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Extracting the speed of sound in quark–gluon plasma with ultrarelativistic lead–lead collisions at the LHC

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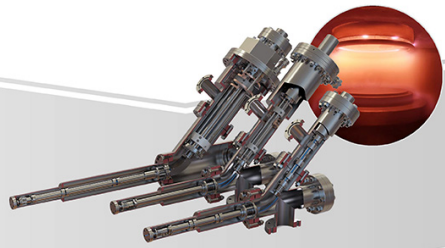
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Extracting the speed of sound in quark–gluon plasma with ultrarelativistic lead–lead collisions at the LHC

The CMS Collaboration

CERN, Geneva, Switzerland

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

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Abstract

Ultrarelativistic nuclear collisions create a strongly interacting state of hot and dense quark–gluon matter that exhibits a remarkable collective flow behavior with minimal viscous dissipation. To gain deeper insights into its intrinsic nature and fundamental degrees of freedom, we determine the speed of sound in an extended volume of quark–gluon plasma using lead–lead (PbPb) collisions at a center-of-mass energy per nucleon pair of 5.02 TeV. The data were recorded by the CMS experiment at the CERN LHC and correspond to an integrated luminosity of 0.607 nb^{-1} . The measurement is performed by studying the multiplicity dependence of the average transverse momentum of charged particles emitted in head-on PbPb collisions. Our findings reveal that the speed of sound in this matter is nearly half the speed of light, with a squared value of $0.241 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (syst)}$ in natural units. The effective medium temperature, estimated using the mean transverse momentum, is $219 \pm 8 \text{ (syst) MeV}$. The measured squared speed of sound at this temperature aligns precisely with predictions from lattice quantum chromodynamic (QCD) calculations. This result provides a stringent constraint on the equation of state of the created medium and direct evidence for a deconfined QCD phase being attained in relativistic nuclear collisions.

Keywords: CMS, quark–gluon plasma, speed of sound, ultra-central, QCD equation of state

1. Introduction

When heavy atomic nuclei collide at relativistic speeds, a transformation occurs, giving rise to an exotic state of matter with a temperature above several trillion kelvin and known as the quark–gluon plasma (QGP) [1–4]. In this

realm of extreme temperatures, quarks and gluons break free from their confined existence inside hadrons, traversing long distances (e.g. several fm) compared to the size of individual nucleons. The emergence of the QGP represents a fundamental prediction of quantum chromodynamics (QCDs) [5, 6], the theory that elucidates the nature of the strong force. More remarkably, this strongly interacting QGP matter is found to exhibit the characteristics of an almost ‘perfect liquid’ with little frictional momentum dissipation [7–10]. Its collective dynamics and macroscopic properties are well described by the principles of nearly ideal relativistic hydrodynamics.



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The equation of state (EoS) reveals the underlying fundamental degrees of freedom of a substance and is an invaluable tool to infer how the substance will respond to changes in its energy density. In fluid-like environments, the study of sound modes arising from longitudinal compression provides a means to determine the corresponding speed of sound, denoted as c_s . This parameter, whose square is defined as the rate of pressure P change in response to variations in energy density ε , $c_s^2 = dP/d\varepsilon$ [11], plays a pivotal role in characterizing the nature of the medium under investigation and in constraining models of corresponding EoS. The exploration of the sound wave propagation in strongly correlated systems, ranging from neutron stars to ultracold atomic gases [12, 13], has garnered significant interest in recent years. Various methodologies have been proposed to experimentally extract the speed of sound in a QGP fluid [14–18], offering a direct means to constrain the QCD EoS. Notably, constraints on the speed of sound in hot QCD matter have been inferred through a comparison of relativistic nuclear collision data with theoretical models within a Bayesian framework [15]. Recently, an effort to directly extract c_s^2 in the QGP phase was made by establishing a connection to an effective static, uniform fluid system [16]. That work was based on only two independent measurements of the charged-particle multiplicity density and mean transverse momentum (p_T) in lead–lead (PbPb) collision data from the ALICE experiment at center-of-mass energies per nucleon pair $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, and yielded a value of $c_s^2 = 0.24 \pm 0.04$ in natural units at a temperature of 222 ± 9 MeV. This result is in line with lattice QCD predictions, albeit subject to significant experimental uncertainties.

To increase the precision by which the speed of sound can be determined, a new hydrodynamic probe was later proposed in [17] utilizing the multiplicity dependence of mean p_T measurements at a fixed $\sqrt{s_{NN}}$. This innovative technique makes use of ‘ultra-central’ collisions in which the ions overlap almost entirely, i.e. collide at a very small impact parameter (b). A conceptual representation of this probe is illustrated in figure 1. The impact parameter of a heavy ion collision determines the size of the nuclear overlap region (system size), which is strongly correlated with the energy and entropy deposited in the initial state and the number of emitted charged particles in the final state (‘multiplicity’, N_{ch}). As the impact parameter decreases and collisions become increasingly central, both the system size and deposited energy increase, while maintaining a nearly constant initial energy density and temperature. However, this trend reaches its limit when $b \rightarrow 0$. In this case, the initial system size is limited by the sizes of the participating nuclei. For symmetric PbPb collisions, this would be the size of a Pb nucleus. More energy and entropy can still be deposited into the fixed volume through fluctuations in the number of interacting partons. By examining the response of the temperature T to the increasing entropy density s at $b \sim 0$, the speed of sound can be extracted based on fundamental thermodynamic laws,

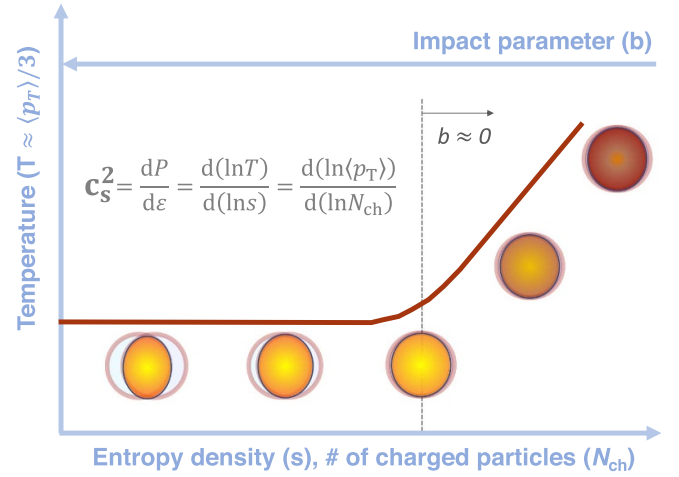


Figure 1. Conceptual representation of temperature vs. entropy density from mid-central to ultra-central heavy ion collisions.

$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{s dT}{T ds} = \frac{d\langle p_T \rangle / \langle p_T \rangle}{dN_{ch} / N_{ch}}. \quad (1)$$

Here, in terms of experimental observables, s is directly proportional to N_{ch} , while the temperature T relates to the average transverse momentum ($\langle p_T \rangle$) of emitted particles with respect to the beam axis [16]. Full hydrodynamic simulations, such as those made possible using the TRAJETUM model [19], have verified the above relationship, although there are features that are not captured, as will be discussed later. As the c_s^2 value depends only on the relative variation in $\langle p_T \rangle$ and N_{ch} , any global changes to the observables, such as an increase in the system entropy through hadronic resonance decays [20], will not affect the result.

In this paper, we present a precise determination of the speed of sound in QGP using ultra-central PbPb collision data at $\sqrt{s_{NN}} = 5.02$ TeV, collected in 2018 by the CMS experiment at the CERN LHC. By achieving a level of precision of several percent, comparable to theoretical uncertainties, our results serve as a robust benchmark for comparison with hydrodynamic simulations and lattice QCD calculations of the EoS. These comparisons provide the most stringent and direct constraints on the degrees of freedom attained by the medium created in these collisions. Tabulated results are provided in the HEPData record for this analysis [21].

2. The CMS detector

The CMS apparatus [22] is a multipurpose, nearly hermetic detector, designed to trigger on [23, 24] and identify electrons, muons, photons, and hadrons [25–27]. The initial triggering is done with the level-1 system, which uses customized hardware to make the rapid online decision whether or not to accept an event and deliver it to the second system, the high

level trigger (HLT). The HLT uses a large CPU farm to perform optimized online event reconstruction and characterize an event. A global ‘particle-flow’ algorithm [28] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon pixel and strip 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. Hadron forward (HF) calorimeters [29], made of steel and quartz fibers, extend the pseudorapidity ($\eta = -\ln(\tan(\theta/2))$, where the polar angle θ is defined relative to the counterclockwise beam) coverage provided by the barrel and endcap detectors. Two zero-degree calorimeters (ZDCs) [30], made of quartz-fibers and plates embedded in tungsten absorbers, are used to detect neutrons from nuclear dissociation events.

3. Data samples, event reconstruction and selection

The data analyzed, before applying the selection described below, consist of 4.27×10^9 minimum bias events, corresponding to an integrated luminosity of 0.607 nb^{-1} . The minimum bias events are triggered by requiring total energy signals above readout thresholds, which are in the range 6–12 GeV, on both sides of the HF calorimeters [24]. Beam-gas interactions and nonhadronic collisions are rejected by requiring the shapes of the clusters in the pixel tracker to be compatible with those expected from particles produced by a PbPb collision [31]. The events are also required to have at least one reconstructed primary vertex associated with two or more tracks within a distance of 15 cm from the nominal interaction point along the beam axis. The primary vertex is selected as the one with the highest track multiplicity in the event. Events with concurrent interactions per bunch crossing contribute to about 0.5% of the full data sample and are rejected based on the correlation of total energy deposited in the HF and ZDC detectors, following the procedure used in [32]. The collision centrality in PbPb events, i.e. the degree of overlap or impact parameter of the two colliding nuclei, is commonly determined by the total transverse energy deposit in both HF calorimeters, $E_{T,\text{sum}}^{\text{HF}}$ [31]. As the main focus of this work is on collisions at small impact parameters, we analyzed only the 10% of PbPb events that had the largest $E_{T,\text{sum}}^{\text{HF}}$. This class contains the ultra-central collision events of interest.

To ease the computational load for high-multiplicity central PbPb collisions, track reconstruction for PbPb events is done in two iterations. The first iteration reconstructs tracks from signals (‘hits’) in the silicon pixel and strip tracker that are compatible with trajectories of particles with $p_T > 1.0 \text{ GeV}$, while the second iteration reconstructs tracks compatible with trajectories of particles with $0.3 < p_T < 1.0 \text{ GeV}$ using solely the pixel detector. In the analysis, the tracks have the additional selection requirement of $|\eta| < 0.5$ for the best

tracking performance. More details on the track reconstruction and selection can be found in [33]. The tracking efficiency (ε_{eff}) and misreconstruction rate (ε_{mis}) are evaluated using the HYDJET [34] event generator, together with a full GEANT4 [35] simulation of the CMS detector response. These factors are combined to obtain an overall correction factor, $\varepsilon_{\text{trk}} = \varepsilon_{\text{eff}}/(1 - \varepsilon_{\text{mis}})$, which is used to account for detector effects on the total number of reconstructed tracks. The ε_{trk} factor is calibrated not only in terms of p_T and η , but also as a function of the detector occupancy. The occupancy is estimated by the total number of clusters registered in the silicon pixel tracker N_{pixel} , where a weak linear decline of ε_{trk} by up to 7% over an increase of N_{pixel} by 30% is observed. In the analysis, each track is assigned a weight of $1/\varepsilon_{\text{trk}}(\eta, p_T, N_{\text{pixel}})$ to account for track reconstruction effects.

4. Measurement method

The main experimental observable of this analysis is the mean transverse momentum $\langle p_T \rangle$ of charged particles in an event as a function of N_{ch} , where $\langle p_T \rangle$ and N_{ch} are measured within the same η and p_T ranges (otherwise, rapidity-dependent entropy fluctuations would lead to a reduced signal [17]). Charged particle p_T spectra for $p_T > 0.3 \text{ GeV}$ are measured for events in 50 GeV intervals of $E_{T,\text{sum}}^{\text{HF}}$ from 3400 GeV to 5200 GeV, with tracking efficiency and misreconstruction effects corrected. To avoid any bias in estimating $\langle p_T \rangle$ and N_{ch} , it is necessary to extrapolate the measured p_T spectra to the full p_T range. The resulting $\langle p_T \rangle$ values (mean of the p_T spectra) from all $E_{T,\text{sum}}^{\text{HF}}$ intervals are then plotted against the corresponding N_{ch} values (integral of the p_T spectra) to form the final observable. The $E_{T,\text{sum}}^{\text{HF}}$ variable essentially serves as a centrality estimator to vary the initial medium entropy density and temperature. In particular, as the $E_{T,\text{sum}}^{\text{HF}}$ values are obtained in a forward η range that does not overlap with the range used to measure the corresponding $\langle p_T \rangle$ and N_{ch} values, potential biases are avoided. For example, hard processes originating early in the collision tend to fragment into large numbers of high- p_T particles, yet these particles may not reflect an increase in the entropy and temperature of the QGP medium.

The extrapolation of the p_T spectra to the full p_T range is performed by fitting a Hagedorn function [36] to the measured p_T spectra over the range of $0.4 < p_T < 4.5 \text{ GeV}$ in each $E_{T,\text{sum}}^{\text{HF}}$ interval. This method is found to provide an excellent description of the data [37] and models (TRAJECTUM and HYDJET). The chosen p_T range for the fitting is varied to evaluate corresponding uncertainties. The fitted functions are then used to extrapolate the missing portions of the p_T spectra in the low- p_T region.

As the extraction of the speed of sound mainly depends on the relative variation of $\langle p_T \rangle$ with respect to N_{ch} (see equation (1)), normalized quantities, $\langle p_T \rangle^{\text{norm}} = \langle p_T \rangle / \langle p_T \rangle^0$ and $N_{\text{ch}}^{\text{norm}} = N_{\text{ch}} / N_{\text{ch}}^0$, are used as the primary observables, where the $\langle p_T \rangle^0$ and N_{ch}^0 represent the mean transverse

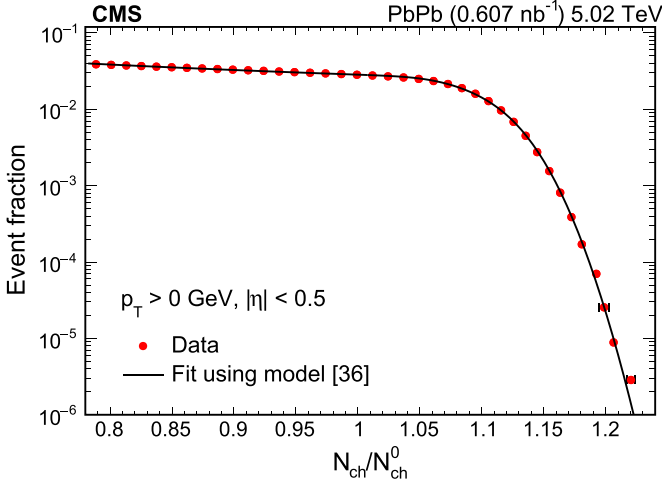


Figure 2. The event fraction distribution as a function of the charged-particle multiplicity, N_{ch} , within the kinematic range of $|\eta| < 0.5$ and extrapolated to the full p_{T} range, in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The N_{ch} value is normalized by its value in the 0%–5% centrality class (N_{ch}^0). The curve represents a fit to the data using the Das *et al* model [39].

momentum and charged-particle multiplicity in a reference event class. Here, the centrality range chosen for the reference event class only needs to be close to that used for the speed of sound determination, and 5% most central events (as determined by $E_{\text{T,sum}}^{\text{HF}}$ and denoted ‘0%–5%’) is used. By normalizing both $\langle p_{\text{T}} \rangle$ and N_{ch} by their values in the reference event class, most of the systematic uncertainties can be minimized. The $\langle p_{\text{T}} \rangle^0$ and N_{ch}^0 values obtained are found to be in good agreement with the ALICE results in the 0%–5% centrality range [37, 38]. Figure 2 shows the event fraction distribution as a function of the normalized multiplicity.

To extract the speed of sound, the expression that describes $\langle p_{\text{T}} \rangle^{\text{norm}}$ as a function of $N_{\text{ch}}^{\text{norm}}$ is taken from [17], as

$$\langle p_{\text{T}} \rangle^{\text{norm}} = \left(\frac{N_{\text{ch}}^{\text{norm}}}{\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \rangle} \right)^{c_s^2}, \quad (2)$$

where,

$$\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \rangle = N_{\text{ch}}^{\text{norm}} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(N_{\text{ch}}^{\text{norm}} - \overline{N_{\text{ch}}^{\text{knee}}})^2}{2\sigma^2}\right)}{\text{erfc}\left(\frac{N_{\text{ch}}^{\text{norm}} - \overline{N_{\text{ch}}^{\text{knee}}}}{\sqrt{2}\sigma}\right)}. \quad (3)$$

Here, $\overline{N_{\text{ch}}^{\text{knee}}}$ and σ represent the mean and root-mean-square width of the charged-particle multiplicity distribution at $b = 0$, normalized by N_{ch}^0 . In figure 2, the $\overline{N_{\text{ch}}^{\text{knee}}}$ value corresponds to the vicinity of the location beyond which the knee-shaped distribution starts rapidly falling. For the region of $N_{\text{ch}}^{\text{norm}} < \overline{N_{\text{ch}}^{\text{knee}}}$, the $\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \rangle$ variable approximately reduces to $N_{\text{ch}}^{\text{norm}}$, so

equation (2) yields a value of unity. For the region of $N_{\text{ch}}^{\text{norm}} > \overline{N_{\text{ch}}^{\text{knee}}}$, the $\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \rangle$ variable saturates at $\overline{N_{\text{ch}}^{\text{knee}}}$ for sufficiently large $N_{\text{ch}}^{\text{norm}}$. In this limit, equation (2) becomes a simple power function, with c_s^2 being the power of the function. The parameters $\overline{N_{\text{ch}}^{\text{knee}}}$ and σ can be constrained by fitting the measured multiplicity distribution using the procedure described in [39]. The multiplicity distribution at fixed values of b is modeled using a Gaussian function. Integrating over b gives a minimum bias multiplicity distribution which can be fitted to data. As shown in figure 2, this fit provides a good description of the data. The results of this fit can be used to estimate the Gaussian mean and width at $b = 0$, yielding $\overline{N_{\text{ch}}^{\text{knee}}} = 1.11$ and $\sigma = 0.0272$ with negligible uncertainties. Using the extracted $\overline{N_{\text{ch}}^{\text{knee}}}$ and σ values, a fit to the measured $\langle p_{\text{T}} \rangle^{\text{norm}}$ as a function of $N_{\text{ch}}^{\text{norm}}$ is performed using equation (2), thereby extracting the speed of sound. In practice, we limit the fit to the very high-multiplicity region of $N_{\text{ch}}^{\text{norm}} > 1.14$, as will be discussed in detail later.

The dominant sources of systematic uncertainties for the measured $\langle p_{\text{T}} \rangle^{\text{norm}}$ and $N_{\text{ch}}^{\text{norm}}$ values originate from the tracking correction and the extrapolation to the full p_{T} range. As mentioned earlier, using normalized quantities minimizes the majority of the systematic uncertainties. Systematic uncertainties are directly evaluated for the normalized quantities, as well as for $\langle p_{\text{T}} \rangle^0$ and c_s^2 . The tracking correction uncertainty is evaluated by varying the default track selections to a set of looser or tighter values. The maximum deviation with respect to the default results is taken as a systematic uncertainty, which is found to be ± 0.01 GeV in $\langle p_{\text{T}} \rangle^0$ and ± 0.002 in the fitted c_s^2 value. The p_{T} extrapolation uncertainty is estimated by varying the range of measured spectra fitted by the Hagedorn function to a lower limit of 0.3 or 0.5 GeV and an upper limit of 4 or 5 GeV. The resulting systematic uncertainty is found to be at most ± 0.023 GeV for $\langle p_{\text{T}} \rangle^0$ and ± 0.012 for the c_s^2 value. Systematic uncertainties for c_s^2 associated with the choice of the lower fit limit in $N_{\text{ch}}^{\text{norm}}$ are estimated by varying the limit from 1.13 to 1.17, resulting in an uncertainty of ± 0.010 in c_s^2 . Total uncertainties are obtained by adding the various sources in quadrature. Systematic uncertainties for $\langle p_{\text{T}} \rangle^{\text{norm}}$ are extracted point-by-point as a function of $N_{\text{ch}}^{\text{norm}}$.

5. Results

The observed multiplicity dependence of the average transverse momentum, both normalized by their values in the 0%–5% centrality class, is presented in figure 3, within the kinematic range of $|\eta| < 0.5$ and extrapolated to the full p_{T} range in central PbPb events. Hydrodynamic simulations from the TRAJECTUM [19, 40, 41] and Gardim *et al* [17] models are also shown for comparison. Both models use an EoS from lattice QCD calculations [42]. The TRAJECTUM model is a computational framework to simulate the full evolution of heavy ion collisions, which includes the modeling of initial stages, a viscous hydrodynamic phase with transport coefficients, and a hadronic gas phase. Parameters of the

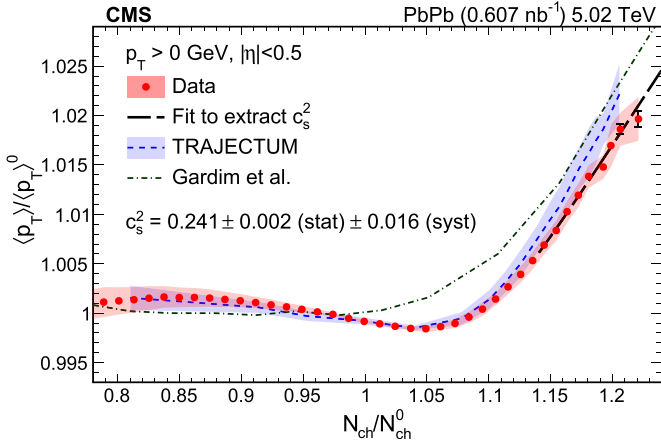


Figure 3. The average transverse momentum of charged particles, $\langle p_T \rangle$, as a function of the charged-particle multiplicity, N_{ch} , within the kinematic range of $|\eta| < 0.5$ and extrapolated to the full p_T range in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Both $\langle p_T \rangle$ and N_{ch} are normalized by their values in the 0%–5% centrality class ($\langle p_T \rangle^0$ and N_{ch}^0). Bars and the red band correspond to statistical and systematic uncertainties, respectively. Hydrodynamic simulations from the TRAJECTUM model [19] and the model by Gardim *et al* [17] are also shown for comparison. The dashed line is a fit to the data using equation (2) in the range of $N_{ch}/N_{ch}^0 > 1.14$.

TRAJECTUM model are constrained by a global Bayesian analysis of a variety of experimental observables [19], where the band shown corresponds to uncertainties within the allowed range of TRAJECTUM configuration parameters. The model of Gardim *et al* [17], besides the hydrodynamic phase, also considers the preequilibrium dynamics and hadronic interactions after thermal freeze-out. No uncertainties are evaluated for this model as only a single set of model parameters is used.

The $\langle p_T \rangle^{\text{norm}}$ value first shows a very weak declining trend toward a local minimum around $N_{ch}^{\text{norm}} \sim 1.05$. At higher multiplicities, corresponding to ultra-central PbPb events, a steep rise is observed, which is consistent with the expected increase in temperature with entropy density, as schematically illustrated in figure 1. The observed trend, including the minimum around $N_{ch}^{\text{norm}} \sim 1.05$, is qualitatively consistent with the prediction by the TRAJECTUM model. A slightly steeper rise at high multiplicities is observed for the TRAJECTUM simulation when compared with the data. This suggests that the speed of sound used in the model may be slightly larger than is found in the QGP. However, this difference is not significant within experimental and theoretical uncertainties. The model by Gardim *et al* also predicts a rise of $\langle p_T \rangle^{\text{norm}}$ at very high multiplicities, with a slope similar to that observed in the data. However, it shows a flat trend at lower multiplicities instead of the local minimum structure around $N_{ch}^{\text{norm}} \sim 1.05$ as seen in the data and the TRAJECTUM model. The origin of the observed local minimum is not currently understood.

To directly extract the speed of sound, the multiplicity dependence of the $\langle p_T \rangle^{\text{norm}}$ data in figure 3 is fitted by equation (2). Because the observed local minimum is not captured by the simplified model in equation (2), the fit is performed only in the high-multiplicity range with $N_{ch}^{\text{norm}} > 1.14$. The final result of the squared speed of sound is found to be $c_s^2 = 0.241 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (syst)}$ in natural units. The same fit is also performed to the prediction from the TRAJECTUM model, resulting in $c_s^2 = 0.283 \pm 0.045$, where the model uncertainty is again determined within the allowed parameter space constrained by a global Bayesian analysis [19].

To constrain the EoS, a simultaneous determination of c_s^2 and its corresponding temperature is necessary. Based on the hydrodynamic simulations discussed in [16, 17], the effective temperature (T_{eff}) of the QGP phase is found to be given approximately by $\langle p_T \rangle / 3$, with $T_{\text{eff}} = \langle p_T \rangle / 3.07$ quoted [16] based on a soft EoS. While the scaling factor relating T_{eff} to $\langle p_T \rangle$ can depend on specific model assumptions, the theoretical uncertainty in this value is believed to be small compared to the quoted experimental uncertainties, thereby having no impact on the main conclusions drawn in this paper. In essence, T_{eff} represents the initial temperature that a uniform fluid at rest would have if it possessed the same amount of energy and entropy as the QGP fluid does when it reaches its freeze-out state, the point at which the quarks become bound into hadrons. Due to longitudinal expansion and cooling, the T_{eff} value is generally lower than the initial temperature of the QGP fluid. Nevertheless, it still characterizes a temperature in the QGP phase, to which the extracted c_s^2 value based on the final-state $\langle p_T \rangle$ and N_{ch} corresponds. Possible effects of shear and bulk viscosity are investigated in [16] and found to not impact this framework, as the shear viscosity increases $\langle p_T \rangle$ by about the same amount that the bulk viscosity decreases it. The $\langle p_T \rangle^0$ value is measured to be $658 \pm 25 \text{ (syst)} \text{ MeV}$, leading to a T_{eff} value for the ultra-central PbPb data of $219 \pm 8 \text{ (syst)} \text{ MeV}$ (it varies by at most 2% toward the very end of N_{ch} distribution within the 0%–5% centrality range). The statistical uncertainty is orders of magnitude smaller than the quoted systematic uncertainties.

Figure 4 depicts c_s^2 as a function of T_{eff} , with the CMS data point obtained from ultra-central PbPb collision data at $\sqrt{s_{NN}} = 5.02$ TeV. The results are compared to the TRAJECTUM model, the c_s^2 value extracted in [16], and lattice QCD predictions of the c_s^2 value as a function of T [6]. The new CMS data allow for an unprecedented level of precision in the experimental determination of the speed of sound in an extended volume of QGP matter. The results exhibit excellent agreement with the lattice QCD prediction, with comparable uncertainties. Thus, our findings provide compelling and direct evidence for the formation of a deconfined QCD phase at LHC energies.

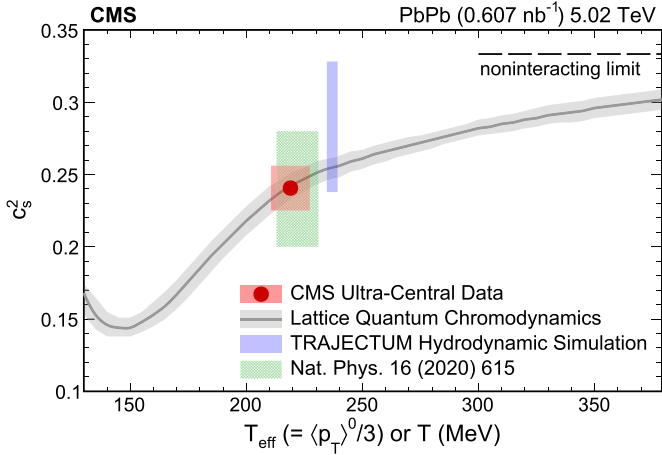


Figure 4. The speed of sound, c_s^2 , as a function of the effective temperature, T_{eff} , with the CMS data point obtained from ultra-central PbPb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The size of the red box indicates systematic uncertainties of c_s^2 and T_{eff} , while statistical uncertainties are smaller than the marker size. Values extracted from the TRAJECTUM simulation [19] following the same fitting procedure as the data and from the earlier work [16] are presented as the other colored boxes. The curve shows the prediction of c_s^2 as a function of T from lattice QCD calculations [6]. The dashed line at the value of $1/3$ corresponds to the upper limit for noninteracting, massless gas (‘ideal gas’) systems [42].

6. Conclusion

In summary, this study presents a measurement with a new hydrodynamic probe in ultrarelativistic nuclear collisions that results in the most precise determination to date of the speed of sound in an extended volume of QGP matter. By determining the dependence of the average transverse momentum on the total multiplicity for charged particles in nearly head-on PbPb collisions at a center-of-mass energy per nucleon pair of 5.02 TeV, a squared speed of sound of 0.241 ± 0.002 (stat) ± 0.016 (syst) in natural units is determined. The effective medium temperature, estimated using the mean transverse momentum, is 219 ± 8 (syst) MeV. The excellent agreement of lattice QCDs predictions with the experimental results provides strong evidence for the existence of a deconfined phase of matter at extremely high temperatures.

Data availability statement

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

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The CMS Collaboration

A Hayrapetyan, A Tumasyan¹

Yerevan Physics Institute, Yerevan, Armenia

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 Schöffbeck, D Schwarz, M Sonawane, S Templ, W Waltenberger, C-E Wulz²

Institut für Hochenergiephysik, Vienna, Austria

M R Darwish³, T Janssen, P Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

B Clerbaux, A K Das, G De Lentdecker, L Favart, P Gianneios, D Hohov, J Jaramillo, A Khalilzadeh, K Lee, M Mahdavihorrami, A Malara, S Paredes, N Postiau, L Thomas, M Vanden Bemden, C Vander Velde, P Vanlaer

Université Libre de Bruxelles, Bruxelles, 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

Ghent University, Ghent, Belgium

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

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

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

Centro Brasileiro de Pesquisas Fisicas, 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 do Estado do Rio de Janeiro, Rio de Janeiro, 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

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

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

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

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

University of Sofia, Sofia, Bulgaria

S Keshri, S Thakur

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

T Cheng, T Javaid, L Yuan

Beihang University, Beijing, People’s Republic of China

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

Department of Physics, Tsinghua University, Beijing, People’s Republic of 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

Institute of High Energy Physics, Beijing, People's Republic of 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**

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, People's Republic of China

Z You

Sun Yat-Sen University, Guangzhou, People's Republic of China

N Lu

University of Science and Technology of People's Republic of China, Hefei, People's Republic of China

G Bauer¹⁴

Nanjing Normal University, Nanjing, People's Republic of China

X Gao¹⁵, **D Leggat**, **H Okawa**

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

Z Lin, **C Lu**, **M Xiao**

Zhejiang University, Hangzhou, Zhejiang, People's Republic of China

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

Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

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

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

M Kovac, **T Sculac**

University of Split, Faculty of Science, Split, Croatia

P Bargassa, **V Brigljevic**, **B K Chitroda**, **D Ferencek**, **S Mishra**, **A Starodumov**¹⁶, **T Susa**

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M Finger, **M Finger Jr**, **A Kveton**

Charles University, Prague, Czech Republic

E Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A A Abdelalim^{17,18}, **E Salama**^{19,20}

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

A Lotfy, **M A Mahmoud**

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

K Ehataht, **M Kadastik**, **T Lange**, **S Nandan**, **C Nielsen**, **J Pata**, **M Raidal**, **L Tani**, **C Veelken**

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H Kirschenmann, **K Osterberg**, **M Voutilainen**

Department of Physics, University of Helsinki, 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**

Helsinki Institute of Physics, Helsinki, Finland

P Luukka, **H Petrow**

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M Besancon, **F Couderc**, **M Dejardin**, **D Denegri**, **J L Faure**, **F Ferri**, **S Ganjour**, **P Gras**, **G Hamel de Monchenault**, **V Lohezic**, **J Malcles**, **J Rander**, **A Rosowsky**, **M.Ö Sahin**, **A Savoy-Navarro**²¹, **P Simkina**, **M Titov**, **M Tornago**

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

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

J -L Agram²², J Andrea, D Apparu, 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
Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, 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
Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D Chokheli, I Lomidze, Z Tsamalaidze¹⁶
Georgian Technical University, Tbilisi, Georgia

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

S Diekmann, A Dodonova, N Eich, D Eliseev, F Engelke, J Erdmann, M Erdmann, P Fackeldey, B Fischer, T Hebbeker, K Hoepfner, F Ivone, A Jung, M y Lee, L Mastrolorenzo, 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 A, Aachen, Germany

C Dziwok, G Flüge, W Haj Ahmad²⁵, T Kress, A Nowack, O Pooth, A Stahl, T Ziemons, A Zotz
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

H Aarup Petersen, M Aldaya Martin, J Alimena, S Amoroso, Y An, 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, G Greau, V Guglielmi, M Guthoff, A Hinzmänn, 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 Otari, 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
Deutsches Elektronen-Synchrotron, 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, A Fröhlich, C Garbers, E Garutti, A Grohsjean, M Hajheidari, 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 Savoie, J Schindler, P Schleper, M Schröder, J Schwandt, M Sommerhalder, H Stadie, G Steinbrück, A Tews, M Wolf
University of Hamburg, Hamburg, 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, M Presilla, G Quast, K Rabbertz, B Regnery, N Shadskiy, I Shvetsov, H J Simonis, M Toms, N Trevisani, R Ulrich, R.F Von Cube, M Wassmer, S Wieland, F Wittig, R Wolf, X Zuo
Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G Anagnostou, G Daskalakis, A Kyriakis, A Papadopoulos³², A Stakia
Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

P Kontaxakis, G Melachroinos, A Panagiotou, I Papavergou, I Paraskevas, N Saoulidou, K Theofilatos, E Tziaferi, K Vellidis, I Zisopoulos
National and Kapodistrian University of Athens, Athens, Greece

G Bakas, T Chatzistavrou, G Karapostoli, K Kousouris, I Papakrivopoulos, E Siamarkou, G Tsiopolitis, A Zacharopoulou
National Technical University of Athens, Athens, 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

University of Ioánnina, Ioánnina, Greece

M Bartók, C Hajdu, D Horvath, K Márton, F Sikler, V Veszpremi

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

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

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

P Raics, B Ujvari, G Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G Bencze, S Czellar, J Molnar, Z Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

T Csorgo, F Nemes, T Novak

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

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S Baradia, S Barman, S Bhattacharya, S Dutta, S Dutta, S Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M M Ameen, P K Behera, S C Behera, S Chatterjee, P Jana, P Kalbhor, J R Komaragiri, D Kumar, L Panwar, P R Pujahari, N R Saha, A Sharma, A K Sikdar, S Verma

Indian Institute of Technology Madras, Madras, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

A Bala, S Banerjee, R M Chatterjee, R K Dewanjee, M Guchait, Sh Jain, A Jaiswal, S Karmakar, S Kumar, G Majumder, K Mazumdar, S Parolia, A Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S Bahinipati, C Kar, D Maity, P Mal, T Mishra, V K Muraleedharan Nair Bindhu, K Naskar, A Nayak, P Sadangi, P Saha, S K Swain, S Varghese, D Vats

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

S Acharya, A Alpina, S Dube, B Gomber, B Kansal, A Laha, B Sahu, S Sharma, K Y Vaish

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

H Bakhshiansohi, E Khazaie, M Zeinali

Isfahan University of Technology, Isfahan, Iran

S Chenarani, S M Etesami, M Khakzad, M Mohammadi Najafabadi

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

M Grunewald

University College Dublin, Dublin, Ireland

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

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

G Abbiendi, C Battilana, D Bonacorsi, L Borghonovi, R Campanini, P Capiluppi, A Castro, F R Cavallo, M Cuffiani, T Diotallevi, F Fabbri, A Fanfani, D Fasanella, P Giacomelli, L Giommi, C Grandi, L Guiducci, S Lo Meo, L Lunerti, S Marcellini, G Masetti, F L Navarria, A Perrotta, F Primavera, A M Rossi, T Rovelli, G P Sirolia

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

S Costa, A Di Mattia, R Potenza, A Tricomi, C Tuve

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

P Assiouras, G Barbagli, G Bardelli, B Camaiani, A Cassese, R Ceccarelli, V Ciulli, C Civinini, R D'Alessandro, E Focardi, T Kello, G Latino, P Lenzi

M Lizzo^a, M Meschini^a, S Paoletti^a, A Papanastassiou^{a,b}, G Sguazzoni^a, L Viliani^a
INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

L Benussi^a, S Bianco^a, S Meola⁵¹, D Piccolo^a
INFN Laboratori Nazionali di Frascati, Frascati, Italy

P Chatagnon^a, F Ferro^a, E Robutti^a, S Tosi^{a,b}
INFN Sezione di Genova^a, Università di Genova^b, Genova, 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 Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

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

R Ardino^a, P Azzi^a, N Bacchetta^{a,53}, P Bortignon^a, A Bragagnolo^{a,b}, R Carlin^{a,b}, P Checchia^a, T Dorigo^a, F Gasparini^{a,b}, U Gasparini^a, E Lusiani^a, M Margoni^{a,b}, F Marini^a, A T Meneguzzo^{a,b}, M Migliorini^{a,b}, F Montecassiano^a, J Pazzini^{a,b}, P Ronchese^{a,b}, R Rossin^{a,b}, F Simonetto^{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}, G Zumerle^{a,b}
INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, 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 Pavia^a, Università di Pavia^b, Pavia, 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,54}, A Rossi^{a,b}, A Santocchia^{a,b}, D Spiga^a, T Tedeschi^{a,b}
INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, 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 Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P Barria^a, 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 Roma^a, Sapienza Università di Roma^b, Roma, Italy

N Amapane^{a,b}, R Arcidiacono^{a,c}, S Argiro^{a,b}, M Arneodo^{a,c}, N Bartosik^a, R Bellan^{a,b}, 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 Leggera^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 Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

S Belforte^a, V Candelise^{a,b}, M Casarsa^a, F Cossutti^a, K De Leo^{a,b}, G Della Ricca^{a,b}
INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S Dogra^a, J Hong^a, C Huh^a, B Kim^a, D.H Kim^a, J Kim, H Lee, S.W Lee^a, C.S Moon^a, Y.D Oh^a, M.S Ryu^a, S Sekmen^a, Y.C Yang^a
Kyungpook National University, Daegu, Republic of Korea

M S Kim^a
Department of Mathematics and Physics - GWNu, Gangneung, Republic of Korea

G Bak^a, P Gwak^a, H Kim^a, D H Moon^a
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

E Asilar, **D Kim**, **T J Kim**, **J A Merlin**
Hanyang University, Seoul, Republic of Korea

S Choi, **S Han**, **B Hong**, **K Lee**, **K S Lee**, **S Lee**,
J Park, **S K Park**, **J Yoo**
Republic of Korea University, Seoul, Republic of Korea

J Goh, **S Yang**
Kyung Hee University, Department of Physics, Seoul,
Republic of Korea

H S Kim, **Y Kim**, **S Lee**
Sejong University, Seoul, Republic of 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**
Seoul National University, Seoul, Republic of 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**
University of Seoul, Seoul, Republic of Korea

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

M Choi, **M R Kim**, **H Lee**, **Y Lee**, **I Yu**
Sungkyunkwan University, Suwon, Republic of Korea

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

K Dreimanis, **A Gaile**, **G Pikurs**, **A Potrebko**,
M Seidel, **V Veckalns**⁵⁵
Riga Technical University, Riga, Latvia

N R Strautnieks
University of Latvia (LU), Riga, Latvia

M Ambroz, **A Juodagalvis**, **A Rinkevicius**,
G Tamulaitis
Vilnius University, Vilnius, Lithuania

N Bin Norjoharuddeen, **I Yusuff**⁵⁶, **Z Zolkapli**
National Centre for Particle Physics, Universiti Malaya, Kuala
Lumpur, Malaysia

J F Benitez, **A Castaneda Hernandez**, **H A**
Encinas Acosta, **L G Gallegos Maríñez**, **M León Coello**,
J A Murillo Quijada, **A Sehrawat**, **L Valencia Palomo**
Universidad de Sonora (UNISON), Hermosillo, Mexico

G Ayala, **H Castilla-Valdez**, **H Crotte Ledesma**,
E De La Cruz-Burelo, **I Heredia-De La Cruz**⁵⁷,
R Lopez-Fernandez, **C A Mondragon Herrera**,
A Sánchez Hernández

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

C Oropeza Barrera, **M Ramírez García**
Universidad Iberoamericana, Mexico City, Mexico

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

I Bubanja, **N Raicevic**
University of Montenegro, Podgorica, Montenegro

P H Butler
University of Canterbury, Christchurch, New Zealand

A Ahmad, **M I Asghar**, **A Awais**, **M I M Awan**, **H R**
Hoorani, **W A Khan**
National Centre for Physics, Quaid-I-Azam University,
Islamabad, Pakistan

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

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

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

K Pozniak, **W Zabolotny**
Warsaw University of Technology, Warsaw, Poland

M Araujo, **D Bastos**, **C Beirão Da Cruz E Silva**,
A Boletti, **M Bozzo**, **T Camporesi**, **G Da Molin**,
P Faccioli, **M Gallinaro**, **J Hollar**, **N Leonardo**,
T Niknejad, **A Petrilli**, **M Pisano**, **J Seixas**,
J Varela, **J W Wulff**
Laboratório de Instrumentação e Física Experimental de
Partículas, Lisboa, Portugal

P Adzic, **P Milenovic**
Faculty of Physics, University of Belgrade, Belgrade, Serbia

M Dordevic, **J Milosevic**, **V Rekovic**
VINCA Institute of Nuclear Sciences, University of Belgrade,
Belgrade, Serbia

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

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

J F de Trocóniz[✉]

Universidad Autónoma de Madrid, Madrid, Spain

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

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

S Bhowmik[✉], S Blanco Fernández[✉], J A Brochero
Cifuentes[✉], I J Cabrillo[✉], A Calderon[✉], J
Duarte Campderros[✉], M Fernandez[✉], G Gomez[✉],
C Lasiosa García[✉], C Martínez Rivero[✉], P Martínez
Ruiz del Arbol[✉], F Matorras[✉], P Matorras Cuevas[✉],
E Navarrete Ramos[✉], J Piedra Gomez[✉], L Scodellaro[✉],
I Vila[✉], J M Vizán García[✉]

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

M K Jayananda[✉], B Kailasapathy^{58 ✉}, D U J Sonnadara[✉],
D D C Wickramaratna[✉]

University of Colombo, Colombo, Sri Lanka

W G D Dharmaratna^{59 ✉}, K Liyanage[✉], N Perera[✉],
N Wickramage[✉]

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

D Abbaneo[✉], C Amendola[✉], E Auffray[✉], G Auzinger[✉],
J Baechler, D Barney[✉], A Bermúdez Martínez[✉],
M Bianco[✉], 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[✉], 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 Sphicas^{60 ✉},
A G Stahl Leiton[✉], A Steen[✉], S Summers[✉], D Treille[✉],
P Tropea[✉], A Tsiros, D Walter[✉], J Wanczyk^{61 ✉}, J Wang,
S Wuchterl[✉], P Zehetner[✉], P Zejdl[✉], W D Zeuner

CERN, European Organization for Nuclear Research, Geneva,
Switzerland

T Bevilacqua^{62 ✉}, L Caminada^{62 ✉}, A Ebrahimi[✉],
W Erdmann[✉], R Horisberger[✉], Q Ingram[✉], H C
Kaestli[✉], D Kotlinski[✉], C Lange[✉], M Missiroli^{62 ✉},
L Nochte^{62 ✉}, T Rohe[✉]

Paul Scherrer Institut, Villigen, Switzerland

T K Aarrestad[✉], K Androsov^{61 ✉}, 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 Mascellani^{61 ✉}, F Nessi-Tedaldi[✉], F Pauss[✉],
V Perovic[✉], S Pigazzini[✉], C Reissel[✉], T Reitenspiess[✉],
B Ristic[✉], F Riti[✉], D Ruini, R Seidita[✉], J Steggemann^{61 ✉},
D Valsecchi[✉], R Wallny[✉]

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

C Amsler^{63 ✉}, 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[✉],
Y Takahashi[✉], R Tramontano[✉]

Universität Zürich, Zurich, Switzerland

C Adloff^{64 ✉}, D Bhowmik, C M Kuo, W Lin, P K Rout[✉], P C
Tiwari^{40 ✉}, S S Yu[✉]

National Central University, Chung-Li, 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[✉]

National Taiwan University (NTU), Taipei, Taiwan

C Asawatangtrakuldee[✉], N Srimanobhas[✉], V
Wachirapusanand[✉]

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

D Agyel[✉], F Boran[✉], Z S Demiroglu[✉], F Dolek[✉],
I Dumanoglu^{65 ✉}, E Eskut[✉], Y Guler^{66 ✉}, E Gurpinar
Guler^{66 ✉}, C Isik[✉], O Kara, A Kayis Topaksu[✉],
U Kiminsu[✉], G Onengut[✉], K Ozdemir^{67 ✉}, A Polatoz[✉],
B Tali^{68 ✉}, U G Tok[✉], S Turkcapar[✉], E Uslan[✉], I S
Zorbakir[✉]

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

M Yalvac⁶⁹

Middle East Technical University, Physics Department, Ankara, Turkey

B Akgun, **I O Atakisi**, **E Gülmez**, **M Kaya**⁷⁰, **O Kaya**⁷¹, **S Tekten**⁷²

Bogazici University, Istanbul, Turkey

A Cakir, **K Cankocak**^{65,73}, **Y Komurcu**, **S Sen**⁷⁴

Istanbul Technical University, Istanbul, Turkey

O Aydılek, **S Cerci**⁶⁸, **V Epshteyn**, **B Hacisahinoglu**, **I Hos**⁷⁵, **B Kaynak**, **S Ozkorucuklu**, **O Potok**, **H Sert**, **C Simsek**, **C Zorbilmez**

Istanbul University, Istanbul, Turkey

B Isildak⁷⁶, **D Sunar Cerci**⁶⁸

Yildiz Technical University, Istanbul, Turkey

A Boyaryntsev, **B Grynyov**

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

L Levchuk

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

D Anthony, **J J Brooke**, **A Bundock**, **F Bury**, **E Clement**, **D Cussans**, **H Flacher**, **M Glowacki**, **J Goldstein**, **H F Heath**, **L Kreczko**, **S Paramesvaran**, **L Robertshaw**, **S Seif El Nasr-Storey**, **V J Smith**, **N Stylianou**⁷⁷, **K Walkingshaw**, **R White**

University of Bristol, Bristol, United Kingdom

A H Ball, **K W Bell**, **A Belyaev**⁷⁸, **C Brew**, **R M Brown**, **D J A Cockerill**, **C Cooke**, **K V Ellis**, **K Harder**, **S Harper**, **M -L Holmberg**⁷⁹, **J Linacre**, **K Manolopoulos**, **D M Newbold**, **E Olaiya**, **D Petyt**, **T Reis**, **G Salvi**, **T Schuh**, **C H Shepherd-Themistocleous**, **I R Tomalin**, **T Williams**

Rutherford Appleton Laboratory, Didcot, United Kingdom

R Bainbridge, **P Bloch**, **C E Brown**, **O Buchmuller**, **V Cacchio**, **C A Carrillo Montoya**, **G S Chahal**⁸⁰, **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 Nash**⁸¹, **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 Virdee**³², **M Vojinovic**, **N Wardle**, **D Winterbottom**

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, United States of America

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

Catholic University of America, Washington, DC, United States of America

B Bam, **R Chudasama**, **S I Cooper**, **S V Gleyzer**, **C U Perez**, **P Rumerio**⁸², **E United States of America**, **R Yi**

The University of Alabama, Tuscaloosa, Alabama, United States of America

A Akpinar, **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**

Boston University, Boston, Massachusetts, United States of America

G Benelli, **X Coubez**²⁷, **D Cutts**, **M Hadley**, **U Heintz**, **J M Hogan**⁸³, **T Kwon**, **G Landsberg**, **K T Lau**, **D Li**, **J Luo**, **S Mondal**, **M Narain**[†], **N Pervan**, **S Sagir**⁸⁴, **F Simpson**, **M Stamenkovic**, **W Y Wong**, **X Yan**, **W Zhang**

Brown University, Providence, Rhode Island, United States of America

S Abbott, **J Bonilla**, **C Brainerd**, **R Breedon**, **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, Davis, Davis, California, United States of America

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, Los Angeles, California, United States of America

R Clare, **J W Gary**, **M Gordon**, **G Hanson**, **W Si**,
S Wimpenny[†]
University of California, Riverside, Riverside, California,
United States of America

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, San Diego, La Jolla, California,
United States of America

A Barzdukas, **L Brennan**, **C Campagnari**,
A Dorsett, **J Incandela**, **J Kim**, **A J Li**,
P Masterson, **H Mei**, **J Richman**, **U Sarica**,
R Schmitz, **F Setti**, **J Shephlock**, **D Stuart**, **T Á Vami**, **S Wang**
University of California, Santa Barbara - Department of
Physics, Santa Barbara, California, United States of America

A Bornheim, **O Cerri**, **A Latorre**, **J Mao**, **H B Newman**,
M Spiropulu, **J.R Vlimant**, **C Wang**,
S Xie, **R.Y Zhu**
California Institute of Technology, Pasadena, California,
United States of America

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**
Carnegie Mellon University, Pittsburgh, Pennsylvania, United
States of America

J P Cumalat, **W T Ford**, **A Hart**, **A Hassani**,
G Karathanasis, **E MacDonald**, **N Manganello**,
A Perloff, **C Savard**, **N Schonbeck**, **K Stenson**,
K A Ulmer, **S R Wagner**, **N Zipper**
University of Colorado Boulder, Boulder, Colorado, United
States of America

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
Cornell University, Ithaca, New York, United States of
America

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 Klijnsma**, **B Klima**, **K H.M Kwok**,
S Lammel, **D Lincoln**, **R Lipton**, **T Liu**,
C Madrid, **K Maeshima**, **C Mantilla**, **D Mason**,
P McBride, **P Merkel**, **S Mrenna**, **S Nahn**,
J Ngadiuba, **D Noonan**, **V Papadimitriou**,
N Pastika, **K Pedro**, **C Pena**⁸⁵, **F Ravera**,
A Reinsvold Hall⁸⁶, **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**, **I Zoi**
Fermi National Accelerator Laboratory, Batavia, Illinois,
United States of America

C Aruta, **P Avery**, **D Bourilkov**, **L Cadamuro**,
P Chang, **V Cherepanov**, **R D Field**, **E Koenig**,
M Kolosova, **J Konigsberg**, **A Korytov**, **K H Lo**,
K Matchev, **N Menendez**, **G Mitselmakher**,
K Mohrman, **A Muthirakalayil Madhu**, **N Rawal**,
D Rosenzweig, **S Rosenzweig**, **K Shi**, **J Wang**
University of Florida, Gainesville, Florida, United States of
America

T Adams, **A Al Kadhimi**, **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 State University, Tallahassee, Florida, United States of
America

B Alsufyani, **M M Baarmand**, **S Butalla**,
T Elkafrawy²⁰, **M Hohmann**, **R Kumar Verma**,
M Rahmani, **E Yanes**
Florida Institute of Technology, Melbourne, Florida, United
States of America

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**
University of Illinois Chicago, Chicago, United States of
America, Chicago, United States of America

M Alhusseini, **D Blend**, **K Dilsiz**⁸⁷, **L Emediato**,
G Karaman, **O K Köseyan**, **J -P Merlo**,
A Mestvirishvili⁸⁸, **J Nachtman**, **O Neogi**, **H Ogul**⁸⁹,
Y Onel, **A Penzo**, **C Snyder**, **E Tiras**⁹⁰
The University of Iowa, Iowa City, Iowa, United States of
America

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

Johns Hopkins University, Baltimore, Maryland, United States of America

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[✉], C Lindsey, J Marquez[✉], N Minafra[✉], M Murray[✉], M Nickel[✉], M Pitt[✉], S Popescu^{✉1}, C Rogan[✉], C Royon[✉], R Salvatico[✉], S Sanders[✉], C Smith[✉], Q Wang[✉], G Wilson[✉]

The University of Kansas, Lawrence, Kansas, United States of America

B Allmond[✉], A Ivanov[✉], K Kaadze[✉], A Kalogeropoulos[✉], D Kim, Y Maravin[✉], K Nam, J Natoli[✉], D Roy[✉], G Sorrentino[✉]

Kansas State University, Manhattan, Kansas, United States of America

F Rebassoo[✉], D Wright[✉]

Lawrence Livermore National Laboratory, Livermore, California, United States of America

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 Paranjpe, L Wang[✉]

University of Maryland, College Park, Maryland, United States of America

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[✉], C Mironov[✉], A Novak[✉], C Paus[✉], D Rankin[✉], C Roland[✉], G Roland[✉], S Rothman[✉], G S F Stephans[✉], Z Wang[✉], B Wyslouch[✉], T J Yang[✉]

Massachusetts Institute of Technology, Cambridge, Massachusetts, United States of America

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 Minnesota, Minneapolis, Minnesota, United States of America

L M Cremaldi[✉]

University of Mississippi, Oxford, Mississippi, United States of America

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[✉]

University of Nebraska-Lincoln, Lincoln, Nebraska, United States of America

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

State University of New York at Buffalo, Buffalo, New York, United States of America

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[✉], A Tishelman-Charny[✉], B Wang[✉], D Wood[✉]

Northeastern University, Boston, Massachusetts, United States of America

S Bhattacharya[✉], J Bueghly, Z Chen[✉], S Dittmer[✉], K A Hahn[✉], Y Liu[✉], Y Miao[✉], D G Monk[✉], M H Schmitt[✉], A Taliencio[✉], M Velasco

Northwestern University, Evanston, Illinois, United States of America

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 Musienko^{✉16}, H Nelson[✉], M Osherson[✉], A Piccinelli[✉], R Ruchti[✉], A Townsend[✉], Y Wan, M Wayne[✉], H Yockey, M Zarucki[✉], L Zygala[✉]

University of Notre Dame, Notre Dame, Indiana, United States of America

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

The Ohio State University, Columbus, Ohio, United States of America

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[✉]

Princeton University, Princeton, New Jersey, United States of America

S Malik[✉]

University of Puerto Rico, Mayaguez, Puerto Rico, United States of America

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 Virdi[✉], F Wang[✉], W Xie[✉]

Purdue University, West Lafayette, Indiana, United States of America

J Dolen[Ⓜ], **N Parashar**[Ⓜ], **A Pathak**[Ⓜ]

Purdue University Northwest, Hammond, Indiana, United States of America

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**[Ⓜ]

Rice University, Houston, Texas, United States of America

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

University of Rochester, Rochester, New York, United States of America

K Goulios[Ⓜ]

The Rockefeller University, New York, New York, United States of America

B Chiarito, **J P Chou**[Ⓜ], **Y Gershtein**[Ⓜ], **E Halkiadakis**[Ⓜ], **M Heindl**[Ⓜ], **D Jaroslawski**[Ⓜ], **O Karacheban**³⁰[Ⓜ], **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**[Ⓜ]

Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States of America

H Acharya, **D Ally**[Ⓜ], **A G Delannoy**[Ⓜ], **S Fiorendi**[Ⓜ], **S Higginbotham**[Ⓜ], **T Holmes**[Ⓜ], **A R Kanuganti**[Ⓜ], **N Karunaratna**[Ⓜ], **L Lee**[Ⓜ], **E Nibigira**[Ⓜ], **S Spanier**[Ⓜ]

University of Tennessee, Knoxville, Tennessee, United States of America

D Aebi[Ⓜ], **M Ahmad**[Ⓜ], **O Bouhali**⁹³[Ⓜ], **R Eusebi**[Ⓜ], **J Gilmore**[Ⓜ], **T Huang**[Ⓜ], **T Kamon**⁹⁴[Ⓜ], **H Kim**[Ⓜ], **S Luo**[Ⓜ], **R Mueller**[Ⓜ], **D Overton**[Ⓜ], **D Rathjens**[Ⓜ], **A Safonov**[Ⓜ]

Texas A&M University, College Station, Texas, United States of America

N Akchurin[Ⓜ], **J Damgov**[Ⓜ], **V Hegde**[Ⓜ], **A Hussain**[Ⓜ], **Y Kazhykarim**, **K Lamichhane**[Ⓜ], **S W Lee**[Ⓜ], **A Mankel**[Ⓜ], **T Peltola**[Ⓜ], **I Volobouev**[Ⓜ], **A Whitbeck**[Ⓜ]

Texas Tech University, Lubbock, Texas, United States of America

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**[Ⓜ]

Vanderbilt University, Nashville, Tennessee, United States of America

B Cardwell[Ⓜ], **B Cox**[Ⓜ], **J Hakala**[Ⓜ], **R Hirosky**[Ⓜ], **A Ledovskoy**[Ⓜ], **C Neu**[Ⓜ], **C E Perez Lara**[Ⓜ]

University of Virginia, Charlottesville, Virginia, United States of America

P E Karchin[Ⓜ]

Wayne State University, Detroit, Michigan, United States of America

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**[Ⓜ]

University of Wisconsin - Madison, Madison, Wisconsin, United States of America

S Afanasiev[Ⓜ], **V Andreev**[Ⓜ], **Yu Andreev**[Ⓜ], **T Aushev**[Ⓜ], **M Azarkin**[Ⓜ], **A Babaev**[Ⓜ], **A Belyaev**[Ⓜ], **V Blinov**⁹⁵[Ⓜ], **E Boos**[Ⓜ], **V Borshch**[Ⓜ], **D Budkouski**[Ⓜ], **V Bunichev**[Ⓜ], **V Chekhovsky**, **R Chistov**⁹⁵[Ⓜ], **M Danilov**⁹⁵[Ⓜ], **A Dermenev**[Ⓜ], **T Dimova**⁹⁵[Ⓜ], **D Druzhkin**⁹⁶[Ⓜ], **M Dubinin**⁸⁵[Ⓜ], **L Dudko**[Ⓜ], **A Ershov**[Ⓜ], **G Gavrilov**[Ⓜ], **V Gavrilov**[Ⓜ], **S Gninenko**[Ⓜ], **V Golovtsov**[Ⓜ], **N Golubev**[Ⓜ], **I Golutvin**[Ⓜ], **I Gorbunov**[Ⓜ], **A Gribushin**[Ⓜ], **Y Ivanov**[Ⓜ], **V Kachanov**[Ⓜ], **V Karjavine**[Ⓜ], **A Karneyev**[Ⓜ], **V Kim**⁹⁵[Ⓜ], **M Kirakosyan**, **D Kirpichnikov**[Ⓜ], **M Kirsanov**[Ⓜ], **V Klyukhin**[Ⓜ], **O Kodolova**⁹⁷[Ⓜ], **V Korenkov**[Ⓜ], **A Kozyrev**⁹⁵[Ⓜ], **N Krasnikov**[Ⓜ], **A Lanev**[Ⓜ], **P Levchenko**⁹⁸[Ⓜ], **N Lychkovskaya**[Ⓜ], **V Makarenko**[Ⓜ], **A Malakhov**[Ⓜ], **V Matveev**⁹⁵[Ⓜ], **V Murzin**[Ⓜ], **A Nikitenko**^{99,97}[Ⓜ], **S Obraztsov**[Ⓜ], **V Oreshkin**[Ⓜ], **V Palichik**[Ⓜ], **V Perelygin**[Ⓜ], **S Petrushanko**[Ⓜ], **S Polikarpov**⁹⁵[Ⓜ], **V Popov**[Ⓜ], **O Radchenko**⁹⁵[Ⓜ], **M Savina**[Ⓜ], **V Savrin**[Ⓜ], **V Shalaev**[Ⓜ], **S Shmatov**[Ⓜ], **S Shulha**[Ⓜ], **Y Skovpen**⁹⁵[Ⓜ], **S Slabospitskii**[Ⓜ], **V Smirnov**[Ⓜ], **A Snigirev**[Ⓜ], **D Sosnov**[Ⓜ], **V Sulimov**[Ⓜ], **E Tcherniaev**[Ⓜ], **A Terkulov**[Ⓜ], **O Teryaev**[Ⓜ], **I Tlisova**[Ⓜ], **A Toropin**[Ⓜ], **L Uvarov**[Ⓜ], **A Uzunian**[Ⓜ], **A Vorobyev**[†], **N Voytishin**[Ⓜ], **B S Yuldashev**¹⁰⁰[Ⓜ], **A Zarubin**[Ⓜ], **I Zhizhin**[Ⓜ], **A Zhokin**[Ⓜ]

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

[†] 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, People's Republic of China

⁹Now at The University of Iowa, Iowa City, Iowa, United States of America

- ¹⁰Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China
- ¹¹Also at People's Republic of China Center of Advanced Science and Technology, Beijing, People's Republic of China
- ¹²Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China
- ¹³Also at People's Republic of China Spallation Neutron Source, Guangdong, People's Republic of China
- ¹⁴Now at Henan Normal University, Xinxiang, People's Republic of 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, United States of America
- ²²Also at Université de Haute Alsace, Mulhouse, France
- ²³Also at Department of Physics, Tsinghua University, Beijing, People's Republic of 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, Jülich, 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 Babes-Bolyai - Facultatea de Fizica, 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
- ⁵⁰Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵¹Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵²Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵³Also at Fermi National Accelerator Laboratory, Batavia, Illinois, United States of America
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Riga Technical University, Riga, Latvia
- ⁵⁶Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁷Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶⁰Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶¹Also at Ecole Polytechnique Fédérale LaUnited States of Americanne, LaUnited States of Americanne, Switzerland
- ⁶²Also at Universität Zürich, Zurich, Switzerland
- ⁶³Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁴Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁵Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁶Also at Konya Technical University, Konya, Turkey
- ⁶⁷Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁸Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁹Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷⁰Also at Marmara University, Istanbul, Turkey
- ⁷¹Also at Milli Savunma University, Istanbul, Turkey
- ⁷²Also at Kafkas University, Kars, Turkey
- ⁷³Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁴Also at Hacettepe University, Ankara, Turkey
- ⁷⁵Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁶Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁷Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁸Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁹Also at University of Bristol, Bristol, United Kingdom
- ⁸⁰Also at IPPP Durham University, Durham, United Kingdom
- ⁸¹Also at Monash University, Faculty of Science, Clayton, Australia

- ⁸²Also at Università di Torino, Torino, Italy
- ⁸³Also at Bethel University, St. Paul, Minnesota, United States of America
- ⁸⁴Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁵Also at California Institute of Technology, Pasadena, California, United States of America
- ⁸⁶Also at United States Naval Academy, Annapolis, Maryland, United States of America
- ⁸⁷Also at Bingöl University, Bingöl, Turkey
- ⁸⁸Also at Georgian Technical University, Tbilisi, Georgia
- ⁸⁹Also at Sinop University, Sinop, Turkey
- ⁹⁰Also at Erciyes University, Kayseri, Turkey
- ⁹¹Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁹²Now at an institute or an international laboratory covered by a cooperation agreement with CERN
- ⁹³Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹⁴Also at Kyungpook National University, Daegu, Republic of Korea
- ⁹⁵Also at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁶Also at Universiteit Antwerpen, Antwerpen, Belgium
- ⁹⁷Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁸Also at Northeastern University, Boston, Massachusetts, United States of America
- ⁹⁹Also at Imperial College, London, United Kingdom
- ¹⁰⁰Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

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