

PAPER • OPEN ACCESS

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

To cite this article: The CMS Collaboration 2024 *Rep. Prog. Phys.* **87** 077801

View the [article online](#) for updates and enhancements.

You may also like

- [The 2022 Plasma Roadmap: low temperature plasma science and technology](#)  
I Adamovich, S Agarwal, E Ahedo et al.
- [Roadmap on methods and software for electronic structure based simulations in chemistry and materials](#)  
Volker Blum, Ryoji Asahi, Jochen Autschbach et al.
- [The 2022 magneto-optics roadmap](#)  
Alexey Kimel, Anatoly Zvezdin, Sangeeta Sharma et al.

www.hidenanalytical.com  
info@hiden.co.uk

**HIDEN ANALYTICAL**

## Instruments for Advanced Science

Mass spectrometers for vacuum, gas, plasma and surface science



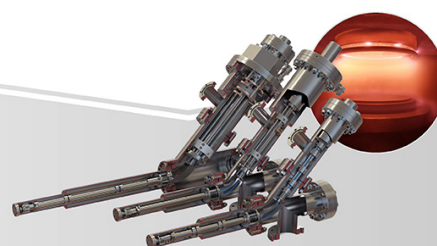
### Residual Gas Analysis

Perform RGA at UHV/XHV. Our RGA configurations include systems for UHV science applications including temperature-programmed desorption and electron/photon stimulated desorption.



### Thin Film Surface Analysis

Conduct both static and dynamic SIMS analysis with a choice of primary ions for full chemical composition and depth profiling. Our SIMS solutions include complete workstations and bolt-on modules.



### Plasma Characterisation

Fully characterise a range of plasmas: RF, DC, ECR and pulsed plasmas, including neutrals and neutral radicals. Extend your analyses to atmospheric pressure processes using the HPR-60, with time-resolved mass/energy analysis.

# 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](mailto:cms-publication-committee-chair@cern.ch)

Received 12 January 2024, revised 3 May 2024

Accepted for publication 14 May 2024

Published 20 June 2024

Corresponding editor: Mrs Natasha Leeper



### 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  $0.607 \text{ nb}^{-1}$ . 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

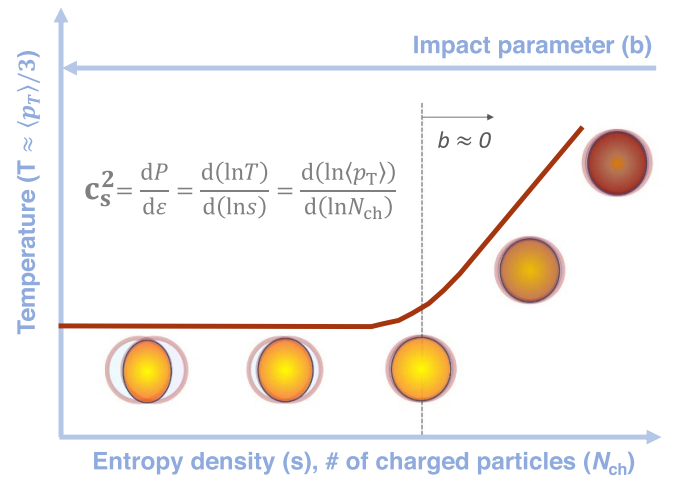
realm of extreme temperatures, quarks and gluons break free from their confined existence inside hadrons, traversing long distances (e.g. several fm) compared to the size of individual nucleons. The emergence of the QGP represents a fundamental prediction of quantum chromodynamics (QCDs) [5, 6], the 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.



Original Content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

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  $\varepsilon$ ,  $c_s^2 = dP/d\varepsilon$  [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  $222 \pm 9$  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.

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

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 TRAJEKTUM 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  $\theta$  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  $4.27 \times 10^9$  minimum bias events, corresponding to an integrated luminosity of  $0.607 \text{ nb}^{-1}$ . 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

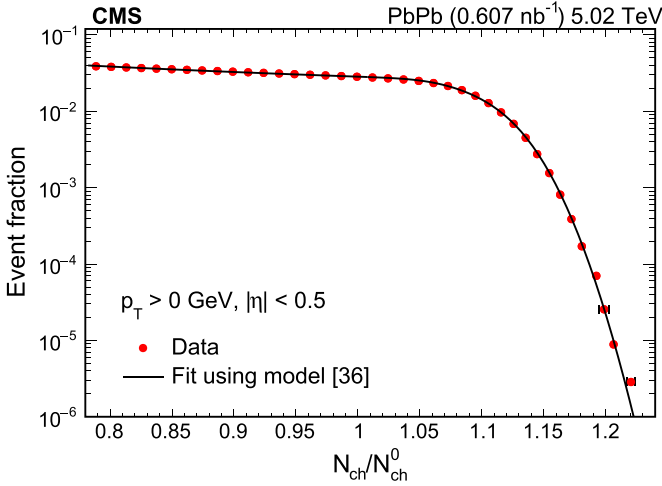
tracking performance. More details on the track reconstruction and selection can be found in [33]. The tracking efficiency ( $\varepsilon_{\text{eff}}$ ) and misreconstruction rate ( $\varepsilon_{\text{mis}}$ ) are evaluated using the HYDJET [34] event generator, together with a full GEANT4 [35] simulation 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  $\varepsilon_{\text{trk}}$  factor is calibrated not only in terms of  $p_T$  and  $\eta$ , 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  $N_{\text{pixel}}$ , where a weak linear decline of  $\varepsilon_{\text{trk}}$  by up to 7% over an increase of  $N_{\text{pixel}}$  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  $N_{\text{ch}}$ , where  $\langle p_T \rangle$  and  $N_{\text{ch}}$  are measured within the same  $\eta$  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  $N_{\text{ch}}$ , 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  $N_{\text{ch}}$  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  $\eta$  range that does not overlap with the range used to measure the corresponding  $\langle p_T \rangle$  and  $N_{\text{ch}}$  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  $N_{\text{ch}}$  (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  $N_{\text{ch}}^0$  represent the mean transverse



**Figure 2.** The event fraction distribution as a function of the charged-particle multiplicity,  $N_{\text{ch}}$ , within the kinematic range of  $|\eta| < 0.5$  and extrapolated to the full  $p_{\text{T}}$  range, in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The  $N_{\text{ch}}$  value is normalized by its value in the 0%–5% centrality class ( $N_{\text{ch}}^0$ ). 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  $N_{\text{ch}}$  by their values in the reference event class, most of the systematic uncertainties can be minimized. The  $\langle p_{\text{T}} \rangle$  and  $N_{\text{ch}}^0$  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,

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

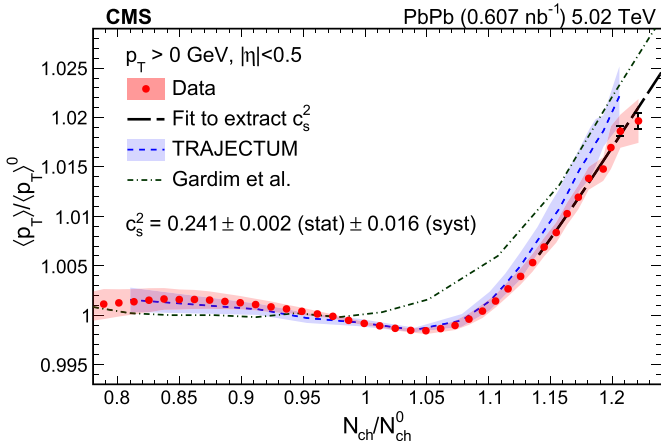
Here,  $\overline{N_{\text{ch}}^{\text{knee}}}$  and  $\sigma$  represent the mean and root-mean-square width of the charged-particle multiplicity distribution at  $b=0$ , normalized by  $N_{\text{ch}}^0$ . In figure 2, the  $\overline{N_{\text{ch}}^{\text{knee}}}$  value corresponds to the vicinity 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  $\sigma$  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  $\sigma$  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  $p_{\text{T}}$  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  $\pm 0.01$  GeV in  $\langle p_{\text{T}} \rangle^0$  and  $\pm 0.002$  in the fitted  $c_s^2$  value. The  $p_{\text{T}}$  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  $\pm 0.023$  GeV for  $\langle p_{\text{T}} \rangle^0$  and  $\pm 0.012$  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  $\pm 0.010$  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  $p_{\text{T}}$  range in central PbPb events. Hydrodynamic simulations from the TRAJECTIONS [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 TRAJECTIONS 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  $N_{ch}/N_{ch}^0 > 1.14$ .

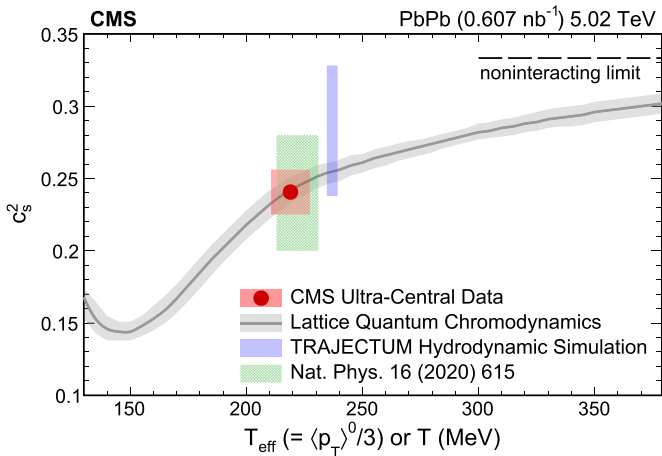
TRAJECTUM model are constrained by a global Bayesian analysis of a variety of experimental observables [19], where the band shown corresponds to uncertainties within the allowed range of TRAJECTUM configuration parameters. The model of Gardim *et al* [17], besides the hydrodynamic phase, also considers 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  $c_s^2 = 0.241 \pm 0.002$  (stat)  $\pm 0.016$  (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 ( $T_{\text{eff}}$ ) 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  $T_{\text{eff}}$  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,  $T_{\text{eff}}$  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  $T_{\text{eff}}$  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  $658 \pm 25$  (syst) MeV, leading to a  $T_{\text{eff}}$  value for the ultra-central PbPb data of  $219 \pm 8$  (syst) 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  $T_{\text{eff}}$ , 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,  $T_{\text{eff}}$ , 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  $T_{\text{eff}}$ , 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  $0.241 \pm 0.002$  (stat)  $\pm 0.016$  (syst) in natural units is determined. The effective medium temperature, estimated using the mean transverse momentum, is  $219 \pm 8$  (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](#).

## Acknowledgments

We thank Fernando Gardim, Andre Veiga Giannini, Govert Nijs, Jean-Yves Ollitrault, and Wilke van der Schee for providing us with the model calculations used in figure 3.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the

LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHEI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, Contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22r1-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the ‘Excellence of Science—EOS’ – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany’s Excellence Strategy—EXC 2121 ‘Quantum Universe’—390833306, and under Project Number 400140256—GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program—ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India;

ICSC—National Research Center for High Performance Computing, Big Data and Quantum Computing, funded by the Next GenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, Project No. 2022/WK/14, and the National Science Center, Contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF ‘a way of making Europe’, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, Grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, Grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## The CMS Collaboration

**A Hayrapetyan, A Tumasyan<sup>1</sup>**

Yerevan Physics Institute, Yerevan, Armenia

**W Adam, J W Andrejkovic, T Bergauer, S Chatterjee, K Damanakis, M Dragicevic, P S Hussain, M Jeitler<sup>2</sup>, N Krammer, A Li, D Liko, I Mikulec, J Schieck<sup>2</sup>, R Schöfbeck, D Schwarz, M Sonawane, S Templ, W Waltenberger, C -E Wulz<sup>2</sup>**

Institut für Hochenergiephysik, Vienna, Austria

**M R Darwish<sup>3</sup>, 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 Tytgat<sup>4</sup>, 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 Mahdavihorrani, 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 Físicas, Rio de Janeiro, Brazil

**W L Aldá Júnior, M Alves Gallo Pereira, M Barroso Ferreira Filho, H Brandao Malbouisson, W Carvalho, J Chinellato<sup>5</sup>, E M Da Costa, G G Da Silveira<sup>6</sup>, D De Jesus Damiao, S Fonseca De Souza, R Gomes De Souza, J Martins<sup>7</sup>, 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 Bernardes<sup>6</sup>, 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<sup>8,9</sup>**

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

**G.M Chen<sup>10</sup>, H S Chen<sup>10</sup>, M Chen<sup>10</sup>, F Iemmi, C H Jiang, A Kapoor<sup>11</sup>, H Liao, Z -A Liu<sup>12</sup>, R Sharma<sup>13</sup>, J N Song<sup>12</sup>, J Tao, C Wang<sup>10</sup>, J Wang, Z Wang<sup>10</sup>, 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 Bauer**<sup>14</sup>

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

**X Gao**<sup>15</sup>, **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**<sup>16</sup>, **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 Stepenov**

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**<sup>17,18</sup>, **E Salama**<sup>19,20</sup>

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**<sup>21</sup>, **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 Agram<sup>22</sup>, 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 Dozen<sup>23</sup>, 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 Tsamalaidze<sup>16</sup>  
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 Araujo<sup>24</sup>, L Vigilante, S Wiedenbeck, S Zaleski  
RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

C Dziwok, G Flügge, W Haj Ahmad<sup>25</sup>, 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 Blekman<sup>26</sup>, K Borras<sup>27</sup>, 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 Gallo<sup>26</sup>, A Geiser, A Giraldi, G Greau, V Guglielmi, M Guthoff, A Hinzmänn, A Jafari<sup>28</sup>, L Jeppe, N Z Jomhari, B Kaech, M Kasemann, C Kleinwort, R Kogler, M Komm, D Krücker, W Lange, D Leyva Pernia, K Lipka<sup>29</sup>,

W Lohmann<sup>30</sup>, 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<sup>31,27</sup>, S Schnake<sup>27</sup>, P Schütze, C Schwanenberger<sup>26</sup>, 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 Wiens<sup>27</sup>, 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 Hartmann<sup>32</sup>, 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 Papadopoulos<sup>32</sup>, 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 Strogas

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 Rádl, 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 Alpana, 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<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy

G Abbiendi, C Battilana, D Bonacorsi, L Borghonovi, R Campanini, P Capiluppi, A Castro, F R Cavallo, M Cuffiani, T Diotalevi, F Fabbri, A Fanfani, D Fasanella, P Giacomelli, L Gionmi, 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 Siroli

INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy

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

INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, 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<sup>a</sup>, M Meschini<sup>a</sup>, S Paoletti<sup>a</sup>, A Papanastassiou<sup>a,b</sup>, G Sguazzoni<sup>a</sup>, L Viliani<sup>a</sup>**  
INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy

**L Benussi<sup>a</sup>, S Bianco<sup>a</sup>, S Meola<sup>51</sup>, D Piccolo<sup>a</sup>**  
INFN Laboratori Nazionali di Frascati, Frascati, Italy

**P Chatagnon<sup>a</sup>, F Ferro<sup>a</sup>, E Robutti<sup>a</sup>, S Tosi<sup>a,b</sup>**  
INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy

**A Benaglia<sup>a</sup>, G Boldrini<sup>a,b</sup>, F Brivio<sup>a</sup>, F Cetorelli<sup>a</sup>, F De Guio<sup>a,b</sup>, M E Dinardo<sup>a,b</sup>, P Dini<sup>a</sup>, S Gennai<sup>a</sup>, R Gerosa<sup>a,b</sup>, A Ghezzi<sup>a,b</sup>, P Govoni<sup>a,b</sup>, L Guzzi<sup>a</sup>, M T Lucchini<sup>a,b</sup>, M Malberti<sup>a</sup>, S Malvezzi<sup>a</sup>, A Massironi<sup>a</sup>, D Menasce<sup>a</sup>, L Moroni<sup>a</sup>, M Paganoni<sup>a,b</sup>, D Pedrini<sup>a</sup>, B S Pinolini<sup>a</sup>, S Ragazzi<sup>a,b</sup>, T Tabarelli de Fatis<sup>a,b</sup>, D Zuolo<sup>a</sup>**  
INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy

**S Buontempo<sup>a</sup>, A Cagnotta<sup>a,b</sup>, F Carnevali<sup>a,b</sup>, N Cavallo<sup>a,c</sup>, F Fabozzi<sup>a,c</sup>, A O M Iorio<sup>a,b</sup>, L Lista<sup>a,b,52</sup>, P Paolucci<sup>a,32</sup>, B Rossi<sup>a</sup>, C Sciacca<sup>a,b</sup>**  
INFN Sezione di Napoli<sup>a</sup>, Università di Napoli ‘Federico II’<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy

**R Ardino<sup>a</sup>, P Azzi<sup>a</sup>, N Bacchetta<sup>a,53</sup>, P Bortignon<sup>a</sup>, A Bragagnolo<sup>a,b</sup>, R Carlin<sup>a,b</sup>, P Checchia<sup>a</sup>, T Dorigo<sup>a</sup>, F Gasparini<sup>a,b</sup>, U Gasparini<sup>a,b</sup>, E Lusiani<sup>a</sup>, M Margoni<sup>a,b</sup>, F Marini<sup>a</sup>, A T Meneguzzo<sup>a,b</sup>, M Migliorini<sup>a,b</sup>, F Montecassiano<sup>a</sup>, J Pazzini<sup>a,b</sup>, P Ronchese<sup>a,b</sup>, R Rossin<sup>a,b</sup>, F Simonetto<sup>a,b</sup>, G Strong<sup>a</sup>, M Tosi<sup>a,b</sup>, A Triossi<sup>a,b</sup>, S Ventura<sup>a</sup>, H Yarar<sup>a,b</sup>, M Zanetti<sup>a,b</sup>, P Zotto<sup>a,b</sup>, A Zucchetta<sup>a,b</sup>, G Zumerle<sup>a,b</sup>**  
INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy

**S Abu Zeid<sup>a,20</sup>, C Aimè<sup>a,b</sup>, A Braghieri<sup>a</sup>, S Calzaferri<sup>a</sup>, D Fiorina<sup>a</sup>, P Montagna<sup>a,b</sup>, V Re<sup>a</sup>, C Riccardi<sup>a,b</sup>, P Salvini<sup>a</sup>, I Vai<sup>a,b</sup>, P Vitulo<sup>a,b</sup>**  
INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy

**S Ajmal<sup>a,b</sup>, G M Bilei<sup>a</sup>, D Ciangottini<sup>a,b</sup>, L Fanò<sup>a,b</sup>, M Magherini<sup>a,b</sup>, G Mantovani<sup>a,b</sup>, V Mariani<sup>a,b</sup>, M Menichelli<sup>a</sup>, F Moscatelli<sup>a,54</sup>, A Rossi<sup>a,b</sup>, A Santocchia<sup>a,b</sup>, D Spiga<sup>a</sup>, T Tedeschi<sup>a,b</sup>**  
INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy

**P Asenov<sup>a,b</sup>, P Azzurri<sup>a</sup>, G Bagliesi<sup>a</sup>, R Bhattacharya<sup>a</sup>, L Bianchini<sup>a,b</sup>, T Boccali<sup>a</sup>, E Bossini<sup>a</sup>, D Bruschini<sup>a,c</sup>, R Castaldi<sup>a</sup>, M A Ciocci<sup>a,b</sup>, M Cipriani<sup>a,b</sup>, V D’Amante<sup>a,d</sup>, R Dell’Orso<sup>a</sup>, S Donato<sup>a</sup>, A Giassi<sup>a</sup>, F Ligabue<sup>a,c</sup>, D Matos Figueiredo<sup>a</sup>, A Messineo<sup>a,b</sup>, M Musich<sup>a,b</sup>, F Palla<sup>a</sup>, A Rizzi<sup>a,b</sup>, G Rolandi<sup>a,c</sup>, S Roy Chowdhury<sup>a</sup>, T Sarkar<sup>a</sup>, A Scribano<sup>a</sup>, P Spagnolo<sup>a</sup>, R Tenchini<sup>a</sup>, G Tonelli<sup>a,b</sup>, N Turini<sup>a,d</sup>, A Venturi<sup>a</sup>, P G Verdini<sup>a</sup>**  
INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy

**P Barria<sup>a</sup>, M Campana<sup>a,b</sup>, F Cavallari<sup>a</sup>, L Cunqueiro Mendez<sup>a,b</sup>, D Del Re<sup>a,b</sup>, E Di Marco<sup>a</sup>, M Diemoz<sup>a</sup>, F Errico<sup>a,b</sup>, E Longo<sup>a,b</sup>, P Meridiani<sup>a</sup>, J Mijuskovic<sup>a,b</sup>, G Organtini<sup>a,b</sup>, F Pandolfi<sup>a</sup>, R Paramatti<sup>a,b</sup>, C Quaranta<sup>a,b</sup>, S Rahatlou<sup>a,b</sup>, C Rovelli<sup>a</sup>, F Santanastasio<sup>a,b</sup>, L Soffi<sup>a</sup>**  
INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy

**N Amapane<sup>a,b</sup>, R Arcidiacono<sup>a,c</sup>, S Argiro<sup>a,b</sup>, M Arneodo<sup>a,c</sup>, N Bartosik<sup>a</sup>, R Bellan<sup>a,b</sup>, A Bellora<sup>a,b</sup>, C Biino<sup>a</sup>, C Borca<sup>a,b</sup>, N Cartiglia<sup>a</sup>, M Costa<sup>a,b</sup>, R Covarelli<sup>a,b</sup>, N Demaria<sup>a</sup>, L Finco<sup>a</sup>, M Grippo<sup>a,b</sup>, B Kiani<sup>a,b</sup>, F Leggera<sup>a</sup>, F Luongo<sup>a,b</sup>, C Mariotti<sup>a</sup>, L Markovic<sup>a,b</sup>, S Maselli<sup>a</sup>, A Mecca<sup>a,b</sup>, E Migliore<sup>a,b</sup>, M Monteno<sup>a</sup>, R Mulargia<sup>a</sup>, M M Obertino<sup>a,b</sup>, G Ortona<sup>a</sup>, L Pacher<sup>a,b</sup>, N Pastrone<sup>a</sup>, M Pelliccioni<sup>a</sup>, M Ruspa<sup>a,c</sup>, F Siviero<sup>a,b</sup>, V Sola<sup>a,b</sup>, A Solano<sup>a,b</sup>, A Staiano<sup>a</sup>, C Tarricone<sup>a,b</sup>, D Trocino<sup>a</sup>, G Umoret<sup>a,b</sup>, E Vlasov<sup>a,b</sup>**  
INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy

**S Belforte<sup>a</sup>, V Candelise<sup>a,b</sup>, M Casarsa<sup>a</sup>, F Cossutti<sup>a</sup>, K De Leo<sup>a,b</sup>, G Della Ricca<sup>a,b</sup>**  
INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy

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

**M S Kim<sup>a</sup>**  
Department of Mathematics and Physics - GWNu, Gangneung, Republic of Korea

**G Baki<sup>a</sup>, P Gwak<sup>a</sup>, H Kim<sup>a</sup>, D H Moon<sup>a</sup>**  
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**<sup>55</sup>  
Riga Technical University, Riga, Latvia

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

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

**N Bin Norjoharuddeen**, **I Yusuff**<sup>56</sup>, **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**<sup>57</sup>,  
**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<sup>Ⓜ</sup>, J M Hernandez<sup>Ⓜ</sup>, M I Josa<sup>Ⓜ</sup>, D Moran<sup>Ⓜ</sup>, C M Morcillo Perez<sup>Ⓜ</sup>, Á Navarro Tobar<sup>Ⓜ</sup>, C Perez Dengra<sup>Ⓜ</sup>, A Pérez-Calero Yzquierdo<sup>Ⓜ</sup>, J Puerta Pelayo<sup>Ⓜ</sup>, I Redondo<sup>Ⓜ</sup>, D D Redondo Ferrero<sup>Ⓜ</sup>, L Romero, S Sánchez Navas<sup>Ⓜ</sup>, L Urda Gómez<sup>Ⓜ</sup>, J Vazquez Escobar<sup>Ⓜ</sup>, C Willmott

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

J F de Trocóniz<sup>Ⓜ</sup>

Universidad Autónoma de Madrid, Madrid, Spain

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

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

S Bhowmik<sup>Ⓜ</sup>, S Blanco Fernández<sup>Ⓜ</sup>, J A Brochero Cifuentes<sup>Ⓜ</sup>, I J Cabrillo<sup>Ⓜ</sup>, A Calderon<sup>Ⓜ</sup>, J Duarte Campderros<sup>Ⓜ</sup>, M Fernandez<sup>Ⓜ</sup>, G Gomez<sup>Ⓜ</sup>, C Lasasa García<sup>Ⓜ</sup>, C Martinez Rivero<sup>Ⓜ</sup>, P Martinez Ruiz del Arbol<sup>Ⓜ</sup>, F Matorras<sup>Ⓜ</sup>, P Matorras Cuevas<sup>Ⓜ</sup>, E Navarrete Ramos<sup>Ⓜ</sup>, J Piedra Gomez<sup>Ⓜ</sup>, L Scodellaro<sup>Ⓜ</sup>, I Vila<sup>Ⓜ</sup>, J M Vizan Garcia<sup>Ⓜ</sup>

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

M K Jayananda<sup>Ⓜ</sup>, B Kailasapathy<sup>58</sup><sup>Ⓜ</sup>, D U J Sonnadara<sup>Ⓜ</sup>, D D C Wickramaratna<sup>Ⓜ</sup>

University of Colombo, Colombo, Sri Lanka

W G D Dharmaratna<sup>59</sup><sup>Ⓜ</sup>, K Liyanage<sup>Ⓜ</sup>, N Perera<sup>Ⓜ</sup>, N Wickramage<sup>Ⓜ</sup>

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

D Abbaneo<sup>Ⓜ</sup>, C Amendola<sup>Ⓜ</sup>, E Auffray<sup>Ⓜ</sup>, G Auzinger<sup>Ⓜ</sup>, J Baechler, D Barney<sup>Ⓜ</sup>, A Bermúdez Martínez<sup>Ⓜ</sup>, M Bianco<sup>Ⓜ</sup>, B Bilin<sup>Ⓜ</sup>, A A Bin Anuar<sup>Ⓜ</sup>, A Bocci<sup>Ⓜ</sup>, C Botta<sup>Ⓜ</sup>, E Brondolin<sup>Ⓜ</sup>, C Caillol<sup>Ⓜ</sup>, G Cerminara<sup>Ⓜ</sup>, N Chernyavskaya<sup>Ⓜ</sup>, D d'Enterria<sup>Ⓜ</sup>, A Dabrowski<sup>Ⓜ</sup>, A David<sup>Ⓜ</sup>, A De Roeck<sup>Ⓜ</sup>, M M Defranchis<sup>Ⓜ</sup>, M Deile<sup>Ⓜ</sup>, M Dobson<sup>Ⓜ</sup>, L Forthomme<sup>Ⓜ</sup>, G Franzoni<sup>Ⓜ</sup>, W Funk<sup>Ⓜ</sup>, S Giani, D Gigi, K Gill<sup>Ⓜ</sup>, F Glege<sup>Ⓜ</sup>, L Gouskos<sup>Ⓜ</sup>, M Haranko<sup>Ⓜ</sup>, J Hegeman<sup>Ⓜ</sup>, B Huber, V Innocente<sup>Ⓜ</sup>, T James<sup>Ⓜ</sup>, P Janot<sup>Ⓜ</sup>, S Laurila<sup>Ⓜ</sup>, P Lecoq<sup>Ⓜ</sup>, E Leutgeb<sup>Ⓜ</sup>, C Lourenço<sup>Ⓜ</sup>, B Maier<sup>Ⓜ</sup>, L Malgeri<sup>Ⓜ</sup>, M Mannelli<sup>Ⓜ</sup>, A C Marini<sup>Ⓜ</sup>, M Matthewman, F Meijers<sup>Ⓜ</sup>, S Mersi<sup>Ⓜ</sup>, E Meschi<sup>Ⓜ</sup>, V Milosevic<sup>Ⓜ</sup>, F Monti<sup>Ⓜ</sup>, F Moortgat<sup>Ⓜ</sup>, M Mulders<sup>Ⓜ</sup>, I Neutelings<sup>Ⓜ</sup>, S Orfanelli, F Pantaleo<sup>Ⓜ</sup>, G Petrucciani<sup>Ⓜ</sup>, A Pfeiffer<sup>Ⓜ</sup>, M Pierini<sup>Ⓜ</sup>, D Piparo<sup>Ⓜ</sup>, H Qu<sup>Ⓜ</sup>, D Rabadý<sup>Ⓜ</sup>, G Reales Gutiérrez, M Rovere<sup>Ⓜ</sup>, H Sakulin<sup>Ⓜ</sup>, S Scarfi<sup>Ⓜ</sup>, C Schwick, M Selvaggi<sup>Ⓜ</sup>,

A Sharma<sup>Ⓜ</sup>, K Shchelina<sup>Ⓜ</sup>, P Silva<sup>Ⓜ</sup>, P Sphicas<sup>60</sup><sup>Ⓜ</sup>, A G Stahl Leiton<sup>Ⓜ</sup>, A Steen<sup>Ⓜ</sup>, S Summers<sup>Ⓜ</sup>, D Treille<sup>Ⓜ</sup>, P Tropea<sup>Ⓜ</sup>, A Tsirou, D Walter<sup>Ⓜ</sup>, J Wanczyk<sup>61</sup><sup>Ⓜ</sup>, J Wang, S Wuchterl<sup>Ⓜ</sup>, P Zehetner<sup>Ⓜ</sup>, P Zejdl<sup>Ⓜ</sup>, W D Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T Bevilacqua<sup>62</sup><sup>Ⓜ</sup>, L Caminada<sup>62</sup><sup>Ⓜ</sup>, A Ebrahimi<sup>Ⓜ</sup>, W Erdmann<sup>Ⓜ</sup>, R Horisberger<sup>Ⓜ</sup>, Q Ingram<sup>Ⓜ</sup>, H C Kaestli<sup>Ⓜ</sup>, D Kotlinski<sup>Ⓜ</sup>, C Lange<sup>Ⓜ</sup>, M Missiroli<sup>62</sup><sup>Ⓜ</sup>, L Noehte<sup>62</sup><sup>Ⓜ</sup>, T Rohe<sup>Ⓜ</sup>

Paul Scherrer Institut, Villigen, Switzerland

T K Aarrestad<sup>Ⓜ</sup>, K Androsov<sup>61</sup><sup>Ⓜ</sup>, M Backhaus<sup>Ⓜ</sup>, A Calandri<sup>Ⓜ</sup>, C Cazzaniga<sup>Ⓜ</sup>, K Datta<sup>Ⓜ</sup>, A De Cosa<sup>Ⓜ</sup>, G Dissertori<sup>Ⓜ</sup>, M Dittmar, M Donegà<sup>Ⓜ</sup>, F Eble<sup>Ⓜ</sup>, M Galli<sup>Ⓜ</sup>, K Gedia<sup>Ⓜ</sup>, F Glessgen<sup>Ⓜ</sup>, C Grab<sup>Ⓜ</sup>, D Hits<sup>Ⓜ</sup>, W Lustermann<sup>Ⓜ</sup>, A -M Lyon<sup>Ⓜ</sup>, R A Manzoni<sup>Ⓜ</sup>, M Marchegiani<sup>Ⓜ</sup>, L Marchese<sup>Ⓜ</sup>, C Martin Perez<sup>Ⓜ</sup>, A Mascellani<sup>61</sup><sup>Ⓜ</sup>, F Nessi-Tedaldi<sup>Ⓜ</sup>, F Pauss<sup>Ⓜ</sup>, V Perovic<sup>Ⓜ</sup>, S Pigazzini<sup>Ⓜ</sup>, C Reissel<sup>Ⓜ</sup>, T Reitenspiess<sup>Ⓜ</sup>, B Ristic<sup>Ⓜ</sup>, F Riti<sup>Ⓜ</sup>, D Ruini, R Seidita<sup>Ⓜ</sup>, J Steggemann<sup>61</sup><sup>Ⓜ</sup>, D Valsecchi<sup>Ⓜ</sup>, R Wallny<sup>Ⓜ</sup>

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

C Amsler<sup>63</sup><sup>Ⓜ</sup>, P Bäertschi<sup>Ⓜ</sup>, D Brzhechko, M.F Canelli<sup>Ⓜ</sup>, K Cormier<sup>Ⓜ</sup>, J K Heikkilä<sup>Ⓜ</sup>, M Huwiler<sup>Ⓜ</sup>, W Jin<sup>Ⓜ</sup>, A Jofrehei<sup>Ⓜ</sup>, B Kilminster<sup>Ⓜ</sup>, S Leontsinis<sup>Ⓜ</sup>, S P Liechti<sup>Ⓜ</sup>, A Macchiolo<sup>Ⓜ</sup>, P Meiring<sup>Ⓜ</sup>, U Molinatti<sup>Ⓜ</sup>, A Reimers<sup>Ⓜ</sup>, P Robmann, S Sanchez Cruz<sup>Ⓜ</sup>, M Senger<sup>Ⓜ</sup>, Y Takahashi<sup>Ⓜ</sup>, R Tramontano<sup>Ⓜ</sup>

Universität Zürich, Zurich, Switzerland

C Adloff<sup>64</sup><sup>Ⓜ</sup>, D Bhowmik, C M Kuo, W Lin, P K Rout<sup>Ⓜ</sup>, P C Tiwari<sup>40</sup><sup>Ⓜ</sup>, S S Yu<sup>Ⓜ</sup>

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

C Asawatangtrakuldee<sup>Ⓜ</sup>, N Srimanobhas<sup>Ⓜ</sup>, V Wachirapusanand<sup>Ⓜ</sup>

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

D Agyel<sup>Ⓜ</sup>, F Boran<sup>Ⓜ</sup>, Z S Demiroglu<sup>Ⓜ</sup>, F Dolek<sup>Ⓜ</sup>, I Dumanoglu<sup>65</sup><sup>Ⓜ</sup>, E Eskut<sup>Ⓜ</sup>, Y Guler<sup>66</sup><sup>Ⓜ</sup>, E Gurpinar Guler<sup>66</sup><sup>Ⓜ</sup>, C Isik<sup>Ⓜ</sup>, O Kara, A Kayis Topaksu<sup>Ⓜ</sup>, U Kiminsu<sup>Ⓜ</sup>, G Onengut<sup>Ⓜ</sup>, K Ozdemir<sup>67</sup><sup>Ⓜ</sup>, A Polatoz<sup>Ⓜ</sup>, B Tali<sup>68</sup><sup>Ⓜ</sup>, U G Tok<sup>Ⓜ</sup>, S Turkcapar<sup>Ⓜ</sup>, E Uslan<sup>Ⓜ</sup>, I S Zorbakir<sup>Ⓜ</sup>

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

**M Yalvac**<sup>69</sup>

Middle East Technical University, Physics Department, Ankara, Turkey

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

Bogazici University, Istanbul, Turkey

**A Cakir**, **K Cankocak**<sup>65,73</sup>, **Y Komurcu**, **S Sen**<sup>74</sup>

Istanbul Technical University, Istanbul, Turkey

**O Aydilek**, **S Cerci**<sup>68</sup>, **V Epshteyn**, **B Hacisahinoglu**, **I Hos**<sup>75</sup>, **B Kaynak**, **S Ozkorucuklu**, **O Potok**, **H Sert**, **C Simsek**, **C Zorbilmez**

Istanbul University, Istanbul, Turkey

**B Isildak**<sup>76</sup>, **D Sunar Cerci**<sup>68</sup>

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**<sup>77</sup>, **K Walkingshaw Pass**, **R White**

University of Bristol, Bristol, United Kingdom

**A H Ball**, **K W Bell**, **A Belyaev**<sup>78</sup>, **C Brew**, **R M Brown**, **D J A Cockerill**, **C Cooke**, **K V Ellis**, **K Harder**, **S Harper**, **M -L Holmberg**<sup>79</sup>, **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**<sup>80</sup>, **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**<sup>81</sup>, **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**<sup>32</sup>, **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 Uniya**, **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**<sup>82</sup>, **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**<sup>27</sup>, **D Cutts**, **M Hadley**, **U Heintz**, **J M Hogan**<sup>83</sup>, **T Kwon**, **G Landsberg**, **K T Lau**, **D Li**, **J Luo**, **S Mondal**, **M Narain**<sup>†</sup>, **N Pervan**, **S Sagir**<sup>84</sup>, **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**<sup>†</sup>

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 Sheplock**, **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 Manganelli**,  
**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 Gece**, **L Gray**, **D Green**, **A Grummer**,

**S Grünendahl**, **D Guerrero**, **O Gutsche**, **R M Harris**,  
**R Heller**, **T C Herwig**, **J Hirschauser**,  
**L Horyn**, **B Jayatilaka**, **S Jindariani**, **M Johnson**,  
**U Joshi**, **T Klijsma**, **B Klima**, **K H.M Kwok**,  
**S Lammel**, **D Lincoln**, **R Lipton**, **T Liu**,  
**C Madrid**, **K Maeshima**, **C Mantilla**, **D Mason**,  
**P McBride**, **P Merkel**, **S Mrenna**, **S Nahn**,  
**J Ngadiuba**, **D Noonan**, **V Papadimitriou**,  
**N Pastika**, **K Pedro**, **C Pena**<sup>85</sup>, **F Ravera**,  
**A Reinsvold Hall**<sup>86</sup>, **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 Kadhim**, **A Askew**, **S Bower**,  
**R Habibullah**, **V Hagopian**, **R Hashmi**, **R.S Kim**,  
**S Kim**, **T Kolberg**, **G Martinez**, **H Prosper**, **P R Prova**,  
**M Wulansatiti**, **R Yohay**, **J Zhang**

Florida State University, Tallahassee, Florida, United States of  
America

**B Alsufyani**, **M M Baarmand**, **S Butalla**,  
**T Elkafrawy**<sup>20</sup>, **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 Alhousseini**, **D Blend**, **K Dilsiz**<sup>87</sup>, **L Emediato**,  
**G Karaman**, **O K Köseyan**, **J -P Merlo**,  
**A Mestvirishvili**<sup>88</sup>, **J Nachtman**, **O Neogi**, **H Ogul**<sup>89</sup>,  
**Y Onel**, **A Penzo**, **C Snyder**, **E Tiras**<sup>90</sup>

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**<sup>91</sup>, **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**<sup>16</sup>, **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 Thiemann**, **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**<sup>92</sup>, **E Popova**<sup>92</sup>, **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 Jaroslowski**, **O Karacheban**<sup>30</sup>, **I Lafflotte**, **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**<sup>93</sup>, **R Eusebi**, **J Gilmore**, **T Huang**, **T Kamon**<sup>94</sup>, **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**<sup>95</sup>, **E Boos**, **V Borshch**, **D Budkouski**, **V Bunichev**, **V Chekhovsky**, **R Chistov**<sup>95</sup>, **M Danilov**<sup>95</sup>, **A Dermenev**, **T Dimova**<sup>95</sup>, **D Druzhkin**<sup>96</sup>, **M Dubinin**<sup>85</sup>, **L Dudko**, **A Ershov**, **G Gavrillov**, **V Gavrillov**, **S Gninenko**, **V Golovtsov**, **N Golubev**, **I Golutvin**, **I Gorbunov**, **A Gribushin**, **Y Ivanov**, **V Kachanov**, **V Karjavine**, **A Karneyev**, **V Kim**<sup>95</sup>, **M Kirakosyan**, **D Kirpichnikov**, **M Kirsanov**, **V Klyukhin**, **O Kodolova**<sup>97</sup>, **V Korenkov**, **A Kozyrev**<sup>95</sup>, **N Krasnikov**, **A Lanev**, **P Levchenko**<sup>98</sup>, **N Lychkovskaya**, **V Makarenko**, **A Malakhov**, **V Matveev**<sup>95</sup>, **V Murzin**, **A Nikitenko**<sup>99,97</sup>, **S Obraztsov**, **V Oreshkin**, **V Palichik**, **V Perelygin**, **S Petrushanko**, **S Polikarpov**<sup>95</sup>, **V Popov**, **O Radchenko**<sup>95</sup>, **M Savina**, **V Savrin**, **V Shalaev**, **S Shmatov**, **S Shulha**, **Y Skovpen**<sup>95</sup>, **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**<sup>†</sup>, **N Voytishin**, **B S Yuldashev**<sup>100</sup>, **A Zarubin**, **I Zhizhin**, **A Zhokin**

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

<sup>†</sup> Deceased

<sup>1</sup> Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup> Also at TU Wien, Vienna, Austria

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

<sup>4</sup> Also at Ghent University, Ghent, Belgium

<sup>5</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup> Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup> Also at UFMS, Nova Andradina, Brazil

<sup>8</sup> Also at Nanjing Normal University, Nanjing, People's Republic of China

<sup>9</sup> Now at The University of Iowa, Iowa City, Iowa, United States of America

- <sup>10</sup>Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China
- <sup>11</sup>Also at People's Republic of China Center of Advanced Science and Technology, Beijing, People's Republic of China
- <sup>12</sup>Also at University of Chinese Academy of Sciences, Beijing, People's Republic of China
- <sup>13</sup>Also at People's Republic of China Spallation Neutron Source, Guangdong, People's Republic of China
- <sup>14</sup>Now at Henan Normal University, Xinxiang, People's Republic of China
- <sup>15</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium
- <sup>16</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- <sup>17</sup>Also at Helwan University, Cairo, Egypt
- <sup>18</sup>Now at Zewail City of Science and Technology, Zewail, Egypt
- <sup>19</sup>Also at British University in Egypt, Cairo, Egypt
- <sup>20</sup>Now at Ain Shams University, Cairo, Egypt
- <sup>21</sup>Also at Purdue University, West Lafayette, Indiana, United States of America
- <sup>22</sup>Also at Université de Haute Alsace, Mulhouse, France
- <sup>23</sup>Also at Department of Physics, Tsinghua University, Beijing, People's Republic of China
- <sup>24</sup>Also at The University of the State of Amazonas, Manaus, Brazil
- <sup>25</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>26</sup>Also at University of Hamburg, Hamburg, Germany
- <sup>27</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>28</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>29</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- <sup>30</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>31</sup>Also at Forschungszentrum Jülich, Jülich, Germany
- <sup>32</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>33</sup>Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- <sup>34</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- <sup>35</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>36</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>37</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- <sup>38</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>39</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>40</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>41</sup>Also at Birla Institute of Technology, Mesra, Mesra, India
- <sup>42</sup>Also at IIT Bhubaneswar, Bhubaneswar, India
- <sup>43</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>44</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>45</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>46</sup>Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>47</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>48</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>49</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>50</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>51</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>52</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>53</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, United States of America
- <sup>54</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>55</sup>Also at Riga Technical University, Riga, Latvia
- <sup>56</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>57</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>58</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>59</sup>Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>60</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>61</sup>Also at Ecole Polytechnique Fédérale LaUnited States of Americane, LaUnited States of Americane, Switzerland
- <sup>62</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>63</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>64</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- <sup>65</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>66</sup>Also at Konya Technical University, Konya, Turkey
- <sup>67</sup>Also at Izmir Bakircay University, Izmir, Turkey
- <sup>68</sup>Also at Adiyaman University, Adiyaman, Turkey
- <sup>69</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>70</sup>Also at Marmara University, Istanbul, Turkey
- <sup>71</sup>Also at Milli Savunma University, Istanbul, Turkey
- <sup>72</sup>Also at Kafkas University, Kars, Turkey
- <sup>73</sup>Now at Istanbul Okan University, Istanbul, Turkey
- <sup>74</sup>Also at Hacettepe University, Ankara, Turkey
- <sup>75</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>76</sup>Also at Yildiz Technical University, Istanbul, Turkey
- <sup>77</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium
- <sup>78</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>79</sup>Also at University of Bristol, Bristol, United Kingdom
- <sup>80</sup>Also at IPPP Durham University, Durham, United Kingdom
- <sup>81</sup>Also at Monash University, Faculty of Science, Clayton, Australia

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

## References

- [1] Shuryak E V 1978 Theory of hadronic plasma *Sov. Phys. JETP* **47** 212
- [2] Collins J C and Perry M J 1975 Superdense matter: neutrons or asymptotically free quarks? *Phys. Rev. Lett.* **34** 1353
- [3] Cabibbo N and Parisi G 1975 Exponential hadronic spectrum and quark liberation *Phys. Lett. B* **59** 67
- [4] Freedman B A and McLerran L D 1977 Fermions and gauge vector mesons at finite temperature and density. 3. the ground state energy of a relativistic quark gas *Phys. Rev. D* **16** 1169
- [5] R C Hwa and X N Wang (eds) 2004 *Quark-Gluon Plasma 3* (World Scientific)
- [6] HotQCD Collaboration 2014 Equation of state in (2+1)-flavor QCD *Phys. Rev. D* **90** 094503
- [7] STAR Collaboration 2005 Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR collaboration's critical assessment of the evidence from RHIC collisions *Nucl. Phys. A* **757** 102
- [8] PHENIX Collaboration 2005 Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX collaboration *Nucl. Phys. A* **757** 184
- [9] BRAHMS Collaboration 2005 Quark gluon plasma and color glass condensate at RHIC? the perspective from the BRAHMS experiment *Nucl. Phys. A* **757** 1
- [10] PHOBOS Collaboration 2005 The PHOBOS perspective on discoveries at RHIC *Nucl. Phys. A* **757** 28
- [11] Heinz U and Snellings R 2013 Collective flow and viscosity in relativistic heavy-ion collisions *Annu. Rev. Nucl. Part. Sci.* **63** 123
- [12] Joseph J, Clancy B, Luo L, Kinast J, Turlapov A and Thomas J E 2007 Measurement of sound velocity in a fermi gas near a feshbach resonance *Phys. Rev. Lett.* **98** 170401
- [13] Patel P B , Yan Z, Mukherjee B, Fletcher R J, Struck J and Zwierlein M W 2020 Universal sound diffusion in a strongly interacting Fermi gas *Science* **370** 1222
- [14] Campanini R and Ferri G 2011 Experimental equation of state in proton-proton and proton-antiproton collisions and phase transition to quark gluon plasma *Phys. Lett. B* **703** 237
- [15] Pratt S, Sangaline E, Sorensen P and Wang H (2015 Constraining the equation of state of super-hadronic matter from heavy-ion collisions *Phys. Rev. Lett.* **114** 202301
- [16] Gardim F G, Giacalone G, Luzum M and Ollitrault J-Y 2020 Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions *Nat. Phys.* **16** 615
- [17] Gardim F G, Giacalone G and Ollitrault J-Y 2020 The mean transverse momentum of ultracentral heavy-ion collisions: a new probe of hydrodynamics *Phys. Lett. B* **809** 135749
- [18] Sorensen A, Oliinychenko D, Koch V and McLerran L 2021 Speed of sound and baryon cumulants in heavy-ion collisions *Phys. Rev. Lett.* **127** 042303
- [19] Nijss G and van der Schee W 2022 Predictions and postdictions for relativistic lead and oxygen collisions with the computational simulation code Trajectum *Phys. Rev. C* **106** 044903
- [20] Qiu Z, Shen C and Heinz U W 2012 Resonance decay contributions to higher-order anisotropic flow coefficients *Phys. Rev. C* **86** 064906
- [21] CMS Collaboration 2023 HEPData record for this analysis (available at: <https://doi.org/10.17182/hepdata.146016>)
- [22] CMS Collaboration 2008 The CMS experiment at the CERN LHC *J. Instrum.* **3** S08004
- [23] CMS Collaboration 2020 Performance of the CMS level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13\text{TeV}$  *J. Instrum.* **15** 10017
- [24] CMS Collaboration 2017 The CMS trigger system *J. Instrum.* **12** 01020
- [25] CMS Collaboration 2021 Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC *J. Instrum.* **16** 05014
- [26] CMS Collaboration 2018 Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13\text{TeV}$  *J. Instrum.* **13** 06015
- [27] CMS Collaboration 2014 Description and performance of track and primary-vertex reconstruction with the CMS tracker *J. Instrum.* **9** 10009
- [28] CMS Collaboration 2017 Particle-flow reconstruction and global event description with the CMS detector *J. Instrum.* **12** 10003
- [29] Bayatian G *et al* 2008 Design, performance and calibration of the CMS forward calorimeter wedges *Eur. Phys. J. C* **53** 139
- [30] Surányi O *et al* 2021 Performance of the CMS zero degree calorimeters in pPb collisions at the LHC *J. Instrum.* **16** 05008
- [31] CMS Collaboration 2017 Charged-particle nuclear modification factors in PbPb and pPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02\text{TeV}$  *J. High Energy Phys.* **JHEP04(2017)039**
- [32] CMS Collaboration 2014 Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76\text{TeV}$  *J. High Energy Phys.* **JHEP02(2014)088**
- [33] CMS Collaboration 2020 Mixed higher-order anisotropic flow and nonlinear response coefficients of charged particles in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  and  $5.02\text{TeV}$  *Eur. Phys. J. C* **80** 534
- [34] Lokhtin I P , Malinina L V, Petrushanko S V, Snigirev A M, Arsene I and Tywoniuk K 2009 Heavy ion event generator HYDJET++ (HYDrodynamics plus JETs) *Comput. Phys. Commun.* **180** 779

- [35] GEANT4 Collaboration 2003 GEANT4—a simulation toolkit *Nucl. Instrum. Methods Phys. Res. A* **506** 250
- [36] Hagedorn R 1983 Multiplicities,  $p_T$  distributions and the expected hadron to quark-gluon phase transition *Riv. Nuovo Cimento* **6** 1–50
- [37] ALICE Collaboration 2019 Transverse momentum spectra and nuclear modification factors of charged particles in Xe-Xe collisions at  $\sqrt{s_{NN}} = 5.44\text{TeV}$  *Phys. Lett. B* **788** 166
- [38] ALICE Collaboration 2016 Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02\text{TeV}$  *Phys. Rev. Lett.* **116** 222302
- [39] Das S J, Giacalone G, Monard P-A and Ollitrault J-Y 2018 Relating centrality to impact parameter in nucleus-nucleus collisions *Phys. Rev. C* **97** 014905
- [40] Giacalone G, Nijs G and van der Schee W 2023 Determination of the neutron skin of Pb208 from ultrarelativistic nuclear collisions *Phys. Rev. Lett.* **131** 202302
- [41] Nijs G and van der Schee W 2023 Ultracentral heavy ion collisions, transverse momentum and the equation of state (arXiv:2312.04623)
- [42] Borsanyi S, Endrődi G, Fodor Z, Jakovác A, Katz S D, Krieg S, Ratti C and Szabó K K 2010 The QCD equation of state with dynamical quarks *J. High Energy Phys.* **JHEP11(2010)077**