. Alimena^{VII}, Y. An^{VII}, I. Andreev^{VII}, J. Bach^{VII}, S. Baxter^{VII}, H. Becerril Gonzalez^{VII}, O. Behnke^{VII}, F. Blekman^{VIII,VII}, K. Borras^{VI,VII}, A. Campbell^{VII}, S. Chatterjee^{VII}, L.X. Coll Saravia^{VII}, G. Eckerlin^{VII}, D. Eckstein^{VII}, E. Gallo^{VIII,VII}, A. Geiser^{VII}, M. Guthoff^{VII}, A. Hinzmann^{VII}, M. Kasemann^{VII}, C. Kleinwort^{VII}, R. Kogler^{VII}, M. Komm^{VII}, D. Krücker^{VII}, F. Labe^{VII}, W. Lange^{VII}, D. Leyva Pernia^{VII}, J.h. Li^{VII}, K.-Y. Lin^{VII}, K. Lipka^{XXI,VII}, W. Lohmann^{XXXIX,VII}, J. Malvaso^{VII}, R. Mankel^{VII}, I.-A. Melzer-Pellmann^{VII}, M. Mendizabal Morentin^{VII}, A.B. Meyer^{VII}, G. Milella^{VII}, K. Moral Figueroa^{VII}, A. Mussgiller^{VII}, L.P. Nair^{VII}, J. Niedziela^{VII}, A. Nürnberg^{VII}, J. Park^{VII}, E. Ranken^{VII}, A. Raspereza^{VII}, D. Rastorguev^{VII}, L. Rygaard^{VII}, M. Scham^{XI,VI,VII}, S. Schnake^{VI,VII}, P. Schütze^{VII}, C. Schwanenberger^{VIII,VII}, D. Schwarz^{VII}, D. Selivanova^{VII}, K. Sharko^{VII}, M. Shchedroloviev^{VII}, A. Sritharan^{VII}, D. Stafford^{VII}, M. Torkian^{VII}, S. Vashishtha^{VII}, A. Ventura Barroso^{VII}, R. Walsh^{VII}, D. Wang^{VII}, Q. Wang^{VII}, K. Wichmann^{VII}, L. Wiens^{VI,VII}, C. Wissing^{VII}, Y. Yang^{VII}, S. Zakharov^{VII}, A. Zimmermann Castro Santos^{VII}, A.R. Alves Altrade^{VIII}, M. Antonello^{VIII}, S. Bollweg^{VIII}, M. Bonanomi^{VIII}, L. Ebeling^{VIII}, K. El Morabit^{VIII}, Y. Fischer^{VIII}, M. Frahm^{VIII}, P.P. Gadow^{VIII}, E. Garutti^{VIII}, A. Grohsjean^{VIII}, A.A. Guvenli^{VIII}, J. Haller^{VIII}, D. Hundhausen^{VIII}, M. Jalalvandi^{VIII}, G. Kasieczka^{VIII}, P. Keicher^{VIII}, R. Klanner^{VIII}, W. Korcari^{VIII}, T. Kramer^{VIII}, C.c. Kuo^{VIII}, J. Lange^{VIII}, A. Lobanov^{VIII}, J. Matthiesen^{VIII}, L. Moureaux^{VIII}, K. Nikolopoulos^{VIII}, K.J. Pena Rodriguez^{VIII}, N. Prouvost^{VIII}, B. Raciti^{VIII}, M. Rieger^{VIII}, D. Savoiu^{VIII}, P. Schleper^{VIII}, M. Schröder^{VIII}, J. Schwandt^{VIII},

T. Tore von Schwartz^{VIII}, M. Sommerhalder^{VIII}, H. Stadié^{VIII}, G. Steinbrück^{VIII}, R. Ward^{VIII}, B. Wiederspan^{VIII}, M. Wolf^{VIII}, C. Yede^{VIII}, A. Brusamolino⁴⁴, E. Butz⁴⁴, Y.M. Chen⁴⁴, T. Chwalek⁴⁴, A. Dierlamm⁴⁴, G.G. Dincer⁴⁴, U. Elicabuk⁴⁴, N. Faltermann⁴⁴, M. Giffels⁴⁴, A. Gottmann⁴⁴, F. Hartmann^{XV,44}, F. Hummer⁴⁴, U. Husemann⁴⁴, J. Kieseler⁴⁴, M. Klute⁴⁴, J. Knolle⁴⁴, R. Kunnilan Muhammed Rafeek⁴⁴, O. Lavoryk⁴⁴, J.M. Lawhorn⁴⁴, S. Maier⁴⁴, N. Meenamthuruthil Radhakrishnan⁴⁴, T. Mehner⁴⁴, M. Molch⁴⁴, A.A. Monsch⁴⁴, M. Mormile⁴⁴, Th. Müller⁴⁴, E. Pfeffer⁴⁴, M. Presilla⁴⁴, G. Quast⁴⁴, K. Rabbertz⁴⁴, B. Regnery⁴⁴, R. Schmieder⁴⁴, T. Selezneva⁴⁴, N. Shadskiy⁴⁴, I. Shvetsov⁴⁴, L. Sowa⁴⁴, L. Stockmeier⁴⁴, K. Tauqeer⁴⁴, M. Toms⁴⁴, B. Topko⁴⁴, N. Trevisani⁴⁴, C. Verstege⁴⁴, T. Voigtländer⁴⁴, R.F. Von Cube⁴⁴, J. Von Den Driesch⁴⁴, C. Winter⁴⁴, R. Wolf⁴⁴, W.D. Zeuner⁴⁴, X. Zuo⁴⁴, G. Anagnostou⁴⁵, G. Daskalakis⁴⁵, A. Kyriakis⁴⁵, P. Iosifidou^{IX}, P. Katris^{IX}, M. Kotsarini^{IX}, G. Melachroinos^{IX}, Z. Painesis^{IX}, N. Plastiras^{IX}, N. Saoulidou^{IX}, K. Theofilatos^{IX}, E. Tziaferi^{IX}, E. Tzovara^{IX}, K. Vellidis^{IX}, I. Zisopoulos^{IX}, T. Chatzistavrou⁴⁶, G. Karapostoli⁴⁶, K. Kousouris⁴⁶, K. Paschos⁴⁶, E. Siamarkou⁴⁶, G. Tsiopolitis⁴⁶, I. Evangelou⁴⁷, C. Foudas⁴⁷, P. Katsoulis⁴⁷, P. Kokkas⁴⁷, P.G. Kosmoglou Kioseoglou⁴⁷, N. Manthos⁴⁷, I. Papadopoulos⁴⁷, J. Stroglogas⁴⁷, C. Hajdu^X, D. Horvath^{XII,XLIII,X}, Á. Kadlecik^X, C. Lee^X, K. Márton^X, A.J. Rád^{XI,X}, F. Sikler^X, V. Veszpremi^X, G. Balint^{XI}, M. Csanád^{XI}, D. Cynolter^{XI}, K. Farkas^{XI}, A. Fehérkuti^{X,XI}, M.M.A. Gadallah^{XII,XI}, M. León Coello^{XI}, G. Pásztor^{XI}, G.I. Veres^{XI}, B. Ujvari⁴⁸, G. Zilizi⁴⁸, G. Bencze^{XII}, S. Czellar^{XII}, J. Molnar^{XII}, Z. Szilasi^{XII}, T. Csorgo^{X,49}, F. Nemes^{X,49}, T. Novak⁴⁹, I. Szanyi^{XXI,49}, S. Bahinipati⁵⁰, R. Raturi⁵⁰, S. Bansal⁵¹, S.B. Beri⁵¹, V. Bhatnagar⁵¹, B. Chauhan⁵¹, S. Chauhan⁵¹, N. Dhirga^{XLVI,51}, A. Kaur⁵¹, H. Kaur⁵¹, M. Kaur⁵¹, S. Kumar⁵¹, T. Sheokand⁵¹, J.B. Singh⁵¹, A. Singla⁵¹, K. Verma⁵¹, A. Bhardwaj⁵², A. Chhetri⁵², B.C. Choudhary⁵², A. Kumar⁵², A. Kumar⁵², M. Naimuddin⁵², S. Phor⁵², C. Prakash⁵², K. Ranjan⁵², M.K. Saini⁵², M. Kumari⁵³, P. Palni⁵³, S. Rana⁵³, A. Rathore⁵³, S. Acharya^{XIII,XIII}, B. Gomber^{XIII}, S. Bhattacharya⁵⁴, S. Das Gupta⁵⁴, S. Dutta⁵⁴, S. Dutta⁵⁴, S. Sarkar⁵⁴, M.M. Ameen⁵⁵, P.K. Behera⁵⁵, S. Chatterjee⁵⁵, G. Dash⁵⁵, A. Dattamunsi⁵⁵, P. Jana⁵⁵, P. Kalbhor⁵⁵, S. Kamble⁵⁵, J.R. Komaragiri^{XLIV,55}, P.R. Pujahari⁵⁵, A.K. Sikdar⁵⁵, R.K. Singh⁵⁵, P. Verma⁵⁵, S. Verma⁵⁵, A. Vijay⁵⁵, S. Nayak⁵⁶, H. Rajpoot⁵⁶, B.K. Sirasva⁵⁶, L. Bhatt⁵⁷, S. Dugad⁵⁷, T. Mishra⁵⁷, G.B. Mohanty⁵⁷, M. Shelake⁵⁷, P. Suryadevara⁵⁷, A. Bala⁵⁸, S. Banerjee⁵⁸, S. Barman^{XLVII,58}, R.M. Chatterjee⁵⁸, J. Chhikara⁵⁸, M. Guchait⁵⁸, Sh. Jain⁵⁸, A. Jaiswal⁵⁸, S. Kumar⁵⁸, M. Maity^{XLVII,58}, G. Majumder⁵⁸, K. Mazumdar⁵⁸, R. Pramanik⁵⁸, R. Saxena⁵⁸, P. Sharma⁵⁸, A. Thachayath⁵⁸, D. Maity^{XLV,59}, P. Mal⁵⁹, K. Naskar^{XLV,59}, A. Nayak^{XLV,59}, K. Pal⁵⁹, P. Sadangi⁵⁹, S. Shuchi⁵⁹, S.K. Swain⁵⁹, S. Varghese^{XLV,59}, D. Vats^{XLV,59}, S. Dube⁶⁰, P. Hazarika⁶⁰, B. Kansal⁶⁰, A. Laha⁶⁰, R. Sharma⁶⁰, S. Sharma⁶⁰, K.Y. Vaish⁶⁰, C. Agrawal⁶¹, B. Babu⁶¹, H. Bakhshiansohi^{VII,XIV}, A. Jafari^{XIV,XIV}, V. Sedighzadeh Dalavi^{XIV}, M. Zeinali^{L,XIV}, S. Bashiri⁶², S. Chenarani^{XLIX,62}, S.M. Etesami⁶², Y. Hosseini⁶², M. Khakzad⁶², E. Khazaie⁶², M. Mohammadi Najafabadi⁶², M. Nourbakhsh⁶², S. Tizchang^{XLVIII,62}, M. Felcini⁶³, M. Grunewald⁶³, M. Abbrescia^{65,66}, M. Barbieri^{65,66}, M. Buonsante^{65,66}, A. Colaleo^{65,66}, D. Creanza^{65,67}, N. De Filippis^{65,67}, M. De Palma^{65,66}, W. Elmetenawee^{XXXVI,65,66}, N. Ferrara^{65,67}, L. Fiore⁶⁵, L. Generoso^{65,66}, L. Longo⁶⁵, M. Louka^{65,66}, G. Maggi^{65,67}, M. Maggi⁶⁵, S. My^{65,66}, F. Nenna^{65,66}, S. Nuzzo^{65,66}, A. Pellicchia^{65,66}, A. Pompili^{65,66}, F.M. Procacci^{65,66}, G. Pugliese^{65,67}, R. Radogna^{65,66}, D. Ramos⁶⁵, A. Ranieri⁶⁵, L. Silvestris⁶⁵, F.M. Simone^{65,67}, Ü. Sözbili⁶⁵, A. Stamerra^{65,66}, D. Troiano^{65,66}, R. Venditti^{65,66}, P. Verwilligen⁶⁵, A. Zaza^{65,66}, G. Abbiendi⁶⁹, S. Balducci^{69,70}, C. Battilana^{69,70}, D. Bonacorsi^{69,70}, P. Capiluppi^{69,70}, F.R. Cavallo⁶⁹, M. Cruciani^{69,70}, M. Cuffiani^{69,70}, G.M. Dallavalle⁶⁹, T. Diotallevi^{69,70}, F. Fabbri⁶⁹, R. Farinelli⁶⁹, D. Fasanella⁶⁹, L. Ferragina^{69,70}, P. Giacomelli⁶⁹,

C. Grandi⁶⁹, L. Guiducci^{69,70}, M. Lorusso^{69,70}, L. Lunerti⁶⁹, S. Marcellini⁶⁹, G. Masetti⁶⁹, F.L. Navarria^{69,70}, G. Paggi^{69,70}, A.M. Rossi^{69,70}, S. Rossi Tisbeni^{69,70}, T. Rovelli^{69,70}, G.P. Siroli^{69,70}, S. Costa^{111,72,73}, A. Di Mattia⁷², A. Lapertosa⁷², R. Potenza^{72,73}, A. Tricomi^{111,72,73}, J. Altork^{75,76}, G. Barbagli⁷⁵, G. Bardelli⁷⁵, A. Calandri^{75,76}, B. Camaiani^{75,76}, A. Cassese⁷⁵, R. Ceccarelli⁷⁵, V. Ciulli^{75,76}, C. Civinini⁷⁵, R. D'Alessandro^{75,76}, L. Damenti^{75,76}, E. Focardi^{75,76}, T. Kello⁷⁵, G. Latino^{75,76}, P. Lenzi^{75,76}, M. Lizzo⁷⁵, M. Meschini⁷⁵, S. Paoletti⁷⁵, A. Papanastassiou^{75,76}, G. Sguazzoni⁷⁵, L. Viliani⁷⁵, L. Benussi⁷⁷, S. Colafranceschi^{111,77}, S. Meola^{111,77}, D. Piccolo⁷⁷, M. Alves Gallo Pereira⁷⁹, F. Ferro⁷⁹, E. Robutti⁷⁹, S. Tosi^{79,80}, A. Benaglia⁸², F. Brivio⁸², V. Camagni^{82,83}, F. Cetorelli^{82,83}, F. De Guio^{82,83}, M.E. Dinardo^{82,83}, P. Dini⁸², S. Gennai⁸², R. Gerosa^{82,83}, A. Ghezzi^{82,83}, P. Govoni^{82,83}, L. Guzzi⁸², G. Lavizzari^{82,83}, M.T. Lucchini^{82,83}, M. Malberti⁸², S. Malvezzi⁸², A. Massironi⁸², D. Menasce⁸², L. Moroni⁸², M. Paganoni^{82,83}, S. Palluotto^{82,83}, D. Pedrini⁸², A. Perego^{82,83}, T. Tabarelli de Fatis^{82,83}, S. Buontempo⁸⁵, F. Confortini^{85,86}, C. Di Fraia^{85,86}, F. Fabozzi^{85,87}, L. Favilla^{85,88}, A.O.M. Iorio^{85,86}, L. Lista^{111,85,86}, P. Paolucci^{111,85}, B. Rossi⁸⁵, P. Azzi⁹⁰, N. Bacchetta^{111,90}, D. Bisello^{90,91}, L. Borella⁹⁰, P. Bortignon^{90,92}, G. Bortolato^{90,91}, A.C.M. Bulla^{90,92}, R. Carlin^{90,91}, P. Checchia⁹⁰, T. Dorigo^{111,90}, F. Gasparini^{90,91}, U. Gasparini^{90,91}, S. Giorgetti⁹⁰, P. Grutta⁹⁰, M. Gulmini^{111,90}, N. Lai⁹⁰, E. Lusiani⁹⁰, M. Margoni^{90,91}, A.T. Meneguzzo^{90,91}, M. Missiroli⁹⁰, J. Pazzini^{90,91}, F. Primavera^{90,91}, P. Ronchese^{90,91}, R. Rossin^{90,91}, F. Simonetto^{90,91}, M. Toffano⁹⁰, M. Tosi^{90,91}, A. Triossi^{90,91}, S. Ventura⁹⁰, P. Zotto^{90,91}, A. Zucchetta^{90,91}, S. Abu Zeid^{111,94}, C. Aimè⁹⁴, A. Braghieri⁹⁴, M. Brunoldi^{94,95}, S. Calzaferri^{94,95}, P. Montagna^{94,95}, M. Pelliccioni^{94,95}, V. Re⁹⁴, C. Riccardi^{94,95}, P. Salvini⁹⁴, I. Vai^{94,95}, P. Vitulo^{94,95}, S. Ajmal^{97,98}, M.E. Ascoti^{97,98}, G.M. Bilei^{111,97,98}, W.D. Buitrago Ceballos⁹⁷, C. Carrivale^{97,98}, D. Ciangottini^{97,98}, L. Della Penna^{97,98}, L. Fanò^{97,98}, V. Mariani^{97,98}, M. Menichelli⁹⁷, F. Moscatelli^{111,97}, A. Rossi^{97,98}, A. Santocchia^{97,98}, D. Spiga⁹⁷, T. Tedeschi^{97,98}, C.A. Alexe^{100,102}, P. Asenov^{100,101}, P. Azzurri¹⁰⁰, G. Bagliesi¹⁰⁰, L. Bianchini^{100,101}, T. Boccali¹⁰⁰, E. Bossini¹⁰⁰, D. Bruschini^{100,102}, R. Castaldi¹⁰⁰, F. Cattafesta^{100,102}, M.A. Ciocci^{100,103}, M. Cipriani^{100,101}, R. Dell'Orso¹⁰⁰, S. Donato^{100,101}, A. Feliziani^{100,103}, R. Forti^{100,101}, A. Giassi¹⁰⁰, F. Ligabue^{100,102}, A.C. Marini^{100,101}, A. Messineo^{100,101}, S. Mishra¹⁰⁰, V.K. Muralaeddharan Nair Bindhu^{100,101}, S. Nandan¹⁰⁰, F. Palla¹⁰⁰, M. Riggirello^{100,102}, A. Rizzi^{100,101}, G. Rolandi^{100,102}, A. Scribano¹⁰⁰, P. Solanki^{100,101}, P. Spagnolo¹⁰⁰, F. Tenchini^{100,101}, R. Tenchini¹⁰⁰, G. Tonelli^{100,101}, N. Turini^{100,103}, F. Vaselli^{100,102}, A. Venturi¹⁰⁰, P.G. Verdini¹⁰⁰, P. Akrap^{105,106}, C. Basile^{105,106}, S.C. Behera¹⁰⁵, F. Cavallari¹⁰⁵, L. Cunqueiro Mendez^{105,106}, F. De Ruggi^{105,106}, D. Del Re^{105,106}, M. Del Vecchio^{105,106}, E. Di Marco¹⁰⁵, M. Diemoz¹⁰⁵, F. Errico¹⁰⁵, L. Frosina^{105,106}, R. Gargiulo^{105,106}, B. Harikrishnan^{105,106}, F. Lombardi^{105,106}, L. Martikainen^{105,106}, G. Organtini^{105,106}, N. Palmeri^{105,106}, R. Paramatti^{105,106}, T. Pauletto^{105,106}, S. Rahatlou^{105,106}, C. Rovelli¹⁰⁵, F. Santanastasio^{105,106}, L. Soffi¹⁰⁵, V. Vladimirov^{105,106}, N. Amapane^{108,109}, R. Arcidiacono^{108,110}, S. Argiro^{108,109}, M. Arneodo^{111,108,109}, N. Bartosik^{108,110}, F. Bashir^{108,109}, R. Bellan^{108,109}, A. Bellora^{108,109}, C. Biino¹⁰⁸, C. Borca^{108,109}, N. Cartiglia¹⁰⁸, M. Costa^{108,109}, R. Covarelli^{108,109}, N. Demaria¹⁰⁸, E. Ferrando^{108,109}, L. Finco¹⁰⁸, M. Grippo^{108,109}, B. Kiani^{108,109}, L. Lanteri^{108,109}, F. Luongo^{108,109}, M. Marchisio Caprioglio^{108,109}, C. Mariotti¹⁰⁸, S. Maselli¹⁰⁸, A. Mecca^{108,109}, L. Menzio^{108,109}, P. Meridiani¹⁰⁸, E. Migliore^{108,109}, M. Monteno¹⁰⁸, M.M. Obertino^{108,109}, G. Ortona¹⁰⁸, L. Pacher^{108,109}, N. Pastrone¹⁰⁸, M. Ruspa^{108,110}, F. Siviero^{108,109}, V. Sola^{108,109}, A. Solano¹⁰⁸, A. Staiano¹⁰⁸, C. Tarricone^{108,109}, D. Trocino¹⁰⁸, G. Umoret^{108,109}, E. Vlasov^{108,109}, R. White^{108,109}, J. Babbar^{111,112,113}, S. Belforte¹¹², V. Candelise^{112,113}, M. Casarsa¹¹², F. Cossutti¹¹², K. De Leo¹¹²,

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Jang¹⁴⁴, B. Kim¹⁴⁴, D. Kim¹⁴⁴, S. Kim¹⁴⁴, H.D. Yoo¹⁴⁴, Y. Lee¹⁴⁵, I. Yu¹⁴⁵, T. Beyrouthy^{111,144}, Y. Gharbia^{111,144}, F. Alazemi^{111,145}, K. Dreimanis^{111,146}, O.M. Eberlins^{111,146}, A. Gaile^{111,146}, M. Klevs^{111,146}, C. Munoz Diaz^{111,146}, D. Osite^{111,146}, G. Pikurs^{111,146}, R. Plese^{111,146}, A. Potrebko^{111,146}, M. Seidel^{111,146}, D. Sidiropoulos Kontos^{111,146}, N.R. Strautnieks^{111,147}, M. Ambrozias^{111,148}, A. Juodagalvis^{111,148}, S. Nargelas^{111,148}, S. Nayak^{111,148}, G. Tamulaitis^{111,148}, I. Yusuff^{111,149}, Z. Zolkapli^{111,149}, J.F. Benitez^{111,150}, A. Castaneda Hernandez^{111,150}, A. Cota Rodriguez^{111,150}, L.E. Cuevas Picos^{111,150}, H.A. Encinas Acosta^{111,150}, L.G. Gallegos Maríñez^{111,150}, J.A. Murillo Quijada^{111,150}, L. Valencia Palomo^{111,150}, G. Ayala^{111,151}, H. Castilla-Valdez^{111,151}, H. Crotte Ledesma^{111,151}, R. Lopez-Fernandez^{111,151}, J. Mejia Guisao^{111,151}, R. Reyes-Almanza^{111,151}, A. 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Tran^{XIX}, L. Uplegger^{XIX}, E.W. Vaandering^{XIX}, C. Wang^{XIX}, I. Zoi^{XIX}, C. Aruta¹⁸², P. Avery¹⁸², D. Bourilkov¹⁸², P. Chang¹⁸², V. Cherepanov¹⁸², M. Dittrich¹⁸², R.D. Field¹⁸², C. Huh¹⁸², E. Koenig¹⁸², M. Kolosova¹⁸², J. Konigsberg¹⁸², A. Korytov¹⁸², G. Mitselmakher¹⁸², K. Mohrman¹⁸², A. Muthirakalayil Madhu¹⁸², N. Rawal¹⁸², S. Rosenzweig¹⁸², Y. Takahashi¹⁸², J. Wang¹⁸², T. Adams¹⁸³, A. Al Kadhimi¹⁸³, D. Alam¹⁸³, A. Askew¹⁸³, S. Bower¹⁸³, R. Goff¹⁸³, R. Hashmi¹⁸³, A. Hassani¹⁸³, T. Kolberg¹⁸³, G. Martinez¹⁸³, M. Mazza¹⁸³, H. Prosper¹⁸³, P.R. Prova¹⁸³, R. Yohay¹⁸³, B. Alsufyani¹⁸⁴, S. Das¹⁸⁴, S. Demarest¹⁸⁴, L. Hasa¹⁸⁴, M. Hohmann¹⁸⁴, M. Lavinsky¹⁸⁴, E. Yanes¹⁸⁴, M.R. Adams¹⁸⁵, N. Barnett¹⁸⁵, A. Baty¹⁸⁵, C. Bennett¹⁸⁵, N. Brandman-hughes¹⁸⁵, R. Cavanaugh¹⁸⁵, S.J. Das¹⁸⁵, R. Escobar Franco¹⁸⁵, O. Evdokimov¹⁸⁵, C.E. Gerber¹⁸⁵, H. Gupta¹⁸⁵, M. Hawksworth¹⁸⁵, A. Hingrajiya¹⁸⁵, D.J. Hofman¹⁸⁵, Z. Huang¹⁸⁵, J.h. Lee¹⁸⁵, C. Mills¹⁸⁵, S. Nanda¹⁸⁵, G. Nigmatkulov¹⁸⁵, B. Ozek¹⁸⁵, V. Pant¹⁸⁵, T. Phan¹⁸⁵, D. Pilipovic¹⁸⁵, R. Pradhan¹⁸⁵, E. Prifti¹⁸⁵, T. Roy¹⁸⁵, D. Shekar¹⁸⁵, N. Singh¹⁸⁵, F. Strug¹⁸⁵, A. Thielen¹⁸⁵, M.B. Tonjes¹⁸⁵, N. Varelas¹⁸⁵, M.A. Wadud¹⁸⁵, A. Wang¹⁸⁵, J. Yoo¹⁸⁵, M. Alhusseini^{XX}, D. Blend^{XX}, K. Dilsiz^{LXXVIII,XX}, O.K. Köseyan^{XX}, A. Mestvirishvili^{V,XX}, O. Neogi^{XX}, H. Ogul^{LXXXIII,XX}, Y. Onel^{XX}, A. Penzo^{XX}, C. Snyder^{XX}, B. Blumenfeld¹⁸⁶, J. Davis¹⁸⁶, A.V. Gritsan¹⁸⁶, Z. Huang¹⁸⁶, L. Kang¹⁸⁶, S. Kyriacou¹⁸⁶, P. Maksimovic¹⁸⁶, N. Pinto¹⁸⁶, M. Roguljic¹⁸⁶, S. Sekhar¹⁸⁶, M.V. Srivastav¹⁸⁶, M. Swartz¹⁸⁶, A. Abreu^{XXI}, L.F. Alcerro Alcerro^{XXI}, J. Anguiano^{XXI}, S. Arteaga Escatel^{XXI}, P. Baringer^{XXI}, A. Bean^{XXI}, R. Bhattacharya^{XXI}, M. Chukwuka^{XXI}, Z. Flowers^{XXI}, D. Grove^{XXI}, J. King^{XXI}, G. Krintiras^{XXI}, M. Lazarovits^{XXI}, C. Le Mahieu^{XXI}, J. Marquez^{XXI}, M. Murray^{XXI}, M. Nickel^{XXI}, S. Popescu^{LXXXIX,XXI}, E. Reynolds^{XXI}, C. Rogan^{XXI}, C. Royon^{XXI}, S. Rudrabhatla^{XXI}, S. Sanders^{XXI}, G. Wilson^{XXI}, A. Ahmad¹⁸⁷, B. Allmond¹⁸⁷, N. Islam¹⁸⁷, A. Ivanov¹⁸⁷, K. Kaadze¹⁸⁷, Y. Maravin¹⁸⁷, J. Natoli¹⁸⁷, G.G. Reddy¹⁸⁷, D. Roy¹⁸⁷, G. Sorrentino¹⁸⁷, Z. Alton¹⁸⁸, A. Baden¹⁸⁸, A. Belloni¹⁸⁸, J. Bistany-riebman¹⁸⁸, S.C. Eno¹⁸⁸, N.J. Hadley¹⁸⁸, S. Jabeen¹⁸⁸, R.G. Kellogg¹⁸⁸, T. Koeth¹⁸⁸, B. Kronheim¹⁸⁸, S. Lascio¹⁸⁸, J. Lee¹⁸⁸, P. Major¹⁸⁸, A.C. Mignerey¹⁸⁸, C. Palmer¹⁸⁸, C. Papageorgakis¹⁸⁸, M.M. Paranjpe¹⁸⁸, E. Popova^{LXXXVIII,188}, A. Shevelev¹⁸⁸, M. Wrotny¹⁸⁸, L. Zhang¹⁸⁸, C. Baldenegro Barrera¹⁸⁹, H. Bossi¹⁸⁹, S. Bright-Thonney¹⁸⁹, I.A. Cali¹⁸⁹, Y.c. Chen¹⁸⁹, P.c. Chou¹⁸⁹, M. D'Alfonso¹⁸⁹, K. Devereaux¹⁸⁹, J. Eysermans¹⁸⁹, C. Freer¹⁸⁹, G. Gomez-Ceballos¹⁸⁹, M. Goncharov¹⁸⁹, G. Grosso¹⁸⁹, P. Harris¹⁸⁹, D. Hoang¹⁸⁹, A. Holtermann¹⁸⁹, G.M. Innocenti¹⁸⁹, K. Ivanov¹⁸⁹, G. Kopp¹⁸⁹, B. Cs. Kovács¹⁸⁹, D. Kovalskyi¹⁸⁹, J. Lang¹⁸⁹, L. Lavezzo¹⁸⁹, Y.-J. Lee¹⁸⁹, P. Lugato¹⁸⁹, C. McGinn¹⁸⁹, E. Moreno¹⁸⁹, A. Novak¹⁸⁹, M.I. Park¹⁸⁹, C. Paus¹⁸⁹, C. Reissel¹⁸⁹, C. Roland¹⁸⁹, G. Roland¹⁸⁹, X. Rong¹⁸⁹, S. Rothman¹⁸⁹, T.a. Sheng¹⁸⁹, G.S.F. Stephens¹⁸⁹, D. Walter¹⁸⁹, J. Wang¹⁸⁹, Z. Wang¹⁸⁹, B. Wyslouch¹⁸⁹, T. J. Yang¹⁸⁹, A. Alpina¹⁹⁰, B. Crossman¹⁹⁰, W.J. Jackson¹⁹⁰, C. Kapsiak¹⁹⁰, M. Krohn¹⁹⁰, D. Mahon¹⁹⁰, J. Mans¹⁹⁰, B. Marzocchi¹⁹⁰, R. Rusack¹⁹⁰, O. Sancar¹⁹⁰, R. Saradhy¹⁹⁰, N. Strobbe¹⁹⁰, K. Bloom¹⁹¹, D.R. Claes¹⁹¹, S.V. Dixit¹⁹¹, G. Haza¹⁹¹, J. Hossain¹⁹¹, C. Joo¹⁹¹, I. Kravchenko¹⁹¹, K.H.M. Kwok¹⁹¹, Y. Mehra¹⁹¹, J. Morris¹⁹¹, A. Rohilla¹⁹¹, J.E. Siado¹⁹¹, A. Vagnerini¹⁹¹, A. Wightman¹⁹¹, H. Bandyopadhyay¹⁹², H.w. Hsia¹⁹², I. Iashvili¹⁹², A. Kalogeropoulos¹⁹², A. Kharchilava¹⁹², A. Mandal¹⁹², C. McLean¹⁹², M. Morris¹⁹², D. Nguyen¹⁹², O. Poncet¹⁹², S. Rappoccio¹⁹², H. Rejeb Sfar¹⁹², W. Terrill¹⁹², A. Williams¹⁹², D. Yu¹⁹², A. Aarif¹⁹³, G. Alverson¹⁹³, E. Barberis¹⁹³, S. Bein¹⁹³, J. Bonilla¹⁹³, B. Bylsma¹⁹³, M. Campana¹⁹³, R. Clark¹⁹³, J. Dervan¹⁹³, Y. Haddad¹⁹³, Y. Han¹⁹³, I. Israr¹⁹³, A. Krishna¹⁹³, M. Lu¹⁹³, N. Manganello¹⁹³, R. Mccarthy¹⁹³, D.M. Morse¹⁹³, T. Oritomo¹⁹³, L. Skinnari¹⁹³, C.S. Thoreson¹⁹³, E. Tsai¹⁹³, D. Wood¹⁹³, S. Dittmer¹⁹⁴, K.A. Hahn¹⁹⁴, S. King¹⁹⁴, D. Li¹⁹⁴, M. McGinnis¹⁹⁴, Y. Miao¹⁹⁴, D.G. Monk¹⁹⁴, M.H. Schmitt¹⁹⁴, A. Taliereio¹⁹⁴, M. Velasco¹⁹⁴, J. Wang¹⁹⁴, D. Wilbern¹⁹⁴, G. Agarwal¹⁹⁵, R. Band¹⁹⁵, R. Bucci¹⁹⁵, S. Castells¹⁹⁵, A. Das¹⁹⁵, A. Datta¹⁹⁵, A. Ehnis¹⁹⁵, R. Goldouzian¹⁹⁵, M. Hildreth¹⁹⁵, T. Ivanov¹⁹⁵, C. Jessop¹⁹⁵, K. Lannon¹⁹⁵, J. Lawrence¹⁹⁵, L. Lutton¹⁹⁵, J. Mariano¹⁹⁵, N. Marinelli¹⁹⁵, P. Mastrapasqua¹⁹⁵, A. Masud¹⁹⁵, T. McCauley¹⁹⁵, C. Mcgrady¹⁹⁵, C. Moore¹⁹⁵, Y. Musienko^{LXXXVIII,195}, H. Nelson¹⁹⁵, M. Osherson¹⁹⁵, A. Piccinelli¹⁹⁵, R. Ruchti¹⁹⁵, A. Townsend¹⁹⁵, Y. Wan¹⁹⁵, M. Wayne¹⁹⁵, H. Yockey¹⁹⁵, M. Carrigan¹⁹⁶, R. De Los Santos¹⁹⁶, L.S. Durkin¹⁹⁶, C. Hill¹⁹⁶, M. Joyce¹⁹⁶, L. Nestor¹⁹⁶, D.A. Wenzl¹⁹⁶, B.L. Winer¹⁹⁶, B. R. Yates¹⁹⁶, H. Bouchamaoui¹⁹⁷, G. Dezoort¹⁹⁷, P. Elmer¹⁹⁷, A. Frankenthal¹⁹⁷, M. Galli¹⁹⁷, B. Greenberg¹⁹⁷, K. Kennedy¹⁹⁷, Y. Lai¹⁹⁷, D. Lange¹⁹⁷, A. Loeliger¹⁹⁷, D. Marlow¹⁹⁷, I. Ojalvo¹⁹⁷, J. Olsen¹⁹⁷, F. Simpson¹⁹⁷, D. Stickland¹⁹⁷, C. Tully¹⁹⁷, S. Yoon¹⁹⁷, S. Malik¹⁹⁸, R. Sharma¹⁹⁸, S. Chandra^{XXII}, A. Gu^{XXII}, L. Gutay^{XXII}, M. Huwiler^{XXII}, M. Jones^{XXII}, A.W. Jung^{XXII}, I.G. Karslioglu^{XXII}, D. Kondratyev^{XXII}, J. Li^{XXII}, M. Liu^{XXII}, M. Macedo^{XXII}, G. Negro^{XXII}, N. Neumeister^{XXII}, G. Paspalaki^{XXII}, S. Piperov^{XXII}, N.R. Saha^{XXII}, J.F. Schulte^{XXII}, R. Sharma^{XXII}, F. Wang^{XXII}, A.L. Wesolek^{XXII}, A. Wildridge^{XXII}, W. Xie^{XXII}, Y. Yao^{XXII}, Y. Zhong^{XXII}, N. Parashar¹⁹⁹, A. Pathak¹⁹⁹, E. Shumka¹⁹⁹, D. Acosta²⁰⁰, A. Agrawal²⁰⁰, C. Arbour²⁰⁰, T. Carnahan²⁰⁰, K.M. Ecklund²⁰⁰, F.J.M. Geurts²⁰⁰, I. Krommydas²⁰⁰, N. Lewis²⁰⁰, W. Li²⁰⁰, J. Lin²⁰⁰, X. Liu²⁰⁰, C. Loizides²⁰⁰, O. Miguel Colin²⁰⁰, B.P. Padley²⁰⁰, R. Redjimi²⁰⁰, J. Rotter²⁰⁰, C. Vico Villalba²⁰⁰, M. Wulansatiti²⁰⁰, E. Yigitbasi²⁰⁰, Y. Zhang²⁰⁰, O. Bessidskaia Bylund²⁰¹, A. Bodek²⁰¹, P. de Barbaro^{LXXXIX,201}, R. Demina²⁰¹, A. Garcia-Bellido²⁰¹, H.S. Hare²⁰¹, O. Hindrichs²⁰¹, N. Parmar²⁰¹, P. Parygin^{LXXXVIII,201}, H. Seo²⁰¹, R. Taus²⁰¹, Y.h. Yu²⁰¹, B. Chiarito²⁰², J.P. Chou²⁰², S.V. Clark²⁰², S. Donnelly²⁰², D. Gadkari²⁰², Y. Gershtein²⁰², E. Halkiadakis²⁰², C. Houghton²⁰², D. Jaroslawski²⁰², A. Kobert²⁰², I. Laflotte²⁰², A. Lath²⁰², J. Martins²⁰², P. Meltzer²⁰², M. Perez Prada²⁰², K. Ramdin²⁰², B. Rand²⁰², J. Reichert²⁰², P. Saha²⁰², S. Salur²⁰², S. Somalwar²⁰², R. Stone²⁰², S.A. Thayil²⁰², S. Thomas²⁰², A. K. Virdi²⁰², J. Vora²⁰², A. Abdelhamid²⁰³, D. Ally²⁰³, A.G. Delannoy²⁰³, S. Fiorendi²⁰³, J. Harris²⁰³, T. Holmes²⁰³, A.R. Kanuganti²⁰³, N. Karunarathna²⁰³, J. Lawless²⁰³, L. Lee²⁰³, E. Nibigira²⁰³, B. Skipworth²⁰³, S. Spanier²⁰³, A. Vendraasco²⁰³, D. Aebi²⁰⁴, M.

Ahmad²⁰⁴, T. Akhter²⁰⁴, K. Androsov²⁰⁴, A. Basnet²⁰⁴, A. Bolshov²⁰⁴, O. Bouhali^{LXXXII,204}, A. Cagnotta²⁰⁴, S. Cooperstein²⁰⁴, V. D'Amante²⁰⁴, R. Eusebi²⁰⁴, P. Flanagan²⁰⁴, J. Gilmore²⁰⁴, Y. Guo²⁰⁴, T. Kamon²⁰⁴, S. Luo²⁰⁴, R. Mueller²⁰⁴, G. Pizzati²⁰⁴, A. Safonov²⁰⁴, N. Akchurin²⁰⁵, J. Damgov²⁰⁵, Y. Feng²⁰⁵, N. Gogate²⁰⁵, W. Jin²⁰⁵, S.W. Lee²⁰⁵, C. Madrid²⁰⁵, A. Mankel²⁰⁵, T. Peltola²⁰⁵, I. Volobouev²⁰⁵, E. Appelt²⁰⁶, Y. Chen²⁰⁶, S. Greene²⁰⁶, A. Gurrola²⁰⁶, W. Johns²⁰⁶, R. Kunnawalkam Elayavalli²⁰⁶, A. Melo²⁰⁶, D. Rathjens²⁰⁶, F. Romeo²⁰⁶, S. Tuo²⁰⁶, J. Velkovska²⁰⁶, J. Zhang²⁰⁶, B. Cardwell²⁰⁷, H. Chung²⁰⁷, B. Cox²⁰⁷, J. Hakala²⁰⁷, G. Hamilton Ilha Machado²⁰⁷, R. Hirosky²⁰⁷, M. Jose²⁰⁷, A. Ledovskoy²⁰⁷, C. Mantilla²⁰⁷, C. Neu²⁰⁷, C. Ramón Álvarez²⁰⁷, Z. Wu²⁰⁷, P.E. Karchin²⁰⁸, A. Aravind²⁰⁹, S. Banerjee²⁰⁹, K. Black²⁰⁹, T. Bose²⁰⁹, E. Chavez²⁰⁹, R. Cruz²⁰⁹, S. Dasu²⁰⁹, P. Everaerts²⁰⁹, C. Galloni²⁰⁹, H. He²⁰⁹, M. Herndon²⁰⁹, A. Herve²⁰⁹, C.K. Koraka²⁰⁹, S. Lomte²⁰⁹, R. Loveless²⁰⁹, J. Marquez²⁰⁹, A. Mohammadi²⁰⁹, S. Mondal²⁰⁹, T. Nelson²⁰⁹, G. Parida²⁰⁹, D. Pinna²⁰⁹, A. Savin²⁰⁹, V. Shang²⁰⁹, V. Sharma²⁰⁹, R. Simeon²⁰⁹, W.H. Smith²⁰⁹, D. Teague²⁰⁹, M. Thakore²⁰⁹, A. Thete²⁰⁹, A. Warden²⁰⁹, S. Afanasiev²¹⁰, V. Alexakhin²¹⁰, Yu. Andreev²¹⁰, D. Budkouski²¹⁰, R. Chistov²¹⁰, M. Danilov²¹⁰, T. Dimova²¹⁰, I. Gorbunov²¹⁰, A. Kameney²¹⁰, V. Karjavine²¹⁰, O. Kodolova²¹⁰, V. Korenkov²¹⁰, I. Korsakov²¹⁰, A. Kozyrev²¹⁰, A. Lanev²¹⁰, A. Malakhov²¹⁰, V. Matveev²¹⁰, A. Nikitenko^{XVII,1,210}, V. Palichik²¹⁰, V. Perelygin²¹⁰, O. Radchenko²¹⁰, M. Savina²¹⁰, V. Shalaev²¹⁰, S. Shmatov²¹⁰, S. Shulha²¹⁰, Y. Skovpen²¹⁰, K. Slizhevskiy²¹⁰, V. Smirnov²¹⁰, O. Teryaev²¹⁰, A. Toropin²¹⁰, N. Voytishin²¹⁰, A. Zarubin²¹⁰, I. Zhizhin²¹⁰, L. Dudko²¹¹, V. Kim^{LXXXVIII,211}, V. Murzin²¹¹, V. Oreshkin²¹¹, D. Sosnov²¹¹

Affiliation Notes

^I Also at Yerevan Physics Institute, Yerevan, Armenia

^{II} Also at Ghent University, Ghent, Belgium

^{III} Also at Nanjing Normal University, Nanjing, China

^{IV} Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

^V Also at Georgian Technical University, Tbilisi, Georgia

^{VI} Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

^{VII} Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

^{VIII} Also at University of Hamburg, Hamburg, Germany

^{IX} Also at National and Kapodistrian University of Athens, Athens, Greece

^X Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

^{XI} Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

^{XII} Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

^{XIII} Also at University of Hyderabad, Hyderabad, India

^{XIV} Also at Isfahan University of Technology, Isfahan, Iran

^{XV} Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

^{XVI} Also at Universität Zürich, Zurich, Switzerland

^{XVII} Also at Imperial College, London, United Kingdom

^{XVIII} Also at California Institute of Technology, Pasadena, California, USA

^{XIX} Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA

^{XX} Also at The University of Iowa, Iowa City, Iowa, USA

^{XXI} Also at The University of Kansas, Lawrence, Kansas, USA

^{XXII} Also at Purdue University, West Lafayette, Indiana, USA

^{XXIII} Also at Yerevan State University, Yerevan, Armenia

^{XXIV} Also at TU Wien, Vienna, Austria

^{XXV} Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil

^{XXVI} Also at The University of the State of Amazonas, Manaus, Brazil

^{XXVII} Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

^{XXVIII} Also at Universidade Estadual de Campinas, Campinas, Brazil

^{XXIX} Also at University of Chinese Academy of Sciences, Beijing, China

^{XXX} Also at Center for High Energy Physics, Peking University, Beijing, China

^{XXXI} Also at University of Chinese Academy of Sciences, Beijing, China

^{XXXII} Now at Henan Normal University, Xinxiang, China

^{XXXIII} Also at University of Shanghai for Science and Technology, Shanghai, China

^{XXXIV} Also at School of Physics, Zhengzhou University, Zhengzhou, China

^{XXXV} Also at Cairo University, Cairo, Egypt

^{XXXVI} Also at Helwan University, Cairo, Egypt

^{XXXVII} Now at Zewail City of Science and Technology, Zewail, Egypt

^{XXXVIII} Also at Université de Haute Alsace, Mulhouse, France

^{XXXIX} Also at Brandenburg University of Technology, Cottbus, Germany

^{XL} Also at Forschungszentrum Jülich, Juelich, Germany

^{XLI} Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

^{XLII} Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

^{XLIII} Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

^{XLIV} Also at Indian Institute of Science (IISc), Bangalore, India

^{XLV} Also at Institute of Physics, Bhubaneswar, India

^{XLVI} Also at Punjab Agricultural University, Ludhiana, India

^{XLVII} Also at University of Visva-Bharati, Santiniketan, India

^{XLVIII} Also at Department of Physics, Faculty of Science, Arak University, Arak, Iran

^{XLIX} Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran

^L Also at Sharif University of Technology, Tehran, Iran

^{LI} Also at Ain Shams University, Cairo, Egypt

^{LII} Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy

^{LIII} Also at UPES - University of Petroleum and Energy Studies, Dehradun, India

^{LIV} Also at James Madison University, Harrisonburg, Maryland, USA

^{LV} Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy

^{LVI} Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy

^{LVII} Also at Lulea University of Technology, Lulea, Sweden

^{LVIII} Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy

^{LIX} Also at Università degli Studi Guglielmo Marconi, Roma, Italy

^{LX} Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia

^{LXI} Also at Saegis Campus, Nugegoda, Sri Lanka

^{LXII} Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka

^{LXIII} Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland

^{LXIV} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

^{LXV} Also at Adiyaman University, Adiyaman, Turkey

^{LXVI} Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey

^{LXVII} Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

^{LXVIII} Also at Istinye University, Istanbul, Turkey

^{LXIX} Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey

^{LXX} Also at Milli Savunma University, Istanbul, Turkey

^{LXXI} Also at Izmir Bakircay University, Izmir, Turkey

^{LXXII} Also at Kafkas University, Kars, Turkey

^{LXXIII} Also at Konya Technical University, Konya, Turkey

^{LXXIV} Also at Marmara University, Istanbul, Turkey

^{LXXV} Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

LXXVI Now at Istanbul Okan University, Istanbul, Turkey
 LXXVII Also at United States Naval Academy, Annapolis, Maryland, USA
 LXXVIII Also at Bingol University, Bingol, Turkey
 LXXIX Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
 LXXX Also at California Lutheran University, Thousand Oaks, California, USA
 LXXXI Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
 LXXXII Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
 LXXXIII Also at Sinop University, Sinop, Turkey
 LXXXIV Also at Università di Torino, Torino, Italy
 LXXXV Also at Monash University, Faculty of Science, Clayton, Australia
 LXXXVI Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
 LXXXVII Also at Another institute or international laboratory covered by a cooperation agreement with CERN
 LXXXVIII Also at Another institute formerly covered by a cooperation agreement with CERN
 LXXXIX Deceased

Collaboration Institutes

- ¹ Marietta Blau Institute for Particle Physics, Vienna, Austria
- ² Universiteit Antwerpen, Antwerpen, Belgium
- ³ Vrije Universiteit Brussel, Brussel, Belgium
- ⁴ Université Libre de Bruxelles, Bruxelles, Belgium
- ⁵ Université Catholique de Louvain, Louvain-la-Neuve, Belgium
- ⁶ Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
- ⁷ Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- ⁸ Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
- ⁹ Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
- ¹⁰ University of Sofia, Sofia, Bulgaria
- ¹¹ Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
- ¹² Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
- ¹³ Beihang University, Beijing, China
- ¹⁴ Department of Physics, Tsinghua University, Beijing, China
- ¹⁵ Institute of High Energy Physics, Beijing, China
- ¹⁶ State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- ¹⁷ State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China
- ¹⁸ Sun Yat-Sen University, Guangzhou, China
- ¹⁹ University of Science and Technology of China, Hefei, China
- ²⁰ Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China
- ²¹ Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
- ²² Zhejiang University, Hangzhou, Zhejiang, China
- ²³ Universidad de Los Andes, Bogota, Colombia
- ²⁴ Universidad de Antioquia, Medellin, Colombia
- ²⁵ University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
- ²⁶ University of Split, Faculty of Science, Split, Croatia
- ²⁷ Institute Rudjer Boskovic, Zagreb, Croatia
- ²⁸ University of Cyprus, Nicosia, Cyprus
- ²⁹ Charles University, Prague, Czech Republic
- ³⁰ Escuela Politecnica Nacional, Quito, Ecuador
- ³¹ Universidad San Francisco de Quito, Quito, Ecuador
- ³² Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
- ³³ Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
- ³⁴ National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- ³⁵ Department of Physics, University of Helsinki, Helsinki, Finland
- ³⁶ Helsinki Institute of Physics, Helsinki, Finland
- ³⁷ Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
- ³⁸ IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ³⁹ Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
- ⁴⁰ Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
- ⁴¹ Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
- ⁴² RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
- ⁴³ RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
- ⁴⁴ Karlsruher Institut fuer Technologie, Karlsruhe, Germany
- ⁴⁵ Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
- ⁴⁶ National Technical University of Athens, Athens, Greece
- ⁴⁷ University of Ioánnina, Ioánnina, Greece
- ⁴⁸ Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ⁴⁹ Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ⁵⁰ IIT Bhubaneswar, Bhubaneswar, India
- ⁵¹ Panjab University, Chandigarh, India
- ⁵² University of Delhi, Delhi, India
- ⁵³ Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India
- ⁵⁴ Saha Institute of Nuclear Physics, HBNI, Kolkata, India
- ⁵⁵ Indian Institute of Technology Madras, Madras, India
- ⁵⁶ IISER Mohali, India, Mohali, India
- ⁵⁷ Tata Institute of Fundamental Research-A, Mumbai, India
- ⁵⁸ Tata Institute of Fundamental Research-B, Mumbai, India
- ⁵⁹ National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
- ⁶⁰ Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶¹ Indian Institute of Technology Hyderabad, Telangana, India
- ⁶² Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶³ University College Dublin, Dublin, Ireland
- ⁶⁴ INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
- ⁶⁵ INFN Sezione di Bari, Bari, Italy
- ⁶⁶ Università di Bari, Bari, Italy
- ⁶⁷ Politecnico di Bari, Bari, Italy
- ⁶⁸ INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
- ⁶⁹ INFN Sezione di Bologna, Bologna, Italy
- ⁷⁰ Università di Bologna, Bologna, Italy
- ⁷¹ INFN Sezione di Catania, Università di Catania, Catania, Italy
- ⁷² INFN Sezione di Catania, Catania, Italy
- ⁷³ Università di Catania, Catania, Italy
- ⁷⁴ INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
- ⁷⁵ INFN Sezione di Firenze, Firenze, Italy
- ⁷⁶ Università di Firenze, Firenze, Italy
- ⁷⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁷⁸ INFN Sezione di Genova, Università di Genova, Genova, Italy
- ⁷⁹ INFN Sezione di Genova, Genova, Italy
- ⁸⁰ Università di Genova, Genova, Italy
- ⁸¹ INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
- ⁸² INFN Sezione di Milano-Bicocca, Milano, Italy
- ⁸³ Università di Milano-Bicocca, Milano, Italy
- ⁸⁴ INFN Sezione di Napoli, Università di Napoli 'Federico II', Napoli, Italy, Università della Basilicata, Potenza, Italy, Scuola Superiore Meridionale (SSM), Napoli, Italy
- ⁸⁵ INFN Sezione di Napoli, Napoli, Italy
- ⁸⁶ Università di Napoli 'Federico II', Napoli, Italy
- ⁸⁷ Università della Basilicata, Potenza, Italy

- ⁸⁸ Scuola Superiore Meridionale (SSM), Napoli, Italy
- ⁸⁹ INFN Sezione di Padova, Università di Padova, Padova, Italy, Università degli Studi di Cagliari, Cagliari, Italy
- ⁹⁰ INFN Sezione di Padova, Padova, Italy
- ⁹¹ Università di Padova, Padova, Italy
- ⁹² Università degli Studi di Cagliari, Cagliari, Italy
- ⁹³ INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁹⁴ INFN Sezione di Pavia, Pavia, Italy
- ⁹⁵ Università di Pavia, Pavia, Italy
- ⁹⁶ INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
- ⁹⁷ INFN Sezione di Perugia, Perugia, Italy
- ⁹⁸ Università di Perugia, Perugia, Italy
- ⁹⁹ INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa Italy, Università di Siena, Siena, Italy
- ¹⁰⁰ INFN Sezione di Pisa, Pisa, Italy
- ¹⁰¹ Università di Pisa, Pisa, Italy
- ¹⁰² Scuola Normale Superiore di Pisa, Pisa, Italy
- ¹⁰³ Università di Siena, Siena, Italy
- ¹⁰⁴ INFN Sezione di Roma, Sapienza Università di Roma, Roma, Italy
- ¹⁰⁵ INFN Sezione di Roma, Roma, Italy
- ¹⁰⁶ Sapienza Università di Roma, Roma, Italy
- ¹⁰⁷ INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
- ¹⁰⁸ INFN Sezione di Torino, Torino, Italy
- ¹⁰⁹ Università di Torino, Torino, Italy
- ¹¹⁰ Università del Piemonte Orientale, Novara, Italy
- ¹¹¹ INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
- ¹¹² INFN Sezione di Trieste, Trieste, Italy
- ¹¹³ Università di Trieste, Trieste, Italy
- ¹¹⁴ College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
- ¹¹⁵ Kuwait University - College of Science - Department of Physics, Safat, Kuwait
- ¹¹⁶ Riga Technical University, Riga, Latvia
- ¹¹⁷ University of Latvia (LU), Riga, Latvia
- ¹¹⁸ Vilnius University, Vilnius, Lithuania
- ¹¹⁹ National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
- ¹²⁰ Universidad de Sonora (UNISON), Hermosillo, Mexico
- ¹²¹ Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico
- ¹²² Universidad Iberoamericana, Mexico City, Mexico
- ¹²³ Benemerita Universidad Autónoma de Puebla, Puebla, Mexico
- ¹²⁴ University of Montenegro, Podgorica, Montenegro
- ¹²⁵ University of Canterbury, Christchurch, New Zealand
- ¹²⁶ National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
- ¹²⁷ AGH University of Krakow, Krakow, Poland
- ¹²⁸ National Centre for Nuclear Research, Swierk, Poland
- ¹²⁹ Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
- ¹³⁰ Warsaw University of Technology, Warsaw, Poland
- ¹³¹ Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
- ¹³² Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ¹³³ VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
- ¹³⁴ Kyungpook National University, Daegu, South Korea
- ¹³⁵ Department of Mathematics and Physics - GWN, Gangneung, South Korea
- ¹³⁶ Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, South Korea
- ¹³⁷ Department of Physics, Chung-Ang University, Seoul, South Korea
- ¹³⁸ Hanyang University, Seoul, South Korea
- ¹³⁹ Korea University, Seoul, South Korea
- ¹⁴⁰ Kyung Hee University, Department of Physics, Seoul, South Korea
- ¹⁴¹ Sejong University, Seoul, South Korea
- ¹⁴² Seoul National University, Seoul, South Korea
- ¹⁴³ University of Seoul, Seoul, South Korea
- ¹⁴⁴ Yonsei University, Department of Physics, Seoul, South Korea
- ¹⁴⁵ Sungkyunkwan University, Suwon, South Korea
- ¹⁴⁶ Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹⁴⁷ Universidad Autónoma de Madrid, Madrid, Spain
- ¹⁴⁸ Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
- ¹⁴⁹ Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
- ¹⁵⁰ University of Colombo, Colombo, Sri Lanka
- ¹⁵¹ University of Ruhuna, Department of Physics, Matara, Sri Lanka
- ¹⁵² PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
- ¹⁵³ ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
- ¹⁵⁴ National Central University, Chung-Li, Taiwan
- ¹⁵⁵ National Taiwan University (NTU), Taipei, Taiwan
- ¹⁵⁶ High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
- ¹⁵⁷ Tunis El Manar University, Tunis, Tunisia
- ¹⁵⁸ Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
- ¹⁵⁹ Hacettepe University, Ankara, Turkey
- ¹⁶⁰ Bogazici University, Istanbul, Turkey
- ¹⁶¹ Istanbul Technical University, Istanbul, Turkey
- ¹⁶² Istanbul University, Istanbul, Turkey
- ¹⁶³ Yildiz Technical University, Istanbul, Turkey
- ¹⁶⁴ National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
- ¹⁶⁵ University of Bristol, Bristol, United Kingdom
- ¹⁶⁶ Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹⁶⁷ Brunel University, Uxbridge, United Kingdom
- ¹⁶⁸ Baylor University, Waco, Texas, USA
- ¹⁶⁹ Bethel University, St. Paul, Minnesota, USA
- ¹⁷⁰ Catholic University of America, Washington, DC, USA
- ¹⁷¹ The University of Alabama, Tuscaloosa, Alabama, USA
- ¹⁷² Boston University, Boston, Massachusetts, USA
- ¹⁷³ Brown University, Providence, Rhode Island, USA
- ¹⁷⁴ University of California, Davis, Davis, California, USA
- ¹⁷⁵ University of California, Los Angeles, California, USA
- ¹⁷⁶ University of California, Riverside, Riverside, California, USA
- ¹⁷⁷ University of California, San Diego, La Jolla, California, USA
- ¹⁷⁸ University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
- ¹⁷⁹ Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
- ¹⁸⁰ University of Colorado Boulder, Boulder, Colorado, USA
- ¹⁸¹ Cornell University, Ithaca, New York, USA
- ¹⁸² University of Florida, Gainesville, Florida, USA
- ¹⁸³ Florida State University, Tallahassee, Florida, USA
- ¹⁸⁴ Florida Institute of Technology, Melbourne, Florida, USA
- ¹⁸⁵ University of Illinois Chicago, Chicago, Illinois, USA
- ¹⁸⁶ Johns Hopkins University, Baltimore, Maryland, USA
- ¹⁸⁷ Kansas State University, Manhattan, Kansas, USA
- ¹⁸⁸ University of Maryland, College Park, Maryland, USA
- ¹⁸⁹ Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
- ¹⁹⁰ University of Minnesota, Minneapolis, Minnesota, USA
- ¹⁹¹ University of Nebraska-Lincoln, Lincoln, Nebraska, USA
- ¹⁹² State University of New York at Buffalo, Buffalo, New York, USA
- ¹⁹³ Northeastern University, Boston, Massachusetts, USA
- ¹⁹⁴ Northwestern University, Evanston, Illinois, USA
- ¹⁹⁵ University of Notre Dame, Notre Dame, Indiana, USA
- ¹⁹⁶ The Ohio State University, Columbus, Ohio, USA
- ¹⁹⁷ Princeton University, Princeton, New Jersey, USA

- ¹⁹⁸ University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁹⁹ Purdue University Northwest, Hammond, Indiana, USA
²⁰⁰ Rice University, Houston, Texas, USA
²⁰¹ University of Rochester, Rochester, New York, USA
²⁰² Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
²⁰³ University of Tennessee, Knoxville, Tennessee, USA
²⁰⁴ Texas A&M University, College Station, Texas, USA
²⁰⁵ Texas Tech University, Lubbock, Texas, USA
²⁰⁶ Vanderbilt University, Nashville, Tennessee, USA
²⁰⁷ University of Virginia, Charlottesville, Virginia, USA
²⁰⁸ Wayne State University, Detroit, Michigan, USA
²⁰⁹ University of Wisconsin - Madison, Madison, Wisconsin, USA
²¹⁰ An institute or international laboratory covered by a cooperation agreement with CERN
²¹¹ An institute formerly covered by a cooperation agreement with CERN

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