Pseudorapidity distributions of charged hadrons in xenon-xenon collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV

The CMS Collaboration*

CERN, Switzerland

1. Introduction

Collisions between ultra-relativistic heavy ions are the only known way of experimentally studying quantum chromodynamics (QCD) matter at high temperatures and energy densities. The current understanding is that in such collisions, a state of matter known as the quark-gluon plasma (QGP) is formed shortly after the initial impact between the nuclei [1].

The pseudorapidity and pseudorapidity distributions of the produced charged particles are key observables that characterise the initial condition and subsequent hydrodynamic evolution of the QGP [2]. The dependence of the charged-particle multiplicity on the colliding system, centre-of-mass energy, and collision geometry can provide information about nuclear shadowing and gluon saturation effects [3], as well as the relative contributions to particle production from hard scattering and soft processes [4]. These observables also provide input for models of the particle production process [5], from which information about the formation and properties of the QGP can be extracted.

In October 2017, the CERN LHC collided xenon (Xe$^{129}$) ions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.44$ TeV, marking the first time ions other than protons and lead (Pb$^{208}$) have been circulated in the LHC. This new collision system provides a unique opportunity to study the dependence of the charged-particle multiplicity on the size of the matter produced at LHC energies. Previous measurements of charged-particle multiplicities in copper-copper (CuCu) and gold-gold (AuAu) collisions at RHIC have been observed to be sensitive to the collision geometry [6]. The XeXe collision data are thus important for determining if this feature is also present at higher energies. Comparisons of the data to predictions of models tuned to describe PbPb collision data [7–9] can also be used to test the extent to which these models are able to describe other collision systems.

In this Letter, measurements of the pseudorapidity density of primary charged hadrons, $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$, in the range $|\eta| < 3.2$ are reported for XeXe collisions delivered by the LHC. Following earlier analyses in proton-proton collisions at 0.9–13 TeV [10–14], proton-lead collisions at 5.02 and 8.16 TeV [15], and PbPb collisions at 2.76 TeV [16], “primary” charged hadrons are defined as prompt charged hadrons and decay products of all particles with proper decay length $c\tau < 1$ cm, where $c$ is the speed of light in vacuum and $\tau$ is the proper lifetime of the particle. Contributions from prompt leptons, decay products of longer-lived particles, and secondary interactions are excluded.

The results are compared to a measurement by the ALICE Collaboration [17] and to predictions from the EPOS LHC v3400 [8,18], HYDJET 1.9 [9], and AMPT 1.26t5 [19] event generators. The EPOS

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

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generator is based on Gribov–Regge theory [20,21] and includes the effect of collective hadronisation in hadron-hadron scattering. The Hijing generator treats a heavy ion collision as a superposition of a hydrodynamically parametrised soft component and a hard component resulting from multi-parton fragmentation. The AMPT generator combines the Hijing event generator [22] with Zhang's parton cascade procedure [23] and the ART model [24] for the last stage of parton hadronisation.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker covering the range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters (HF), made of steel and quartz-fibres and located on either side of the interaction point, extend the pseudorapidity coverage provided by the barrel and endcap detectors to $|\eta| < 5.2$. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. The beam pickup timing for experiments (BPIX) devices are located around the beam pipe at a distance of 175 m from the interaction point on either side and provide precise information on the timing of the incoming beams. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [25].

Charged hadrons are reconstructed using the silicon pixel detectors installed during the Phase 1 upgrade [26], which consist of four concentric cylindrical shells (layers) in the barrel region (BPIX) and three disks on both sides of the interaction point in the forward region (FPiX). The BPIX and FPiX consist of a total of 1184 and 672 modules, respectively, and provide excellent position resolution with their 100 × 150 μm pixels. In this Letter, the layers of the BPIX are denoted in increasing order of their radial distance from the beam axis, i.e. the layer closest to the beam axis is referred to as layer 1, the next closest layer is referred to as layer 2, and so on, while the disks of the FPiX are referred to in increasing order of their longitudinal distance from the nominal interaction point.

3. Event selection

This analysis is based on approximately 1.36 million events. The average interaction probability per bunch crossing was 1.8%. Events are selected in two stages: (i) online, a coincidence of signals from both BPIX devices and at least one energy deposit above 3 GeV on either side of the HF are required; (ii) offline, three energy deposits above 3 GeV on each side of the HF and at least one reconstructed vertex, according to the tracklet-based vertex reconstruction method described in Ref. [16], are required. A study of noncolliding ion bunches shows that the above requirements are sufficient to reject all backgrounds not originating from interactions between xenon ions. Consequently, the contribution of background events from beam, beam-halo, and cosmic ray sources to the observed yields is negligible.

Contamination from electromagnetic (EM) interactions between xenon ions is studied using simulated events generated by STARLIGHT 2.2 [27] interfaced with BPMJET-III 3.0-5 [28], and is estimated to be around 1%. The event selection efficiency is estimated by fitting the distribution of the total transverse energy in the HF calorimeter using a template extracted from simulated Eros LHC events [16]. Variations in the fit parameters, as well as other observables correlated with event activity, are used to determine the uncertainty in this method. In combination with the contamination rate, an overall value of 95 ± 3% is quoted for the event selection efficiency.

Nuclei are extensive objects, and their collisions can be characterised by the centrality, which is related to the impact parameter of the collision. The centrality can be estimated from the sum of the transverse energy in the HF calorimeter [16,29]. The distribution of the total transverse energy, after correcting for the event selection efficiency, is divided into equal partitions and used to classify events into centralities. The centrality represents a percentile of the total nuclear interaction cross section [16]; the most central collisions, i.e. the collisions with the smallest impact parameter, are denoted by lower percentiles. To minimise the amount of EM contamination, which is concentrated in the 20% most peripheral events, the analysis is restricted to events with centrality in the 0–80% range, where the event selection is fully efficient.

The event centrality is also related to the number of participating nucleons $N_{\text{part}}$, which is determined from a Glauber model calculation [30,31]. For this calculation, the nucleon-nucleon inelastic cross section is taken to be 68.4 ± 0.5 mb [31], while the nuclear radius, skin depth, and deformation parameter $b_2$ of the xenon nucleus are set to 5.36 ± 0.1 fm, 0.59 ± 0.07 fm [32], and 0.18 ± 0.02 [17], respectively. Simulated Eros LHC events are used to account for the energy resolution of the HF calorimeters and fluctuations in event activity, which smear the centrality distributions. The resulting values and associated uncertainties for $N_{\text{part}}$ are listed in the supplemental material [URL will be inserted by publisher].

4. Analysis

The measurement of $dN_{\text{ch}}/d\eta$ is performed using tracklets, which are pairs of pixel clusters from two different layers (disks) of the silicon pixel detector. Pairs of pixel clusters that are produced by the same charged particle have small differences in $\eta$ and azimuthal angle $\phi$ with respect to the primary vertex. These correlations are exploited in the analysis to reconstruct tracklets that reflect the original distribution of primary charged hadrons. The vertex and tracklet reconstruction algorithms are described in Ref. [16].

Six possible types of tracklets can be formed from distinct combinations of the four layers of the BPIX. In addition, three types of tracklets can be formed from unique combinations of the three disks of the FPiX. The individual measurements from all nine combinations are averaged and symmetrised about $\eta = 0$ to obtain the final results. The different combinations are also useful for layer-by-layer systematic checks, as they have different sensitivities to the particle momentum spectrum. Particles with $p_T$ above 40 MeV can be reconstructed using the two BPIX layers closest to the beam pipe.

The angular distance between the two clusters that make up a tracklet is defined as

$$\Delta\tau = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2},$$

where $\eta_{i(j)}$ is the pseudorapidity of the pixel cluster position in the $i(j)$th layer or disk, calculated with respect to the primary vertex position, and $\phi_{i(j)}$ is defined similarly for the azimuthal angle. The $\Delta\tau$ distribution for tracklets reconstructed from layers 1 and 2 of the BPIX is shown in Fig. 1. The spectrum is compared to fully simulated events generated by Epos LHC, Hijing, and AMPT.

Tracklets with $\Delta\tau < 0.5$ are selected for analysis. This selection criterion suppresses the combinatorial background from uncorrelated background clusters and low transverse momentum ($p_T$) particles that loop around in the high magnetic field and leave
multiple charge deposits per layer of the pixel detector. The reconstructed tracklet spectrum is then corrected to the hadron-level event definition by applying a number of correction factors accounting for the geometric acceptance, reconstruction efficiency, and event selection efficiency. These correction factors are derived from MC simulations generated with the aforementioned event generators. The detector response is simulated with Geant4 and processed through the same event reconstruction chain as the collision data. All simulations are produced with the same vertex distribution along the interaction region as is observed in data.

Simulations generated with Epos LHC are used as the primary reference for the derivation of these correction factors because the $\Delta r$ spectrum obtained from these simulated events most closely resembles the corresponding spectrum in data at large $\Delta r$, where the combinatorial background is dominant. The other event generators are used in the study of systematic uncertainties. The correction factors are calculated as functions of the primary vertex position, pseudorapidity, and tracklet multiplicity. Typical values of these correction factors at $|\eta|=0$ ($1.6$) range from $1.12$ ($0.95$) at low multiplicities to $1.01$ ($0.85$) at high multiplicities.

The Jacobian transformation from $\eta$ to rapidity, $y$, can also be derived from simulations by relating the rapidity density of charged hadrons to the corresponding pseudorapidity density in each $\eta$ interval. The particle composition in data is assumed to fall within the range of particle compositions predicted by the various event generators. The final transformation factors applied are the mean values of the factors derived from each event generator.

The sum of transverse energy in the HF, on which the event selection is based, is correlated with the charged-hadron multiplicity in the region around $\eta=0$ where the measurement is made. Hence, the event selection criteria are susceptible to multiplicity fluctuations and may lead to a nonnegligible bias in the results. The magnitude of this bias is studied using various MC event generators by comparing the average $dN_{ch}/dy$ at midrapidity, defined as $|\eta|<0.5$, for two sets of generated events: (i) events selected based on the transverse energy sum in the HF, and (ii) events selected based on $N_{\text{part}}$, weighted to have the same distribution of $N_{\text{part}}$ as the former selection. This provides a comparison of results with and without the selection bias while also accounting for detector effects that smear the $N_{\text{part}}$ distribution of selected events. The bias caused by the event selection criteria is found to be negligible in the centrality interval used in this analysis.

5. Systematic uncertainties

The uncertainties resulting from various systematic effects affecting the measurement are evaluated. The sources of these systematic uncertainties include differences between data and simulation for effects such as the probability of pixel cluster splitting, pixel cluster reconstruction efficiency, and the fraction of uncorrelated pixel clusters, as well as the uncertainties in the alignment of pixel detector modules, tracklet selection criteria, parametrisation of correction factors, consistency between different tracklet combinations, and model dependence of the correction factors. Additionally, the uncertainty in the event selection is taken into account as an independent, fully correlated uncertainty. The individual contributions are then summed in quadrature to give the total systematic uncertainty.

Pixel cluster splitting refers to when the charge deposit from a single charged particle is reconstructed as two pixel clusters in close proximity. The difference in the relative fraction of split clusters between data and simulation can be estimated by artificially splitting the pixel clusters in simulation and comparing the resulting modified $\Delta r$ distribution of cluster pairs in simulation to that in data. This difference is found to be no more than 2%, which results in a variation of $1.8\%$ in the $dN_{ch}/dy$ results. The pixel cluster reconstruction efficiency can be estimated by studying the fraction of tracklets reconstructed from pixel clusters from the first and third layers that have a matching pixel cluster in the second layer. The ratio of this efficiency in data and simulation shows a relative difference of $0.5\%$, which has an effect of $0.5\%$ when propagated to the final results. The pixel cluster positions are smeared by the uncertainty in the alignment of the pixel detector modules, and the effect on the final results is found to be $-0.1\%$. The difference in the number of uncorrelated pixel clusters in data and simulation is estimated by comparing the tracklet $\Delta r$ distributions in the region $\Delta r>0.3$, where tracklets reconstructed from two uncorrelated clusters are dominant. Additional pixel clusters (on the order of $1\%$) were randomly added to the simulated events such that the tracklet $\Delta r$ distributions at large $\Delta r$ match those in data. A difference of $0.5\%$ in the final results is observed at $0<\eta<0$, which increases monotonically with $|\eta|$ to $2.4\%$ at $|\eta|=3.2$.

The tracklet selection criteria affect the minimum $p_T$ and signal-to-background ratio of reconstructed tracklets. The sensitivity of the correction factors to these effects is checked by varying the nominal selection criterion on $\Delta r$ by ±0.1. The effect of such variations on the final results is found to be about $0.2\%$. The multiplicity variable used in the parametrisation of the correction factors can be changed to be the number of pixel clusters, which is independent of the tracklet reconstruction efficiency. The effects of such a change are negligible. In any given $\eta$ range, measurements can be made using multiple tracklet combinations. The maximum deviation of the measurements obtained using each tracklet combination from the final averaged and symmetrised result, which ranges from $1.0$ to $2.1\%$ within $|\eta|<1.4$ and up to $5.0\%$ at larger values of $|\eta|$, is quoted as a systematic uncertainty. The model dependence of the correction factors is studied by using different sets of correction factors derived from Hijing and Ampt, which have different descriptions of the particle production mechanisms. The predicted particle spectra and composition can differ significantly among the event generators, which affect the correction for leptons and the extrapolation of the measured tracklet spectra to $p_T=0$. The maximum deviation from the nominal results is quoted as an uncertainty, and ranges from $2.0\%$ to $2.2\%$ within $|\eta|<1.0$ to a maximum of $5.0\%$ around $|\eta|=2.0$. The model dependence of the Jacobian transformation from $\eta$ to rapidity is also evaluated in a similar manner, and the maximum deviation, which ranges from
0.5% around $|\eta| = 1.4$ to 2.1% (2.5%) around $|\eta| = 0$ (3.2), is quoted as an additional uncertainty for the $dN_{ch}/dy$ results.

The determination of event centrality depends on the hadronic event selection efficiency, as well as the amount of contamination from EM processes. Since the inefficiency is limited to the most peripheral collisions, the effect of the uncertainty in the event selection efficiency is to shift the events into other centrality intervals. Hence, to evaluate the uncertainty in the final results, different sets of centrality calibrations, derived after varying the event selection efficiency by its uncertainty, are used to categorise the data. This leads to a difference of 0.4–25.7% in the final results, largest in the 75–80% centrality interval and decreasing towards more central collisions, which is fully correlated across different centrality intervals and $|\eta|$ values. The uncertainties in the $N_{part}$ values are determined by propagating the uncertainties in the parameters of the Glauber model, which are listed in Section 3, and which range from 0.7 to 8.9%.

A summary of the systematic uncertainties is given in Table 1. With the exception of the uncertainties in the event selection efficiency and the $N_{part}$ values, the systematic uncertainties are largely independent of centrality and highly correlated point-to-point in the region $|\eta| < 1.4$, where only combinations of BPIX layers contribute to the result.

### Table 1

<table>
<thead>
<tr>
<th>Source</th>
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<td>Pixel cluster splitting</td>
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<tr>
<td>Pixel cluster reconstruction efficiency</td>
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<tr>
<td>Alignment uncertainty</td>
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<tr>
<td>Uncorrelated pixel clusters</td>
<td>0.5–2.4</td>
</tr>
<tr>
<td>Tracklet selection</td>
<td>0.2</td>
</tr>
<tr>
<td>Tracklet reconstruction efficiency</td>
<td>&lt;0.05</td>
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<tr>
<td>Consistency between tracklet combinations</td>
<td>10–50</td>
</tr>
<tr>
<td>Model dependence (Jacobian transformation)</td>
<td>2–5.0</td>
</tr>
<tr>
<td>Model dependence</td>
<td>0.5–2.5</td>
</tr>
<tr>
<td>Event selection efficiency (0–5% to 75–80%)</td>
<td>0.4–25.7</td>
</tr>
<tr>
<td>Glauber model calculation</td>
<td>0.7–8.9</td>
</tr>
</tbody>
</table>

Fig. 2. Averaged and symmetrised $dN_{ch}/dy$ distributions in XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV (grey squares), for events in the 0–80% centrality interval (upper), as well as the 0–5% (red squares) and 50–55% (blue circles) centrality intervals (lower). Predictions from the Epos LHC v3400 [8,18], HYDJET 1.9 [9], and AMPT L265 [19] event generators are also shown for comparison. The ratios of the $dN_{ch}/dy$ distributions for events in the 0–5% to those in the 50–55% centrality interval, normalised to unity at midrapidity, are shown in the bottom panel. The bands around the data points denote the total systematic uncertainties, while the statistical uncertainties are negligible.

Fig. 3. Averaged and symmetrised charged-hadron $dN_{ch}/dy$ distribution in XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for events with 0–80% centrality (grey squares). The band around the data points denotes the total systematic uncertainties, while the statistical uncertainties are negligible. Predictions from the Epos LHC v3400 [8,18], HYDJET 1.9 [9], and AMPT L265 [19] event generators are also shown in comparison. None of the event generators describe the plateau around $y = 0$.

Fig. 4 (upper) shows the charged-hadron $dN_{ch}/dy$ at midrapidity as a function of centrality. For events in the 0–5% centrality comparison. None of the event generators describe the plateau around $y = 0$.
interval, $dN_{ch}/dη$ is found to be $1187 \pm 36$ (syst) at midrapidity. This is nearly a factor of two greater than the interpolated $dN_{ch}/dη$ in proton-proton collisions at the same energy [11] after scaling by $A$, the atomic number of the nuclei. The results are compared to a measurement at the same energy for charged particles by the ALICE Collaboration [17], which includes leptons in the analysis. Within the total uncertainties, the measurements are consistent in the 0–60% centrality interval, although the ALICE Collaboration reports a slightly higher $dN_{ch}/dη$ for more peripheral collisions.

The results are also compared to previous measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV by the CMS [16] and ALICE [37,38] Collaborations. As one would expect, for the same centrality, $dN_{ch}/dη$ increases with energy and system size. It is interesting to note that for different colliding nuclei at the same energy, $dN_{ch}/dη$ is proportional to $2A$. This is evident from Fig. 4 (lower), where $dN_{ch}/dη/2A$ is shown as functions of centrality for a variety of colliding nuclei and energies. These results show that the feature observed at lower energies, that the geometry of the colliding systems plays an important role in determining the production of particles [6], is also present at the much higher LHC energies.

To study the relevance for particle production of the number of participating nucleons, $(dN_{ch}/dη)(N_{\text{part}})$ is shown as a function of $(N_{\text{part}})$ in Fig. 5 (upper). The results are compared to a measurement at the same energy by the ALICE Collaboration and to previous measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. As can be seen, the per-participant multiplicity for XeXe and PbPb collisions with similar $(N_{\text{part}})$, but corresponding to different centrality classes in the two collision systems, are inconsistent. This is most apparent when nearly completely overlapping XeXe collisions (0–5% centrality or $(N_{\text{part}}) \approx 236$) are compared to PbPb collisions with similar $(N_{\text{part}})$, for which the corresponding centrality is approximately 15–20%. However, as shown in Fig. 5 (lower), where $(N_{\text{part}})/2A$ is used as a proxy for centrality (the correspondence between centrality and $(N_{\text{part}})/2A$ is tabulated in the supplemental material [URL will be inserted by publisher]), the per-participant charged-hadron multiplicity for different colliding nuclei are equal within uncertainties when the geometry (centrality) and energy of the compared systems are the same.

An equivalent representation of Fig. 5 (lower) is shown in Fig. 6, where $dN_{ch}/dη/2A$ is shown as a function of $(N_{\text{part}})/2A$. In this form, it is clear that multiparticle production scales as $2A$ times a function of $(N_{\text{part}})/2A$, indicating a dependence on both the system size (given by $2A$) and the geometry of the colliding
system (represented by \( N_{\text{part}}/2A \)). Considering that multiparticle production processes in heavy ion collisions are highly complex—starting with the initial impact of the two nuclei, through the creation and evolution of a relativistic fluid, and followed by a hadronisation and scattering phase—it is not surprising that the result depends on both the colliding system and energy, in a non-trivial way.

7. Summary

The pseudorapidity distributions of charged hadrons in xenon-xenon collisions at a centre-of-mass energy of 5.44 TeV per nucleon pair are reported. Using data taken with the upgraded 4-layer silicon pixel detectors, the charged-hadron pseudorapidity densities, \( dN_{ch}/d\eta \), are measured to an extended \( \eta \) range of \( |\eta| < 3.2 \). For events in the 0-5% centrality interval, the \( dN_{ch}/d\eta \) at midrapidity is measured to be \( 1187 \pm 36 \) (syst), with a negligible statistical uncertainty. The results are found to be consistent with the ALICE Collaboration’s measurement. The charged-hadron rapidity density is also presented, and is found to be consistent with a rapidity plateau in the region \( |\eta| < 1 \). The results are compared to predictions from the Epos LHC v3400, Hydjet 1.9, and AMPT 1.26Ts event generators. None of the event generators are able to fully describe the measurements in terms of the magnitude, pseudorapidity dependence, and centrality dependence of the \( dN_{ch}/d\eta \) distributions, although Epos LHC describes the shape well. The per-participant \( dN_{ch}/d\eta \) at midrapidity in XeXe collisions is observed to rise faster with \( N_{\text{part}} \) than in PbPb collisions. However, when comparing events with similar fractional overlap, the per-participant \( dN_{ch}/d\eta \) is consistent between the two collision systems. The results also show that the \( dN_{ch}/d\eta \) at midrapidity is a function of the collision geometry after normalising by 2A, where \( A \) is the atomic number of the nuclei. This is observed for a variety of collision systems and energies, both at RHIC and the LHC, demonstrating that final-state charged-hadron multiplicities are strongly dependent on the collision geometry. These results provide important constraints on models and generators which describe multiparticle production in heavy ion collisions at high energies. They may also help in the characterisation of the initial conditions of the quark gluon plasma, which is needed for the understanding of its subsequent hydrodynamic evolution, as well as the properties of this fluid.

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Appendix A. Supplementary material

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The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia


Institut für Hochenergiephysik, Wien, Austria

V. Chekhnovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

Universiteit Antwerpen, Antwerpen, Belgium


Vrije Universiteit Brussel, Brussel, Belgium


Université Libre de Bruxelles, Bruxelles, Belgium


Ghent University, Ghent, Belgium


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


Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil


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


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

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, 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

University of Sofia, Sofia, Bulgaria

W. Fang, X. Gao, L. Yuan

Beihang University, Beijing, China


Institute of High Energy Physics, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Wang
Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado
Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac
University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac
University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa
Institute Rudjer Boskovic, Zagreb, Croatia

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr
Charles University, Prague, Czech Republic

E. Ayala
Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin
Universidad San Francisco de Quito, Quito, Ecuador

A. Ellithi Kamel, M.A. Mahmoud, Y. Mohammed
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen
Department of Physics, University of Helsinki, Helsinki, Finland

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva
Lappeenranta University of Technology, Lappeenranta, Finland

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


Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France


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

S. Gadrat

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


Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze

Georgian Technical University, Tbilisi, Georgia

D. Lomidze

Tbilisi State University, Tbilisi, Georgia


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


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


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


Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany


Karlsruher Institut für Technologie, Karlsruhe, Germany


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


National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece


University of Ioánnina, Ioánnina, Greece


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

G. Benecke, C. Hajdu, D. Horvath, Á. Hunyadi, F. Sikler, T.A. Vámi, V. Veszpremi, G. Vesztergombi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISC), Bangalore, India


National Institute of Science Education and Research, HBNI, Bhubaneswar, India


Panjab University, Chandigarh, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India


Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani 26, E. Eskandari Tadavani, S.M. Etesami 26, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh 27, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia a,b, C. Calabria a,b, A. Colaleo a, D. Creanza a,c, L. Cristella a,b, N. De Filippis a,c, M. De Palma a,b, A. Di Florio a,b, F. Errico a,b, L. Fiore a, A. Gelmi a,b, G. Iaselli a,c, M. Ince a,b, S. Lezki a,b, G. Maggi a,c, M. Maggi a, G. Miniello a,b, S. My a,b, S. Nuzzo a,b, A. Pompilia a,b, G. Pugliese a,c, R. Radogna a, A. Ranieri a, G. Selvaggi a,b, A. Sharma a, L. Silvestris a, R. Venditti a, P. Verwilligen a, G. Zito a

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

G. Abbiendi a, C. Battilana a,b, D. Bonacorsi a,b, L. Borgonovi a,b, S. Braibant-Giacomelli a,b, R. Campanini a,b, P. Capiluppi a,b, A. Castro a,b, F.R. Cavallo a, S.S. Chhibra a,b, C. Ciocca a, G. Codispoti a,b, M. Cuffiani a,b, G.M. Dallavalle a, F. Fabbri a, A. Fanfani a,b, E. Fontanesi, P. Giacomelli a, C. Grandi a, L. Guiducci a,b, S. Lo Meo a, S. Marcellini a, G. Masetti a, A. Montanari a, F.L. Navarria a,b, A. Perrotta a, F. Primavera a,b, A.M. Rossi a,b, T. Rovelli a,b, G.P. Siroli a,b, N. Tosi a

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

S. Albergo a,b, A. Di Mattia a, R. Potenza a,b, A. Tricomi a,b, C. Tuve a,b

a INFN Sezione di Catania, Catania, Italy
b Università di Catania, Catania, Italy
G. Barbagli a, K. Chatterjee a,b, V. Ciulli a,b, C. Civinini a, R. D'Alessandro a,b, E. Focardi a,b, G. Latino, P. Lenzi a,b, M. Meschini a, S. Paoletti a, L. Russo a, b, G. Sguazzoni a, D. Strom a, L. Viliani a

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

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo
INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro a, F. Ravera a,b, E. Robutti a, S. Tosi a,b

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

A. Benaglia a, A. Beschi b, L. Brianza a,b, F. Brivio a,b, V. Ciriolo a,b, S. Di Guida a,b, M.E. Dinardo a,b, S. Fiorendi a,b, S. Gennai a, A. Ghezzi a,b, P. Govoni a,b, M. Malberti a,b, S. Malvezzi a, A. Massironi a,b, D. Menasce a, F. Monti, L. Moroni a, M. Paganoni a,b, D. Pedrini a, S. Ragazzi a,b, T. Tabarelli de Fatis a,b, D. Zuolo a,b

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

data

S. Buontempo a, N. Cavallo c, A. De Iorio a,b, A. Di Crescenzo a,b, F. Fabozzi a,c, F. Fienga a, G. Galati a, A.O.M. Iorio a,b, W.A. Khan a, L. Lista a, S. Meola a,d,15, P. Paolucci a,15, C. Sciacc a,b, E. Voevodina a,b

a INFN Sezione di Napoli, Napoli, Italy
b Università di Napoli Federico II, Napoli, Italy
c Università della Basilicata, Potenza, Italy
d Università G. Marconi, Roma, Italy

data

P. Azzi a, N. Bacchetta a, D. Bisello a,b, A. Boletti a,b, A. Bragagnolo, R. Carlin a,b, P. Checchia a, M. Dall’Osso a,b, P. De Castro Manzano a, T. Dorigo a, U. Dosselli a, F. Gasparini a,b, U. Gasparini a,b, A. Gozzelino a, S.Y. Hoh, S. Lacaprara a, P. Lujan, M. Margoni a,b, A.T. Meneguzzo a,b, J. Pazzini a,b, P. Ronchese a,b, R. Rossin a,b, F. Simonetto a,b, A. Tiko, E. Torassa a, M. Zanetti a,b, P. Zotto a,b, G. Zumerle a,b

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

data

A. Braghieri a, A. Magnani a, P. Montagna a,b, S.P. Ratti a,b, V. Re a, M. Ressegotti a,b, C. Riccardi a,b, P. Salvini a, I. Vai a,b, P. Vitulo a,b

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

data

M. Biasini a,b, G.M. Bilei a, C. Cecchi a,b, D. Ciangottini a,b, L. Fanò a,b, P. Lariccia a,b, R. Leonardi a,b, E. Manoni a, G. Mantovani a,b, V. Mariani a,b, M. Menichelli a, A. Rossi a,b, A. Santocchia a,b, D. Spiga a

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

data

K. Androsov a, P. Azzurri a, G. Bagliesi a, L. Bianchini a, T. Boccali a, L. Borrello, R. Castaldi a, M.A. Ciocci a,b, R. Dell’Orso a, G. Fedi a, F. Fiori a,c, L. Giannini a,c, A. Giassi a, M.T. Grippo a, F. Ligabue a,c, E. Manca a,c, G. Mandorli a,c, A. Messineo a,b, F. Palla a, A. Rizzi a,b, P. Spagnolo a, R. Tenchini a, G. Tonelli a,b, A. Venturi a, P.G. Verdini a

a INFN Sezione di Pisa, Pisa, Italy
b Università di Pisa, Pisa, Italy
c Scuola Normale Superiore di Pisa, Pisa, Italy
L. Barone a,b, F. Cavallari a, M. Cipriani a,b, D. Del Re a,b, E. Di Marco a,b, M. Diemoz a, S. Gelli a,b, E. Longo a,b, B. Marzocchi a,b, P. Meridiani a, G. Organtini a,b, F. Pandolfi a, R. Paramatti a,b, F. Preiato a,b, S. Rahatlou a,b, C. Rovellia, F. Santanastasio a,b

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

N. Amapane a,b, R. Arcidiacono a,c, S. Argiro a,b, M. Arneodo a,c, N. Bartosik a, R. Bellan a,b, C. Biino a, N. Cartiglia a, F. Cenna a,b, S. Cometti a, M. Costa a,b, R. Covarelli a,b, N. Demaria a, B. Kiani a,b, C. Mariotti a, S. Maselli a, E. Migliore a,b, V. Monaco a,b, E. Monteila a,b, M. Montenoa, M.M. Obertino a,b, L. Pacher a,b, N. Pastrone a, M. Pelliccioni a, G.L. Pinna Angioni a,b, A. Romero a,b, M. Ruspa a,c, R. Sacchi a,b, K. Shchelina a,b, V. Sola a,b, A. Solano a,b, D. Soldi a,b, A. Staiano a

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

S. Belforte a, V. Candelise a,b, M. Casarsa a, F. Cossutti a, A. Da Rold a,b, G. Della Ricca a,b, F. Vazzoler a,b, A. Zanetti a

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


Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J. Goh 29, T.J. Kim

Hanyang University, Seoul, Republic of Korea


Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea


Seoul National University, Seoul, Republic of Korea


University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania


National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico


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

S. Carrillo Moreno, C. Oronpeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaiib, M. Waqas

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


National Centre for Nuclear Research, Swierk, Poland


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


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


Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia


Institute for Nuclear Research, Moscow, Russia

CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland


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


Universität Zürich, Zurich, Switzerland


National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand


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

B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Ozkorucuklu, S. Tekten, E.A. Yetkin

Bogazici University, Istanbul, Turkey

Florida State University, Tallahassee, USA


Florida Institute of Technology, Melbourne, USA


University of Illinois at Chicago (UIC), Chicago, USA


The University of Iowa, Iowa City, USA


Johns Hopkins University, Baltimore, USA


The University of Kansas, Lawrence, USA


Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA


University of Maryland, College Park, USA


Massachusetts Institute of Technology, Cambridge, USA


University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

University of Nebraska-Lincoln, Lincoln, USA


State University of New York at Buffalo, Buffalo, USA


Northeastern University, Boston, USA


Northwestern University, Evanston, USA


University of Notre Dame, Notre Dame, USA


The Ohio State University, Columbus, USA


Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA


Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA


Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, P. Tan, R. Taus

University of Rochester, Rochester, USA


Rutgers, The State University of New Jersey, Piscataway, USA
A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA


Texas A&M University, College Station, USA


Texas Tech University, Lubbock, USA


Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA


Wayne State University, Detroit, USA


University of Wisconsin – Madison, Madison, WI, USA

1 Deceased.
2 Also at IFPU, CEFA, Université Paris-Saclay, Gif-sur-Yvette, France.
3 Also at Universidade Estadual de Campinas, Campinas, Brazil.
4 Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
5 Also at Université Libre de Bruxelles, Bruxelles, Belgium.
6 Also at University of Chinese Academy of Sciences, Beijing, China.
7 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
8 Also at Joint Institute for Nuclear Research, Dubna, Russia.
9 Now at Cairo University, Cairo, Egypt.
10 Also at Fayoum University, El-Fayoum, Egypt.
11 Now at British University in Egypt, Cairo, Egypt.
12 Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.
13 Also at Université de Haute Alsace, Mulhouse, France.
14 Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
15 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
16 Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
17 Also at University of Hamburg, Hamburg, Germany.
18 Also at Brandenburg University of Technology, Cottbus, Germany.
19 Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
20 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
21 Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
22 Also at Indian Institute of Technology Bhbaneswar, Bhubaneswar, India.
23 Also at Institute of Physics, Bhubaneswar, India.
24 Also at Shoolini University, Solan, India.
25 Also at University of Visva-Bharati, Santiniketan, India.
26 Also at Isfahan University of Technology, Isfahan, Iran.
27 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
28 Also at Università degli Studi di Siena, Siena, Italy.
29 Also at Kyung Hee University, Department of Physics, Seoul, Republic of Korea.
30 Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
31 Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
32 Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

Also at Institute for Nuclear Research, Moscow, Russia.

Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.

Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at University of Florida, Gainesville, USA.

Also at P.N. Lebedev Physical Institute, Moscow, Russia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at Institute for Nuclear Research, Moscow, Russia.

Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at National and Kapodistrian University of Athens, Athens, Greece.

Also at Institute of Physics, University of South Carolina, Columbia, USA.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Padova a, Università di Padova b, Università di Trento (Trento) c, Padova, Italy.

Also at University of Belgrade, Belgrade, Serbia.