EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PH-EP-2012-155
27 May 2012

Production of muons from heavy flavour decays and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

The ALICE Collaboration*

Abstract

The ALICE Collaboration has measured the inclusive production of muons from heavy flavour decays at forward rapidity, $2.5 < y < 4$, in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The p_{t}-differential inclusive cross section of muons from heavy flavour decays in pp collisions is compared to perturbative QCD calculations. The nuclear modification factor is studied as a function of p_{t} and collision centrality. A weak suppression is measured in peripheral collisions. In the most central collisions, a suppression of a factor of about 3–4 is observed in $6 < p_{\mathrm{t}} < 10$ GeV/c. The suppression shows no significant p_{t} dependence.

Keywords: LHC, ALICE experiment, ultra-relativistic heavy ion collisions, heavy flavour production, nuclear modification factor
PACS: 25.75.-q, 25.75.Cj, 13.20-v

*See Appendix A for the list of collaboration members

The study of ultra-relativistic heavy ion collisions is aimed at investigating the properties of strongly-interacting matter in extreme conditions of high temperature and energy density expected to be reached. Quantum Chromodynamics (QCD) calculations on the lattice predict under such conditions the formation of a deconfined partonic phase, the Quark-Gluon Plasma (QGP), and chiral symmetry is restored [1]. Heavy quarks (charm and beauty), abundantly produced at the Large Hadron Collider (LHC), are sensitive probes of the properties of the QGP. Due to their large masses, they are created mainly in hard scattering processes during the early stage of the collision and subsequently interact with the hot and dense medium. In particular, measurement of open heavy flavour hadrons may probe the energy density of the system through the mechanism of in-medium energy loss of heavy quarks. The in-medium effects are usually quantified by means of the nuclear modification factor $R_{\rm AA}$ of the transverse momentum ($p_{\rm t}$) distribution. Using the nuclear overlap function from the Glauber model [2], $R_{\rm AA}$ can be expressed as:

$$R_{\rm AA}(p_{\rm t}) = \frac{1}{\langle T_{\rm AA}\rangle} \cdot \frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm t}}{{\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm t}}, \quad (1)$$

where $\langle T_{\rm AA}\rangle$ is the average nuclear overlap function in a given centrality class. The term ${\rm d}N_{\rm AA}/{\rm d}p_{\rm t}$ is the $p_{\rm t}$-differential yield in nucleus-nucleus (AA) collisions, while ${\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm t}$ is the $p_{\rm t}$-differential inclusive cross section in pp collisions. The value of $R_{\rm AA}$ is unity for hard probes if no nuclear modification is present. A $R_{\rm AA}$ value smaller than unity can arise from partonic energy loss as well as other nuclear effects. According to QCD, the radiative energy loss of gluons should be larger than that of quarks and, due to the dead cone effect [3–6], heavy quark energy loss should be further reduced with respect to that of light quarks. The contribution from other interaction mechanisms, for instance collisional energy loss [7, 8], in-medium fragmentation, recombination and coalescence [9–11], could also lead to a modification of heavy-flavour hadron $p_{\rm t}$ distributions in AA collisions. Finally, initial state effects [12, 13] could complicate the interpretation of any deviation from unity of the $R_{\rm AA}$ in terms of energy loss effects, particularly in the low $p_{\rm t}$ region. The study of p–A collisions is required to quantify the role of initial state effects. The PHENIX and STAR Collaborations have reported a strong suppression of electrons from heavy flavour decays at mid-rapidity, in central Au–Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV at RHIC [14–16]. Recently, a significant suppression of D mesons [17] and J/ψ's from B decays [18] was measured at mid-rapidity in central Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV by ALICE and CMS at the LHC, respectively. A complementary measurement of heavy flavour suppression at forward rapidity, at the same energy, is of great interest in order to provide new constraints on models which aim at describing the nuclear modification factor as partonic energy loss.

In this Letter, we report the first measurement at the LHC of the production of muons from heavy flavour decays at forward rapidity ($2.5 < y < 4$), with the ALICE experiment [19], in pp and Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. The measured $p_{\rm t}$-differential inclusive cross section of muons from heavy flavour decays in pp collisions at $\sqrt{s}$ = 2.76 TeV is compared to perturbative QCD (pQCD) calculations. In-medium effects are investigated by means of the nuclear modification factor as a function of $p_{\rm t}$ in $4 < p_{\rm t} < 10$ GeV/c, and as a function of collision centrality in $6 < p_{\rm t} < 10$ GeV/c.

The ALICE experiment is described in detail in [19]. The apparatus is composed of a central barrel (pseudo-rapidity coverage $|\eta| < 0.9$), a muon spectrometer ($-4 < \eta < -2.5$[1]) and a set of detectors for global collision characterization and triggering located in the forward and backward pseudo-rapidity regions. The VZERO, made of two scintillator arrays covering the $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, is used for triggering, centrality determination and background removal. The two Zero Degree Calorimeters (ZDC), located at $\pm$ 114 m from the interaction point, are used in offline rejection of background events. The Silicon Pixel Detector (SPD), a two-layer central barrel that constitutes the innermost part of the Inner Tracking System (ITS), is included in the trigger logic. The SPD provides also the interaction vertex reconstruction. The muon spectrometer consists of a 10 interaction length

[1] In the ALICE reference frame, the muon spectrometer covers a negative η range and consequently a negative y range. The results are presented with a positive y notation.

(λ_I) passive front absorber, a beam shield, an iron wall, a 3 T·m dipole magnet and a set of tracking and trigger chambers. Tracking is performed by means of five stations of cathode pad chambers, with the third station inside the dipole magnet. The tracking system is supplemented by two trigger stations of resistive plate chambers, behind a 1.2 m thick iron wall with thickness 7.2 λ_I. The latter absorbs hadrons that punch through the front absorber, as well as secondary hadrons produced inside it and low momentum muons, mainly from pion and kaon decays.

The Pb–Pb data were collected during the 2010 run. The rate of hadronic collisions was about 100 Hz, corresponding to a luminosity of $1.3 \cdot 10^{25}$ cm^{-2}s^{-1}. The results presented in this Letter are based on the analysis of minimum bias (MB) trigger events. The MB trigger required the following conditions: a signal in at least two pixel chips in the outer layer of the SPD and a signal on each VZERO detector. The beam-induced background was reduced by using the timing information from the VZERO and ZDC detectors, and by exploiting the correlation between the number of hits and track segments in the SPD. Moreover, a minimal energy deposit in the ZDC was required in order to reject electromagnetic interactions. Finally, only events with an interaction vertex within ± 10 cm from the center of the detector along the beam line were analyzed. Pb–Pb collisions were classified according to their degree of centrality by means of the sum of amplitudes of the signals in the VZERO detectors, as described in [20, 21]. The analysis was limited to the 80% most central events for which the MB trigger was fully efficient. This leads to a data sample of $16.6 \cdot 10^6$ Pb–Pb collisions which, in the following, will be divided into five centrality classes: 0–10%, 10–20%, 20–40%, 40–60% and 60–80% (the two last bins will be grouped together for the study of $R_{AA}(p_t)$). The corresponding integrated luminosity is $L_{int} = 2.71 \pm 0.09$ μb^{-1}. The values of the mean number of participating nucleons and mean nuclear overlap function are given in Table 1. They were determined with the Glauber Monte-Carlo simulation assuming an inelastic nucleon-nucleon cross section of 64 mb [20]. The strategy of cuts applied to reconstructed tracks is similar to the

Table 1: Mean number of participating nucleons ($\langle N_{part} \rangle$) and mean nuclear overlap function ($\langle T_{AA} \rangle$) for different centrality classes, expressed in percentiles of the hadronic Pb–Pb cross section.

Centrality	$\langle N_{part} \rangle$	$\langle T_{AA} \rangle$ mb^{-1}
0–10%	357 ± 4	23.48 ± 0.97
10–20%	261 ± 4	14.43 ± 0.57
20–40%	157 ± 3	6.85 ± 0.28
40–60%	69 ± 2	2.00 ± 0.11
60–80%	23 ± 1	0.42 ± 0.03
40–80%	46 ± 2	1.20 ± 0.07

one used for pp collisions [22]. Various selection cuts were used in order to improve the purity of the data sample. Tracks were required to be reconstructed in the geometrical acceptance of the muon spectrometer. A track candidate measured in the muon tracking chambers was then required to be matched with the corresponding track measured in the trigger chambers. This results in a very effective rejection of the hadronic background that is absorbed in the iron wall. Furthermore, the correlation between momentum and Distance of Closest Approach (distance between the extrapolated muon track and the interaction vertex, in the plane perpendicular to the beam direction and containing the vertex) was used to remove the remaining beam-induced background tracks that do not point to the interaction vertex, and fake tracks (tracks not associated to one single particle crossing the spectrometer). After these selections, the data sample consists of $10 \cdot 10^6$ muon candidates. The R_{AA} measurement of muons from heavy flavour decays will be performed at high p_t ($p_t >$ 4-6 GeV/c) where the main background component consists of muons from primary pion and kaon decays. The Pb–Pb distributions are corrected for acceptance and for tracking and trigger efficiency ($A \times \varepsilon$) using the procedure described in [22]. The global $A \times \varepsilon$ is close to 80% for $p_t > 4$ GeV/c. The dependence of the trigger and tracking efficiency on the detector occupancy, which is correlated with the collision centrality, was evaluated by means of the embedding procedure [23]. A decrease of the efficiency of about 4% $\pm$ 1% is observed in the 10% most central collisions.

The $R_{\rm AA}$ of muons from heavy flavour decays in the forward rapidity region is calculated according to Eq. (1), which can be written as:

$$R_{\rm AA}^{\mu^{\pm}\leftarrow{\rm HF}}(p_{\rm t}) = \frac{1}{\langle T_{\rm AA}\rangle} \cdot \frac{{\rm d}N_{\rm PbPb}^{\mu^{\pm}}/{\rm d}p_{\rm t} - {\rm d}N_{\rm PbPb}^{\mu^{\pm}\leftarrow\pi^{\pm},{\rm K}^{\pm}}/{\rm d}p_{\rm t}}{{\rm d}\sigma_{\rm pp}^{\mu^{\pm}\leftarrow{\rm HF}}/{\rm d}p_{\rm t}} \quad (2)$$

where ${\rm d}N_{\rm PbPb}^{\mu^{\pm}}/{\rm d}p_{\rm t}$ and ${\rm d}N_{\rm PbPb}^{\mu^{\pm}\leftarrow\pi^{\pm},{\rm K}^{\pm}}/{\rm d}p_{\rm t}$ are the inclusive muon and charged pion and kaon decay muon $p_{\rm t}$ distributions at forward rapidity in Pb–Pb collisions, respectively.

The pp reference, ${\rm d}\sigma_{\rm pp}^{\mu^{\pm}\leftarrow{\rm HF}}/{\rm d}p_{\rm t}$, was obtained from the analysis of muon-triggered events collected during a pp run at $\sqrt{s}$ = 2.76 TeV, in March 2011, with integrated luminosity of 19 nb^{-1} after event selection cuts. The analysis technique from the event and track selection to the normalization, is the same as that described in [22]. Figure 1 shows the measured $p_{\rm t}$-differential inclusive cross section of muons

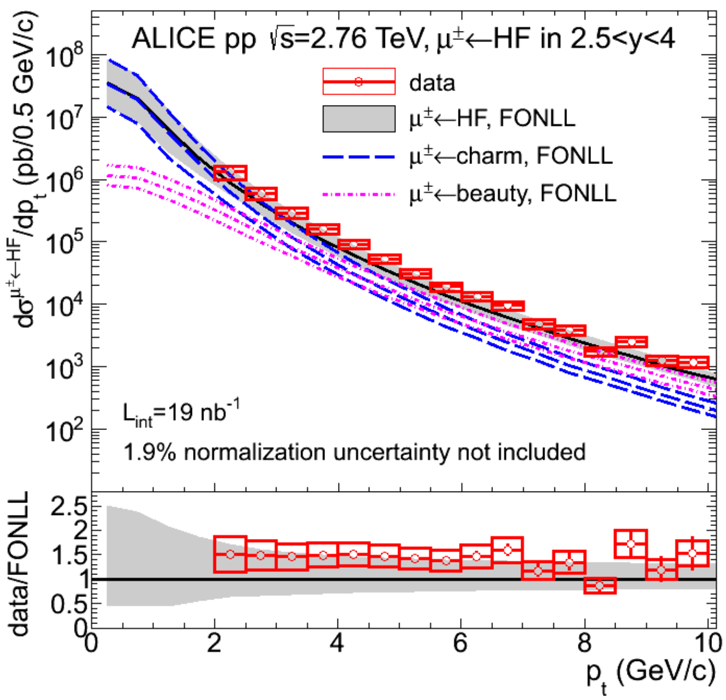

Fig. 1: (Color online) Transverse momentum differential inclusive cross section of muons from heavy flavour decays in $2.5 < y < 4$, in pp collisions at $\sqrt{s}$ = 2.76 TeV. The error bars (open boxes) are the statistical (systematic) uncertainties. The solid curve and the band show FONLL [24, 25] calculations and theoretical uncertainties, respectively. The FONLL calculations are also reported for muons from charm (long dashed curves) and beauty (dashed curves) decays, separately. The lower panel shows the ratio between data and FONLL calculations.

from heavy flavour decays in the kinematic region $2.5 < y < 4$ and $2 < p_{\rm t} < 10$ GeV/c. In the range $p_{\rm t} > 4$ GeV/c ($p_{\rm t} > 6$ GeV/c), regions of interest for the $R_{\rm AA}^{\mu^{\pm}\leftarrow{\rm HF}}(p_{\rm t})$ measurement, the contribution of muons from primary light hadron decays (mainly primary pion and kaon decays) that was subtracted amounts to about 19% (12%) of the total yield. The error bars are statistical uncertainties. The open boxes represent the systematic uncertainties varying from 15% to 24%, depending on $p_{\rm t}$. This includes the contributions from background subtraction (ranging from a maximum of about 24% at $p_{\rm t}$ = 2 GeV/c to 14% at $p_{\rm t}$ = 10 GeV/c), detector response (3%) and residual mis-alignment of tracking chambers (1% $\times$ $p_{\rm t}$, in GeV/c). The systematic uncertainty on the minimum bias pp cross section (1.9%), used in the normalization, is not shown. The data are compared to Fixed Order Next-to-Leading Log (FONLL) pQCD predictions [24,25] (curve, with shaded band for the uncertainty). The ratio between data and FONLL calculations is also shown. The measured p_t-differential inclusive cross section of muons from heavy flavour decays is well reproduced by the calculations within experimental and theoretical uncertainties, although at the upper limit of the predictions. A similar behaviour was also reported in pp collisions at $\sqrt{s}$ = 7 TeV [22]. The contributions of muons from charm and beauty decays from the FONLL calculations are displayed separately in Fig. 1. According to these predictions, the component of muons from beauty decays exceeds that of muons from charm decays for $p_t \gtrsim 6$ GeV/c.

The p_t distribution of muons from heavy flavour decays in Pb–Pb collisions at forward rapidity is obtained by subtracting the muon background component (mainly muons from primary pion and kaon decays) from the corrected inclusive muon p_t-differential distribution. The presence of unknown nuclear effects, in particular medium-induced parton energy loss at forward rapidity, prevents subtraction of this contribution by means of Monte-Carlo simulations, as was done in pp collisions [22]. Hence, the contribution of muons from primary $\pi^{\pm}$ and $K^{\pm}$ decays at forward rapidity in Pb–Pb collisions was estimated by extrapolating to forward rapidity ($2.5 < y < 4$) the p_t distributions of pions and kaons measured at central rapidity ($|y| < 0.8$) in pp and Pb–Pb collisions [26] and generating the corresponding p_t distributions of decay muons with a simulation of the decay kinematics and of the front absorber. For the rapidity extrapolation, it was assumed that the suppression of pions and kaons is independent of rapidity up to $y = 4$. This assumption is motivated by the observation, by the ATLAS Collaboration, that the central-to-peripheral nuclear modification factor of charged hadrons does not show any η-dependence up to $\eta = 2.5$ within uncertainties [27]. The systematic uncertainty introduced by this assumption was conservatively estimated by varying R_{AA} from 0 (full suppression) up to two times its value. The entire background-estimation procedure is detailed in the following.

The p_t distribution of pions and kaons at forward rapidity in Pb–Pb collisions in a given centrality range is expressed as:

$$\mathrm{d}N_{\mathrm{PbPb}}^{\pi^{\pm},\mathrm{K}^{\pm}}/\mathrm{d}p_t = \langle T_{\mathrm{AA}}\rangle \cdot \mathrm{d}\sigma_{\mathrm{pp}}^{\pi^{\pm},\mathrm{K}^{\pm}}/\mathrm{d}p_t \cdot [R_{\mathrm{AA}}^{\pi^{\pm},\mathrm{K}^{\pm}}(p_t)]_{y=0}. \tag{3}$$

The mid-rapidity pion and kaon p_t distributions measured in pp collisions were extrapolated to forward rapidity using [28]:

$$\mathrm{d}N_{\mathrm{pp}}^{\pi^{\pm},\mathrm{K}^{\pm}}/\mathrm{d}p_t = \int_{2.5}^{4} \mathrm{d}y \cdot [\mathrm{d}^2 N_{\mathrm{pp}}^{\pi^{\pm},\mathrm{K}^{\pm}}/\mathrm{d}p_t\mathrm{d}y]_{y=0} \cdot \exp\left(\frac{-y^2}{2\sigma_y^2}\right), \tag{4}$$

with σ_y = 3.18. The latter is the average of the values obtained with the PYTHIA [29] and PHOJET [30] event generators.

Then, the muon p_t distributions in $2.5 < y < 4$ in pp and Pb–Pb collisions were obtained by means of fast simulations using the resultant pion and kaon p_t distributions as input. The effect of the front absorber was taken into account by considering only pions and kaons that decay before reaching a distance corresponding to one interaction length in the absorber.

The input charged pion p_t distributions were measured up to p_t = 20 GeV/c for all centrality classes used in the analysis. The kaon p_t distributions were determined only at low p_t. Therefore, the K^0_S p_t distributions measured up to 16 GeV/c were used, considering that $N(K^+) + N(K^-) = 2 \cdot N(K^0_S)$. A further extrapolation up to 40 GeV/c, by means of a power law fit, was needed. In addition, the K^0_S p_t distributions were measured only for the 0–5% and 60–80% centrality classes. As a consequence, the p_t distributions of muons from pion and kaon decays at forward rapidity were determined only in these two centrality classes. For the other centrality classes used in this analysis (Table 1), the $\mathrm{d}N_{\mathrm{PbPb}}^{\mu^{\pm}\leftarrow\pi^{\pm},\mathrm{K}^{\pm}}/\mathrm{d}p_t$ distributions were obtained by scaling the $R_{\mathrm{AA}}^{\mu^{\pm}\leftarrow\pi^{\pm}}(p_t)$ with the double ratio $R_{\mathrm{AA}}^{\mu^{\pm}\leftarrow\pi^{\pm},\mathrm{K}^{\pm}}(p_t)/R_{\mathrm{AA}}^{\mu^{\pm}\leftarrow\pi^{\pm}}(p_t)$ which was found to be the same in the 0–5% and 60–80% centrality classes, within a maximum variation of 9% included in the systematic uncertainty.

This procedure allowed us to estimate $\mathrm{d}N^{\mu^{\pm}\leftarrow\pi^{\pm},\mathrm{K}^{\pm}}_{\mathrm{PbPb}}/\mathrm{d}p_{\mathrm{t}}$ and then to deduce the nuclear modification of muons from heavy flavour decays at forward rapidity according to Eq. (2). The background contribution to the muon p_{t} distribution increases with decreasing p_{t}. Hence, in order to limit the systematic uncertainty on its subtraction, R_{AA} was computed for $p_{\mathrm{t}} > 4$ GeV/c.

The systematic uncertainties on the R_{AA} of muons from heavy flavour decays originate from the pp reference, the corresponding Pb–Pb yields and the average nuclear overlap function. The systematic uncertainty on the pp reference, previously discussed, is about 15–17% for $p_{\mathrm{t}} > 4$ GeV/c. The systematic uncertainty on the yields of muons from heavy flavour decays in Pb–Pb includes contributions from:

– the inclusive muon yields in Pb–Pb collisions, about 6–10%, containing the systematic uncertainty on the detector response (3.5%), the residual mis-alignment (1% $\times$ p_{t}, in GeV/c) and the centrality dependence of the efficiency determined with the embedding procedure (1%);

– the yields of muons from primary pion and kaon decays in pp collisions at forward rapidity, about 17%, due to the systematic uncertainty on the input mid-rapidity distributions, the extrapolation procedure (σ_{y} parameter) and the absorber effect (pion and kaon mean free path in the absorber);

– the $R^{\mu^{\pm}\leftarrow\pi^{\pm}}_{\mathrm{AA}}(p_{\mathrm{t}})$, about 14–17%, due to the systematic uncertainty on the input mid-rapidity pion p_{t} distributions;

– the $R^{\mu^{\pm}\leftarrow\pi^{\pm},\mathrm{K}^{\pm}}_{\mathrm{AA}}(p_{\mathrm{t}})/R^{\mu^{\pm}\leftarrow\pi^{\pm}}_{\mathrm{AA}}(p_{\mathrm{t}})$ double ratio, up to 9% at p_{t} = 10 GeV/c;

– the unknown suppression at forward rapidity for muons from primary pion and kaon decays. As mentioned, a conservative systematic uncertainty was considered by varying $R^{\mu^{\pm}\leftarrow\pi^{\pm},\mathrm{K}^{\pm}}_{\mathrm{AA}}(p_{\mathrm{t}})$ from 0 to two times its value, with the additional condition that the upper limit does not exceed unity. In these conditions, the component of muons from primary pions and kaons that was subtracted in $4 < p_{\mathrm{t}} < 10$ GeV/c can reach 14% (21%) of the total muon yield in central (peripheral) collisions.

Finally, the systematic uncertainty on the normalization includes the 1.9% uncertainty on the minimum bias cross section measurement in pp collisions and the uncertainty of 4.3% (centrality class 0–10%) to 7.3% (centrality class 60–80%) on $\langle T_{\mathrm{AA}}\rangle$.

Figure 2 presents the R_{AA} of muons from heavy flavour decays in $2.5 < y < 4$, as a function of p_{t} in central (0–10%, left) and peripheral (40–80%, right) collisions. The vertical bars are the statistical uncertainties. The p_{t}-dependent systematic uncertainties are displayed by the open boxes and include all the contributions previously discussed, except the normalization uncertainty that is displayed at $R_{\mathrm{AA}} = 1$. A larger suppression is observed in central collisions than in peripheral collisions, with no significant p_{t} dependence within uncertainties.

The centrality dependence of the R_{AA} of muons from heavy flavour decays was studied in the range $6 < p_{\mathrm{t}} < 10$ GeV/c where the contribution of muons from B decays becomes dominant in pp collisions according to the central value of the FONLL calculations (Fig. 1). The analysis was carried out in five centrality classes from 0–10% to 60–80% (Table 1). The resulting R_{AA} is displayed as a function of $\langle N_{\mathrm{part}}\rangle$ in Fig. 3. The contribution to the total systematic uncertainty which is fully correlated between centrality classes (filled boxes), including the pp reference and normalization, is displayed separately from the remaining uncorrelated systematic uncertainty (open boxes). The R_{AA} of muons from heavy flavour decays at forward rapidity exhibits a strong suppression with increasing centrality, reaching a factor of about 3–4 in the 10% most central collisions.

The ALICE Collaboration has measured the production of prompt D mesons in $2 < p_{\mathrm{t}} < 16$ GeV/c at mid-rapidity ($|y| < 0.5$) [17] and the CMS Collaboration reported on that of non-prompt J/ψ from beauty decays, in $6.5 < p_{\mathrm{t}} < 30$ GeV/c and $|y| < 2.4$ [18]. The corresponding suppression of D mesons and J/ψ

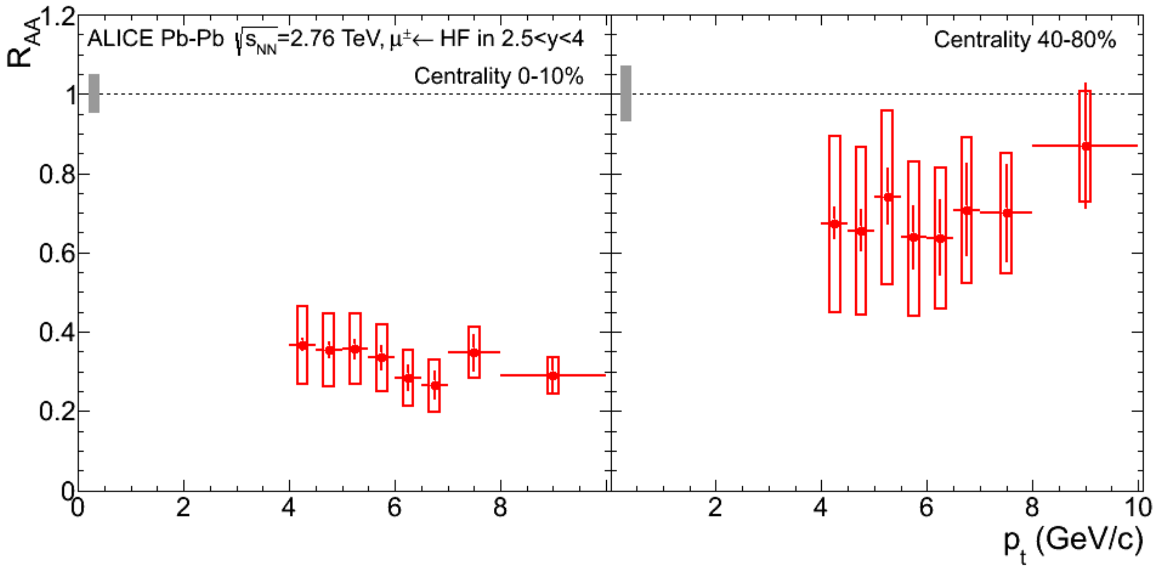

Fig. 2: (Color online) R_{AA} of muons from heavy flavour decays in $2.5 < y < 4$ as a function of p_{t}, in the 0–10% (left) and 40–80% (right) centrality classes, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. Open (full) boxes represent the systematic (normalization) uncertainty. Horizontal bars show the bin widths.

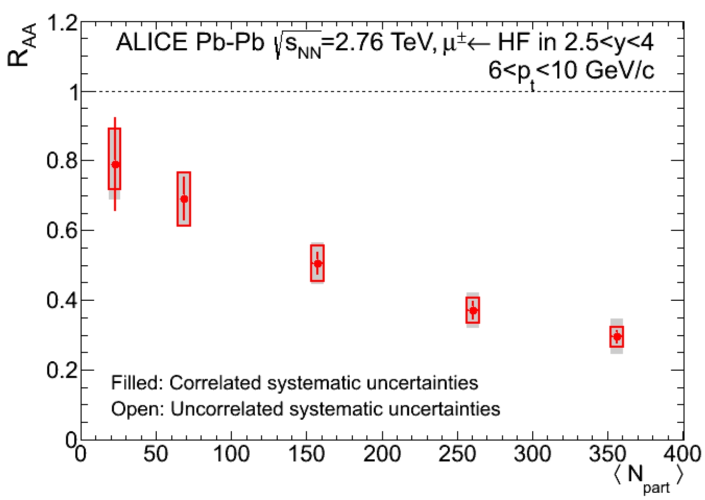

Fig. 3: (Color online) R_{AA} of muons from heavy flavour decays as a function of the mean number of participanting nucleons, in $2.5 < y < 4$ and $6 < p_{\mathrm{t}} < 10$ GeV/c. The horizontal bars indicate the uncertainty on $\langle N_{\mathrm{part}} \rangle$.

from beauty decays in those studies is similar to that reported here for muons from heavy flavour decays, although in a different p_{t} and rapidity region.

In conclusion, we have reported on the first measurement of the production of high-p_{t} muons from heavy flavour decays at forward rapidity, in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV with the ALICE detector. FONLL pQCD calculations describe well the pp data within experimental and theoretical uncertainties, with the data being close to the upper limit of the model predictions. The R_{AA} of high p_{t} muons from heavy flavour decays indicate a clear suppression increasing towards the most central collisions. The measured suppression is almost independent of p_{t}, in the region $4 < p_{\mathrm{t}} < 10$ GeV/c. These results provide clear evidence for large in-medium effects for heavy quarks in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. The forthcoming p–Pb collisions will complement these measurements, by providing insight into the possible contribution of initial nuclear matter effects, although those are expected to be less important in the high p_{t} region studied here.

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1 Acknowledgements

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex.

The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector:

Calouste Gulbenkian Foundation from Lisbon and Swiss Fonds Kidagan, Armenia;

Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP);

National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC);
Ministry of Education and Youth of the Czech Republic;
Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation;
The European Research Council under the European Community's Seventh Framework Programme;
Helsinki Institute of Physics and the Academy of Finland;
French CNRS-IN2P3, the 'Region Pays de Loire', 'Region Alsace', 'Region Auvergne' and CEA, France;
German BMBF and the Helmholtz Association;
General Secretariat for Research and Technology, Ministry of Development, Greece;
Hungarian OTKA and National Office for Research and Technology (NKTH);
Department of Atomic Energy and Department of Science and Technology of the Government of India;
Istituto Nazionale di Fisica Nucleare (INFN) of Italy;
MEXT Grant-in-Aid for Specially Promoted Research, Japan;
Joint Institute for Nuclear Research, Dubna;
National Research Foundation of Korea (NRF);
CONACYT, DGAPA, México, ALFA-EC and the HELEN Program (High-Energy physics Latin-American–European Network);
Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands;
Research Council of Norway (NFR);
Polish Ministry of Science and Higher Education;
National Authority for Scientific Research - NASR (Autoritatea Naţională pentru Cercetare Ştiinţifică - ANCS);
Federal Agency of Science of the Ministry of Education and Science of Russian Federation, International Science and Technology Center, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and CERN-INTAS;
Ministry of Education of Slovakia;
Department of Science and Technology, South Africa;
CIEMAT, EELA, Ministerio de Educación y Ciencia of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency);
Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW);
Ukraine Ministry of Education and Science;
United Kingdom Science and Technology Facilities Council (STFC);
The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.

A The ALICE Collaboration

B. Abelev[68] , J. Adam[33] , D. Adamová[73] , A.M. Adare[120] , M.M. Aggarwal[77] , G. Aglieri Rinella[29] , A.G. Agocs[60] , A. Agostinelli[21] , S. Aguilar Salazar[56] , Z. Ahammed[116] , A. Ahmad Masoodi[13] , N. Ahmad[13] , S.A. Ahn[62] , S.U. Ahn[63,36] , A. Akindinov[46] , D. Aleksandrov[88] , B. Alessandro[94] , R. Alfaro Molina[56] , A. Alici[97,9] , A. Alkin[2] , E. Almaráz Aviña[56] , J. Alme[31] , T. Alt[35] , V. Altini[27] , S. Altinpinar[14] , I. Altsybeev[117] , C. Andrei[70] , A. Andronic[85] , V. Anguelov[82] , J. Anielski[54] , C. Anson[15] , T. Antičić[86] , F. Antinori[93] , P. Antonioli[97] , L. Aphecetche[102] , H. Appelshäuser[52] , N. Arbor[64] , S. Arcelli[21] , A. Arend[52] , N. Armesto[12] , R. Arnaldi[94] , T. Aronsson[120] , I.C. Arsene[85] , M. Arslandok[52] , A. Asryan[117] , A. Augustinus[29] , R. Averbeck[85] , T.C. Awes[74] , J. Äystö[37] , M.D. Azmi[13] , M. Bach[35] , A. Badalà[99] , Y.W. Baek[63,36] , R. Bailhache[52] , R. Bala[94] , R. Baldini Ferroli[9] , A. Baldisseri[11] , A. Baldit[63] , F. Baltasar Dos Santos Pedrosa[29] , J. Bán[47] , R.C. Baral[48] , R. Barbera[23] , F. Barile[27] , G.G. Barnaföldi[60] , L.S. Barnby[90] , V. Barret[63] , J. Bartke[104] , M. Basile[21] , N. Bastid[63] , S. Basu[116] , B. Bathen[54] , G. Batigne[102] , B. Batyunya[59] , C. Baumann[52] , I.G. Bearden[71] , H. Beck[52] , I. Belikov[58] , F. Bellini[21] , R. Bellwied[110] , E. Belmont-Moreno[56] , G. Bencedi[60] , S. Beole[25] , I. Berceanu[70] , A. Bercuci[70] , Y. Berdnikov[75] , D. Berenyi[60] , A.A.E. Bergognon[102] , D. Berzano[94] , L. Betev[29] , A. Bhasin[80] , A.K. Bhati[77] , J. Bhom[114] , L. Bianchi[25] , N. Bianchi[65] , C. Bianchin[19] , J. Bielčík[33] , J. Bielčíková[73] , A. Bilandzic[72,71] , S. Bjelogrlic[45] , F. Blanco[7] , F. Blanco[110] , D. Blau[88] , C. Blume[52] , M. Boccioli[29] , N. Bock[15] , S. Böttger[51] , A. Bogdanov[69] , H. Bøggild[71] , M. Bogolyubsky[43] , L. Boldizsár[60] , M. Bombara[34] , J. Book[52] , H. Borel[11] , A. Borissov[119] , S. Bose[89] , F. Bossú[25] , M. Botje[72] , B. Boyer[42] , E. Braidot[67] , P. Braun-Munzinger[85] , M. Bregant[102] , T. Breitner[51] , T.A. Browning[83] , M. Broz[32] , R. Brun[29] , E. Bruna[25,94] , G.E. Bruno[27] , D. Budnikov[87] , H. Buesching[52] , S. Bufalino[25,94] , K. Bugaiev[2] , O. Busch[82] , Z. Buthelezi[79] , D. Caballero Orduna[120] , D. Caffarri[19] , X. Cai[39] , H. Caines[120] , E. Calvo Villar[91] , P. Camerini[20] , V. Canoa Roman[8,1] , G. Cara Romeo[97] , F. Carena[29] , W. Carena[29] , N. Carlin Filho[107] , F. Carminati[29] , C.A. Carrillo Montoya[29] , A. Casanova Díaz[65] , J. Castillo Castellanos[11] , J.F. Castillo Hernandez[85] , E.A.R. Casula[18] , V. Catanescu[70] , C. Cavicchioli[29] , C. Ceballos Sanchez[6] , J. Cepila[33] , P. Cerello[94] , B. Chang[37,123] , S. Chapeland[29] , J.L. Charvet[11] , S. Chattopadhyay[116] , S. Chattopadhyay[89] , I. Chawla[77] , M. Cherney[76] , C. Cheshkov[29,109] , B. Cheynis[109] , V. Chibante Barroso[29] , D.D. Chinellato[108] , P. Chochula[29] , M. Chojnacki[45] , S. Choudhury[116] , P. Christakoglou[72,45] , C.H. Christensen[71] , P. Christiansen[28] , T. Chujo[114] , S.U. Chung[84] , C. Cicalo[96] , L. Cifarelli[21,29] , F. Cindolo[97] , J. Cleymans[79] , F. Coccetti[9] , F. Colamaria[27] , D. Colella[27] , G. Conesa Balbastre[64] , Z. Conesa del Valle[29] , P. Constantin[82] , G. Contin[20] , J.G. Contreras[8] , T.M. Cormier[119] , Y. Corrales Morales[25] , P. Cortese[26] , I. Cortés Maldonado[1] , M.R. Cosentino[67] , F. Costa[29] , M.E. Cotallo[7] , E. Crescio[8] , P. Crochet[63] , E. Cruz Alaniz[56] , E. Cuautle[55] , L. Cunqueiro[65] , A. Dainese[19,93] , H.H. Dalsgaard[71] , A. Danu[50] , D. Das[89] , I. Das[42] , K. Das[89] , S. Dash[40] , A. Dash[108] , S. De[116] , G.O.V. de Barros[107] , A. De Caro[24,9] , G. de Cataldo[98] , J. de Cuveland[35] , A. De Falco[18] , D. De Gruttola[24] , H. Delagrange[102] , A. Deloff[100] , V. Demanov[87] , N. De Marco[94] , E. Dénes[60] , S. De Pasquale[24] , A. Deppman[107] , G. D Erasmo[27] , R. de Rooij[45] , M.A. Diaz Corchero[7] , D. Di Bari[27] , T. Dietel[54] , S. Di Liberto[95] , A. Di Mauro[29] , P. Di Nezza[65] , R. Divià[29] , Ø. Djuvsland[14] , A. Dobrin[119,28] , T. Dobrowolski[100] , I. Domínguez[55] , B. Dönigus[85] , O. Dordic[17] , O. Driga[102] , A.K. Dubey[116] , L. Ducroux[109] , P. Dupieux[63] , M.R. Dutta Majumdar[116] , A.K. Dutta Majumdar[89] , D. Elia[98] , D. Emschermann[54] , H. Engel[51] , H.A. Erdal[31] , B. Espagnon[42] , M. Estienne[102] , S. Esumi[114] , D. Evans[90] , G. Eyyubova[17] , D. Fabris[19,93] , J. Faivre[64] , D. Falchieri[21] , A. Fantoni[65] , M. Fasel[85] , R. Fearick[79] , A. Fedunov[59] , D. Fehlker[14] , L. Feldkamp[54] , D. Felea[50] , B. Fenton-Olsen[67] , G. Feofilov[117] , A. Fernández Téllez[1] , A. Ferretti[25] , R. Ferretti[26] , J. Figiel[104] , M.A.S. Figueredo[107] , S. Filchagin[87] , D. Finogeev[44] , F.M. Fionda[27] , E.M. Fiore[27] , M. Floris[29] , S. Foertsch[79] , P. Foka[85] , S. Fokin[88] , E. Fragiacomo[92] , U. Frankenfeld[85] , U. Fuchs[29] , C. Furget[64] , M. Fusco Girard[24] , J.J. Gaardhøje[71] , M. Gagliardi[25] , A. Gago[91] , M. Gallio[25] , D.R. Gangadharan[15] , P. Ganoti[74] , C. Garabatos[85] , E. Garcia-Solis[10] , I. Garishvili[68] , J. Gerhard[35] , M. Germain[102] , C. Geuna[11] , A. Gheata[29] , M. Gheata[50,29] , B. Ghidini[27] , P. Ghosh[116] , P. Gianotti[65] , M.R. Girard[118] , P. Giubellino[29] , E. Gladysz-Dziadus[104] , P. Glässel[82] , R. Gomez[106] , A. Gonschior[85] , E.G. Ferreiro[12] , L.H. González-Trueba[56] , P. González-Zamora[7] , S. Gorbunov[35] , A. Goswami[81] , S. Gotovac[103] , V. Grabski[56] , L.K. Graczykowski[118] , R. Grajcarek[82] , A. Grelli[45] , C. Grigoras[29] , A. Grigoras[29] , V. Grigoriev[69] , A. Grigoryan[121] , S. Grigoryan[59] , B. Grinyov[2] , N. Grion[92] , P. Gros[28] , J.F. Grosse-Oetringhaus[29] , J.-Y. Grossiord[109] , R. Grosso[29] , F. Guber[44] , R. Guernane[64] , C. Guerra Gutierrez[91] , B. Guerzoni[21] , M. Guilbaud[109] , K. Gulbrandsen[71] , T. Gunji[113] , A. Gupta[80] , R. Gupta[80] , H. Gutbrod[85] , Ø. Haaland[14] , C. Hadjidakis[42] , M. Haiduc[50] , H. Hamagaki[113] , G. Hamar[60] , B.H. Han[16] , L.D. Hanratty[90] , A. Hansen[71] , Z. Harmanova[34] , J.W. Harris[120] , M. Hartig[52] , D. Hasegan[50] , D. Hatzifotiadou[97] , A. Hayrapetyan[29,121] , S.T. Heckel[52] , M. Heide[54] , H. Helstrup[31] , A. Herghelegiu[70] , G. Herrera Corral[8] , N. Herrmann[82] , B.A. Hess[115] , K.F. Hetland[31] , B. Hicks[120] , P.T. Hille[120] , B. Hippolyte[58] , T. Horaguchi[114] , Y. Hori[113] , P. Hristov[29] , I. Hřivnáčová[42] , M. Huang[14] , T.J. Humanic[15] , D.S. Hwang[16] , R. Ichou[63] , R. Ilkaev[87] ,

I. Ilkiv[100], M. Inaba[114], E. Incani[18], G.M. Innocenti[25], P.G. Innocenti[29], M. Ippolitov[88], M. Irfan[13], C. Ivan[85], V. Ivanov[75], M. Ivanov[85], A. Ivanov[117], O. Ivanytskyi[2], A. Jachołkowski[29], P. M. Jacobs[67], H.J. Jang[62], S. Jangal[58], M.A. Janik[118], R. Janik[32], P.H.S.Y. Jayarathna[110], S. Jena[40], D.M. Jha[119], R.T. Jimenez Bustamante[55], L. Jirden[29], P.G. Jones[90], H. Jung[36], A. Jusko[90], A.B. Kaidalov[46], V. Kakoyan[121], S. Kalcher[35], P. Kaliňák[47], T. Kalliokoski[37], A. Kalweit[53], K. Kanaki[14], J.H. Kang[123], V. Kaplin[69], A. Karasu Uysal[29,122], O. Karavichev[44], T. Karavicheva[44], E. Karpechev[44], A. Kazantsev[88], U. Kebschull[51], R. Keidel[124], P. Khan[89], M.M. Khan[13], S.A. Khan[116], A. Khanzadeev[75], Y. Kharlov[43], B. Kileng[31], D.W. Kim[36], M.Kim[36], M. Kim[123], S.H. Kim[36], D.J. Kim[37], S. Kim[16], J.H. Kim[16], J.S. Kim[36], B. Kim[123], T. Kim[123], S. Kirsch[35], I. Kisel[35], S. Kiselev[46], A. Kisiel[29,118], J.L. Klay[4], J. Klein[82], C. Klein-Bösing[54], M. Kliemant[52], A. Kluge[29], M.L. Knichel[85], A.G. Knospe[105], K. Koch[82], M.K. Köhler[85], A. Kolojvari[117], V. Kondratiev[117], N. Kondratyeva[69], A. Konevskikh[44], A. Korneev[87], R. Kour[90], M. Kowalski[104], S. Kox[64], G. Koyithatta Meethaleveedu[40], J. Kral[37], I. Králik[47], F. Kramer[52], I. Kraus[85], T. Krawutschke[82,30], M. Krelina[33], M. Kretz[35], M. Krivda[90,47], F. Krizek[37], M. Krus[33], E. Kryshen[75], M. Krzewicki[85], Y. Kucheriaev[88], C. Kuhn[58], P.G. Kuijer[72], I. Kulakov[52], J. Kumar[40], P. Kurashvili[100], A.B. Kurepin[44], A. Kurepin[44], A. Kuryakin[87], V. Kushpil[73], S. Kushpil[73], H. Kvaerno[17], M.J. Kweon[82], Y. Kwon[123], P. Ladrón de Guevara[55], I. Lakomov[42], R. Langoy[14], S.L. La Pointe[45], C. Lara[51], A. Lardeux[102], P. La Rocca[23], C. Lazzeroni[90], R. Lea[20], Y. Le Bornec[42], M. Lechman[29], S.C. Lee[36], K.S. Lee[36], G.R. Lee[90], F. Lefèvre[102], J. Lehnert[52], L. Leistam[29], M. Lenhardt[102], V. Lenti[98], H. León[56], M. Leoncino[94], I. León Monzón[106], H. León Vargas[52], P. Lévai[60], J. Lien[14], R. Lietava[90], S. Lindal[17], V. Lindenstruth[35], C. Lippmann[85,29], M.A. Lisa[15], L. Liu[14], P.I. Loenne[14], V.R. Loggins[119], V. Loginov[69], S. Lohn[29], D. Lohner[82], C. Loizides[67], K.K. Loo[37], X. Lopez[63], E. López Torres[6], G. Løvhøiden[17], X.-G. Lu[82], P. Luettig[52], M. Lunardon[19], J. Luo[39], G. Luparello[45], L. Luquin[102], C. Luzzi[29], R. Ma[120], K. Ma[39], D.M. Madagodahettige-Don[110], A. Maevskaya[44], M. Mager[53,29], D.P. Mahapatra[48], A. Maire[82], M. Malaev[75], I. Maldonado Cervantes[55], L. Malinina[59,,i], D. Mal'Kevich[46], P. Malzacher[85], A. Mamonov[87], L. Manceau[94], L. Mangotra[80], V. Manko[88], F. Manso[63], V. Manzari[98], Y. Mao[39], M. Marchisone[63,25], J. Mareš[49], G.V. Margagliotti[20,92], A. Margotti[97], A. Marín[85], C.A. Marin Tobon[29], C. Markert[105], I. Martashvili[112], P. Martinengo[29], M.I. Martínez[1], A. Martínez Davalos[56], G. Martínez García[102], Y. Martynov[2], A. Mas[102], S. Masciocchi[85], M. Masera[25], A. Masoni[96], L. Massacrier[109,102], M. Mastromarco[98], A. Mastroserio[27,29], Z.L. Matthews[90], A. Matyja[104,102], D. Mayani[55], C. Mayer[104], J. Mazer[112], M.A. Mazzoni[95], F. Meddi[22], A. Menchaca-Rocha[56], J. Mercado Pérez[82], M. Meres[32], Y. Miake[114], L. Milano[25], J. Milosevic[17,,ii], A. Mischke[45], A.N. Mishra[81], D. Miśkowiec[85,29], C. Mitu[50], J. Mlynarz[119], B. Mohanty[116], A.K. Mohanty[29], L. Molnar[29], L. Montaño Zetina[8], M. Monteno[94], E. Montes[7], T. Moon[123], M. Morando[19], D.A. Moreira De Godoy[107], S. Moretto[19], A. Morsch[29], V. Muccifora[65], E. Mudnic[103], S. Muhuri[116], M. Mukherjee[116], H. Müller[29], M.G. Munhoz[107], L. Musa[29], A. Musso[94], B.K. Nandi[40], R. Nania[97], E. Nappi[98], C. Nattrass[112], N.P. Naumov[87], S. Navin[90], T.K. Nayak[116], S. Nazarenko[87], G. Nazarov[87], A. Nedosekin[46], M.Niculescu[50,29], B.S. Nielsen[71], T. Niida[114], S. Nikolaev[88], V. Nikolic[86], S. Nikulin[88], V. Nikulin[75], B.S. Nilsen[76], M.S. Nilsson[17], F. Noferini[97,9], P. Nomokonov[59], G. Nooren[45], N. Novitzky[37], A. Nyanin[88], A. Nyatha[40], C. Nygaard[71], J. Nystrand[14], A. Ochirov[117], H. Oeschler[53,29], S. Oh[120], S.K. Oh[36], J. Oleniacz[118], C. Oppedisano[94], A. Ortiz Velasquez[28,55], G. Ortona[25], A. Oskarsson[28], P. Ostrowski[118], J. Otwinowski[85], K. Oyama[82], K. Ozawa[113], Y. Pachmayer[82], M. Pachr[33], F. Padilla[25], P. Pagano[24], G. Paić[55], F. Painke[35], C. Pajares[12], S. Pal[11], S.K. Pal[116], A. Palaha[90], A. Palmeri[99], V. Papikyan[121], G.S. Pappalardo[99], W.J. Park[85], A. Passfeld[54], B. Pastirčák[47], D.I. Patalakha[43], V. Paticchio[98], A. Pavlinov[119], T. Pawlak[118], T. Peitzmann[45], H. Pereira Da Costa[11], E. Pereira De Oliveira Filho[107], D. Peresunko[88], C.E. Pérez Lara[72], E. Perez Lezama[55], D. Perini[29], D. Perrino[27], W. Peryt[118], A. Pesci[97], V. Peskov[29,55], Y. Pestov[3], V. Petráček[33], M. Petran[33], M. Petris[70], P. Petrov[90], M. Petrovici[70], C. Petta[23], S. Piano[92], A. Piccotti[94], M. Pikna[32], P. Pillot[102], O. Pinazza[29], L. Pinsky[110], N. Pitz[52], D.B. Piyarathna[110], M. Płoskoń[67], J. Pluta[118], T. Pocheptsov[59], S. Pochybova[60], P.L.M. Podesta-Lerma[106], M.G. Poghosyan[29,25], K. Polák[49], B. Polichtchouk[43], A. Pop[70], S. Porteboeuf-Houssais[63], V. Pospíšil[33], B. Potukuchi[80], S.K. Prasad[119], R. Preghenella[97,9], F. Prino[94], C.A. Pruneau[119], I. Pshenichnov[44], S. Puchagin[87], G. Puddu[18], J. Pujol Teixido[51], A. Pulvirenti[23,29], V. Punin[87], M. Putiš[34], J. Putschke[119,120], E. Quercigh[29], H. Qvigstad[17], A. Rachevski[92], A. Rademakers[29], S. Radomski[82], T.S. Räihä[37], J. Rak[37], A. Rakotozafindrabe[11], L. Ramello[26], A. Ramírez Reyes[8], S. Raniwala[81], R. Raniwala[81], S.S. Räsänen[37], B.T. Rascanu[52], D. Rathee[77], K.F. Read[112], J.S. Real[64], K. Redlich[100,57], P. Reichelt[52], M. Reicher[45], R. Renfordt[52], A.R. Reolon[65], A. Reshetin[44], F. Rettig[35], J.-P. Revol[29], K. Reygers[82], L. Riccati[94], R.A. Ricci[66], T. Richert[28], M. Richter[17], P. Riedler[29], W. Riegler[29], F. Riggi[23,99], B. Rodrigues Fernandes Rabacal[29], M. Rodríguez Cahuantzi[1], A. Rodriguez Manso[72], K. Røed[14], D. Rohr[35],

D. Röhrich[14] , R. Romita[85] , F. Ronchetti[65] , P. Rosnet[63] , S. Rossegger[29] , A. Rossi[29,19] , C. Roy[58] , P. Roy[89] , A.J. Rubio Montero[7] , R. Rui[20] , E. Ryabinkin[88] , A. Rybicki[104] , S. Sadovsky[43] , K. Šafařík[29] , R. Sahoo[41] , P.K. Sahu[48] , J. Saini[116] , H. Sakaguchi[38] , S. Sakai[67] , D. Sakata[114] , C.A. Salgado[12] , J. Salzwedel[15] , S. Sambyal[80] , V. Samsonov[75] , X. Sanchez Castro[58] , L. Šándor[47] , A. Sandoval[56] , S. Sano[113] , M. Sano[114] , R. Santo[54] , R. Santoro[98,29,9] , J. Sarkamo[37] , E. Scapparone[97] , F. Scarlassara[19] , R.P. Scharenberg[83] , C. Schiaua[70] , R. Schicker[82] , C. Schmidt[85] , H.R. Schmidt[115] , S. Schreiner[29] , S. Schuchmann[52] , J. Schukraft[29] , Y. Schutz[29,102] , K. Schwarz[85] , K. Schweda[85,82] , G. Scioli[21] , E. Scomparin[94] , R. Scott[112] , P.A. Scott[90] , G. Segato[19] , I. Selyuzhenkov[85] , S. Senyukov[26,58] , J. Seo[84] , S. Serci[18] , E. Serradilla[7,56] , A. Sevcenco[50] , A. Shabetai[102] , G. Shabratova[59] , R. Shahoyan[29] , N. Sharma[77] , S. Sharma[80] , S. Rohni[80] , K. Shigaki[38] , M. Shimomura[114] , K. Shtejer[6] , Y. Sibiriak[88] , M. Siciliano[25] , E. Sicking[29] , S. Siddhanta[96] , T. Siemiarczuk[100] , D. Silvermyr[74] , c. Silvestre[64] , G. Simatovic[55,86] , G. Simonetti[29] , R. Singaraju[116] , R. Singh[80] , S. Singha[116] , V. Singhal[116] , T. Sinha[89] , B.C. Sinha[116] , B. Sitar[32] , M. Sitta[26] , T.B. Skaali[17] , K. Skjerdal[14] , R. Smakal[33] , N. Smirnov[120] , R.J.M. Snellings[45] , C. Søgaard[71] , R. Soltz[68] , H. Son[16] , M. Song[123] , J. Song[84] , C. Soos[29] , F. Soramel[19] , I. Sputowska[104] , M. Spyropoulou-Stassinaki[78] , B.K. Srivastava[83] , J. Stachel[82] , I. Stan[50] , I. Stan[50] , G. Stefanek[100] , T. Steinbeck[35] , M. Steinpreis[15] , E. Stenlund[28] , G. Steyn[79] , J.H. Stiller[82] , D. Stocco[102] , M. Stolpovskiy[43] , K. Strabykin[87] , P. Strmen[32] , A.A.P. Suaide[107] , M.A. Subieta Vásquez[25] , T. Sugitate[38] , C. Suire[42] , M. Sukhorukov[87] , R. Sultanov[46] , M. Šumbera[73] , T. Susa[86] , A. Szanto de Toledo[107] , I. Szarka[32] , A. Szczepankiewicz[104] , A. Szostak[14] , M. Szymanski[118] , J. Takahashi[108] , J.D. Tapia Takaki[42] , A. Tauro[29] , G. Tejeda Muñoz[1] , A. Telesca[29] , C. Terrevoli[27] , J. Thäder[85] , D. Thomas[45] , R. Tieulent[109] , A.R. Timmins[110] , D. Tlusty[33] , A. Toia[35,29] , H. Torii[113] , L. Toscano[94] , D. Truesdale[15] , W.H. Trzaska[37] , T. Tsuji[113] , A. Tumkin[87] , R. Turrisi[93] , T.S. Tveter[17] , J. Ulery[52] , K. Ullaland[14] , J. Ulrich[61,51] , A. Uras[109] , J. Urbán[34] , G.M. Urciuoli[95] , G.L. Usai[18] , M. Vajzer[33,73] , M. Vala[59,47] , L. Valencia Palomo[42] , S. Vallero[82] , N. van der Kolk[72] , P. Vande Vyvre[29] , M. van Leeuwen[45] , L. Vannucci[66] , A. Vargas[1] , R. Varma[40] , M. Vasileiou[78] , A. Vasiliev[88] , V. Vechernin[117] , M. Veldhoen[45] , M. Venaruzzo[20] , E. Vercellin[25] , S. Vergara[1] , R. Vernet[5] , M. Verweij[45] , L. Vickovic[103] , G. Viesti[19] , O. Vikhlyantsev[87] , Z. Vilakazi[79] , O. Villalobos Baillie[90] , A. Vinogradov[88] , L. Vinogradov[117] , Y. Vinogradov[87] , T. Virgili[24] , Y.P. Viyogi[116] , A. Vodopyanov[59] , K. Voloshin[46] , S. Voloshin[119] , G. Volpe[27,29] , B. von Haller[29] , D. Vranic[85] , G. Øvrebekk[14] , J. Vrláková[34] , B. Vulpescu[63] , A. Vyushin[87] , V. Wagner[33] , B. Wagner[14] , R. Wan[58,39] , M. Wang[39] , D. Wang[39] , Y. Wang[82] , Y. Wang[39] , K. Watanabe[114] , M. Weber[110] , J.P. Wessels[29,54] , U. Westerhoff[54] , J. Wiechula[115] , J. Wikne[17] , M. Wilde[54] , G. Wilk[100] , A. Wilk[54] , M.C.S. Williams[97] , B. Windelband[82] , L. Xaplanteris Karampatsos[105] , C.G. Yaldo[119] , Y. Yamaguchi[113] , H. Yang[11] , S. Yang[14] , S. Yasnopolskiy[88] , J. Yi[84] , Z. Yin[39] , I.-K. Yoo[84] , J. Yoon[123] , W. Yu[52] , X. Yuan[39] , I. Yushmanov[88] , C. Zach[33] , C. Zampolli[97] , S. Zaporozhets[59] , A. Zarochentsev[117] , P. Závada[49] , N. Zaviyalov[87] , H. Zbroszczyk[118] , P. Zelnicek[51] , I.S. Zgura[50] , M. Zhalov[75] , X. Zhang[63,39] , H. Zhang[39] , F. Zhou[39] , D. Zhou[39] , Y. Zhou[45] , J. Zhu[39] , J. Zhu[39] , X. Zhu[39] , A. Zichichi[21,9] , A. Zimmermann[82] , G. Zinovjev[2] , Y. Zoccarato[109] , M. Zynovyev[2] , M. Zyzak[52]

Affiliation notes

[i] Also at: M.V.Lomonosov Moscow State University, D.V.Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

[ii] Also at: ”Vinča” Institute of Nuclear Sciences, Belgrade, Serbia

Collaboration Institutes

[1] Benemérita Universidad Autónoma de Puebla, Puebla, Mexico

[2] Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

[3] Budker Institute for Nuclear Physics, Novosibirsk, Russia

[4] California Polytechnic State University, San Luis Obispo, California, United States

[5] Centre de Calcul de l’IN2P3, Villeurbanne, France

[6] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

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

[8] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico

[9] Centro Fermi – Centro Studi e Ricerche e Museo Storico della Fisica “Enrico Fermi”, Rome, Italy

[10] Chicago State University, Chicago, United States

[11] Commissariat à l’Energie Atomique, IRFU, Saclay, France

[12] Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

[13] Department of Physics Aligarh Muslim University, Aligarh, India
[14] Department of Physics and Technology, University of Bergen, Bergen, Norway
[15] Department of Physics, Ohio State University, Columbus, Ohio, United States
[16] Department of Physics, Sejong University, Seoul, South Korea
[17] Department of Physics, University of Oslo, Oslo, Norway
[18] Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
[19] Dipartimento di Fisica dell’Università and Sezione INFN, Padova, Italy
[20] Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
[21] Dipartimento di Fisica dell’Università and Sezione INFN, Bologna, Italy
[22] Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN, Rome, Italy
[23] Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy
[24] Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
[25] Dipartimento di Fisica Sperimentale dell’Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
[27] Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
[28] Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[29] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[30] Fachhochschule Köln, Köln, Germany
[31] Faculty of Engineering, Bergen University College, Bergen, Norway
[32] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[33] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[34] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[35] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[36] Gangneung-Wonju National University, Gangneung, South Korea
[37] Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland
[38] Hiroshima University, Hiroshima, Japan
[39] Hua-Zhong Normal University, Wuhan, China
[40] Indian Institute of Technology, Mumbai, India
[41] Indian Institute of Technology Indore (IIT), Indore, India
[42] Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
[43] Institute for High Energy Physics, Protvino, Russia
[44] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[45] Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
[46] Institute for Theoretical and Experimental Physics, Moscow, Russia
[47] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[48] Institute of Physics, Bhubaneswar, India
[49] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[50] Institute of Space Sciences (ISS), Bucharest, Romania
[51] Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[52] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[53] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
[54] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
[55] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[56] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[57] Institut of Theoretical Physics, University of Wroclaw
[58] Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
[59] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[60] KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary
[61] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[62] Korea Institute of Science and Technology Information, Daejeon, South Korea

[63] Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France
[64] Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
[65] Laboratori Nazionali di Frascati, INFN, Frascati, Italy
[66] Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
[67] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[68] Lawrence Livermore National Laboratory, Livermore, California, United States
[69] Moscow Engineering Physics Institute, Moscow, Russia
[70] National Institute for Physics and Nuclear Engineering, Bucharest, Romania
[71] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[72] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
[73] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
[74] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[75] Petersburg Nuclear Physics Institute, Gatchina, Russia
[76] Physics Department, Creighton University, Omaha, Nebraska, United States
[77] Physics Department, Panjab University, Chandigarh, India
[78] Physics Department, University of Athens, Athens, Greece
[79] Physics Department, University of Cape Town, iThemba LABS, Cape Town, South Africa
[80] Physics Department, University of Jammu, Jammu, India
[81] Physics Department, University of Rajasthan, Jaipur, India
[82] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[83] Purdue University, West Lafayette, Indiana, United States
[84] Pusan National University, Pusan, South Korea
[85] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[86] Rudjer Bošković Institute, Zagreb, Croatia
[87] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[88] Russian Research Centre Kurchatov Institute, Moscow, Russia
[89] Saha Institute of Nuclear Physics, Kolkata, India
[90] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[91] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[92] Sezione INFN, Trieste, Italy
[93] Sezione INFN, Padova, Italy
[94] Sezione INFN, Turin, Italy
[95] Sezione INFN, Rome, Italy
[96] Sezione INFN, Cagliari, Italy
[97] Sezione INFN, Bologna, Italy
[98] Sezione INFN, Bari, Italy
[99] Sezione INFN, Catania, Italy
[100] Soltan Institute for Nuclear Studies, Warsaw, Poland
[101] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[102] SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
[103] Technical University of Split FESB, Split, Croatia
[104] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[105] The University of Texas at Austin, Physics Department, Austin, TX, United States
[106] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[107] Universidade de São Paulo (USP), São Paulo, Brazil
[108] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[109] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
[110] University of Houston, Houston, Texas, United States
[111] University of Technology and Austrian Academy of Sciences, Vienna, Austria
[112] University of Tennessee, Knoxville, Tennessee, United States
[113] University of Tokyo, Tokyo, Japan
[114] University of Tsukuba, Tsukuba, Japan
[115] Eberhard Karls Universität Tübingen, Tübingen, Germany

[116] Variable Energy Cyclotron Centre, Kolkata, India
[117] V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
[118] Warsaw University of Technology, Warsaw, Poland
[119] Wayne State University, Detroit, Michigan, United States
[120] Yale University, New Haven, Connecticut, United States
[121] Yerevan Physics Institute, Yerevan, Armenia
[122] Yildiz Technical University, Istanbul, Turkey
[123] Yonsei University, Seoul, South Korea
[124] Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany