Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p + Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The transverse momentum (p_T) distribution of primary charged particles is measured in minimum bias (non-single-diffractive) p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector at the LHC. The p_T spectra measured near central rapidity in the range $0.5 < p_T < 20$ GeV/c exhibit a weak pseudorapidity dependence. The nuclear modification factor $R_{p\mathrm{Pb}}$ is consistent with unity for p_T above 2 GeV/c. This measurement indicates that the strong suppression of hadron production at high p_T observed in Pb + Pb collisions at the LHC is not due to an initial-state effect. The measurement is compared to theoretical calculations.

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Measurements of particle production in proton-nucleus collisions at high energies allow the study of fundamental properties of quantum chromodynamics (QCD) at low parton fractional momentum x and high gluon densities (see Ref. [1] for a recent review). They also provide a reference measurement for the studies of deconfined matter created in nucleus-nucleus collisions [2].

Parton energy loss in hot QCD matter is expected to lead to a modification of energetic jets in this medium (jet quenching) [3]. Originating from energetic partons produced in initial hard collisions, hadrons at high transverse momentum p_T are an important observable for the study of deconfined matter. Experiments at RHIC have shown [4,5] that the production of charged hadrons at high p_T in Au + Au collisions is suppressed compared to the expectation from an independent superposition of nucleon-nucleon collisions (binary collision scaling).

By colliding Pb nuclei at the LHC, it was shown [6–8] that the production of charged hadrons in central collisions at a center-of-mass (c.m.s.) collision energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV shows a stronger suppression than at RHIC, indicating a state of QCD matter with an even higher energy density. At the LHC, the suppression remains substantial up to 100 GeV/c [7,8] and is also seen in reconstructed jets [9]. A p + Pb control experiment is needed to establish whether the initial state of the colliding nuclei plays a role in the observed suppression of hadron production at high p_T in Pb + Pb collisions. In addition, p + Pb data should also provide tests of models that describe QCD matter at high gluon density, giving insight into phenomena such as parton shadowing or gluon saturation [1].

In this Letter, we present a measurement of the p_T distributions of charged particles in p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data were recorded with the ALICE detector [10] during a short LHC p + Pb run performed in September 2012 in preparation for the main run scheduled at the beginning of 2013. Each beam contained 13 bunches; 8 pairs of bunches were colliding in the ALICE interaction region, providing a luminosity of about 8×10^{25} cm^{-2} s^{-1}. The interaction region had an rms width of 6.3 cm in the longitudinal direction and of about 60 μm in the transverse directions.

The trigger required a signal in either of two arrays of 32 scintillator tiles each, covering full azimuth and $2.8 < \eta_{\mathrm{lab}} < 5.1$ (VZERO-A) and $-3.7 < \eta_{\mathrm{lab}} < -1.7$ (VZERO-C), respectively. The pseudorapidity in the detector reference frame, $\eta_{\mathrm{lab}} = -\ln[\tan(\theta/2)]$, with θ the polar angle between the charged particle and the beam axis, is defined such that the proton beam has negative η_{lab}. This configuration led to a trigger rate of about 200 Hz, with a hadronic collision rate of about 150 Hz. The efficiency of the VZERO trigger was estimated from a control sample of events triggered by signals from two zero degree calorimeters positioned symmetrically at 112.5 m from the interaction point, with an energy resolution of about 20% for single neutrons of a few TeV.

The off-line event selection is identical to that used for the analysis of charged-particle pseudorapidity density ($dN_{\mathrm{ch}}/d\eta_{\mathrm{lab}}$) reported in Ref. [11]. A signal is required in both VZERO-A and VZERO-C. Beam gas and other machine-induced background events with deposited energy above the thresholds in the VZERO or zero degree calorimeters detectors are suppressed by requiring the signal timing to be compatible with that of a nominal p + Pb interaction. The remaining background after these requirements is estimated from triggers on noncolliding bunches and found to be negligible. The resulting sample

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of events consists of non-single-diffractive (NSD) collisions as well as single-diffractive and electromagnetic interactions. The efficiency of the trigger and off-line event selection for the different interactions is estimated using a combination of event generators; see Ref. [11] for details. An efficiency of 99.2% for NSD collisions is estimated, with a negligible contamination from single-diffractive and electromagnetic interactions. The number of events used for the analysis is 1.7×10^6.

The primary vertex position is determined with tracks reconstructed in the inner tracking system and the time projection chamber by using the χ^2 minimization procedure described in Ref. [8]. The event vertex reconstruction algorithm is fully efficient for events with at least one track in the acceptance, $|\eta_{\rm lab}| < 1.4$ (when the center of the interaction region is included as an additional constraint). An event is accepted if the coordinate of the reconstructed vertex measured along the beam direction is within ± 10 cm around the center of the interaction region.

Primary charged particles are defined as all prompt particles produced in the collision, including decay products, except those from weak decays of strange hadrons. Selections based on the number of space points and the quality of the track fit, as well as on the distance of closest approach to the reconstructed vertex, are applied to the reconstructed tracks (see Ref. [8] for details). The efficiency and purity of the primary charged-particle selection are estimated from a Monte Carlo simulation using the DPMJET event generator [12] with particle transport through the detector using GEANT3 [13]. The systematic uncertainties on corrections are estimated via a comparison to a Monte Carlo simulation using the HIJING event generator [14]. The overall primary charged-particle reconstruction efficiency (the product of tracking efficiency and acceptance) for $|\eta_{\rm lab}| < 0.8$ is 79% at $p_T = 0.5$ GeV$/c$, reaches 81% at 0.8 GeV$/c$, and decreases to 72% for $p_T > 2$ GeV$/c$. From Monte Carlo simulations, it is estimated that the residual contamination from secondary particles is 1.6% at $p_T = 0.5$ GeV$/c$ and decreases to about 0.6% for $p_T > 2$ GeV$/c$.

The transverse momentum of charged particles is determined from the track curvature in the magnetic field of 0.5 T. The p_T resolution is estimated from the space-point residuals to the track fit and verified by the width of the invariant mass of K^0_S mesons reconstructed in their decay to two charged pions. For the selected tracks, the relative p_T resolution is 1.3% at $p_T = 0.5$ GeV$/c$, has a minimum of 1.0% at $p_T = 1$ GeV$/c$, and increases linearly to 2.2% at $p_T = 20$ GeV$/c$. The uncertainty on the p_T resolution is $\pm 0.7\%$ at $p_T = 20$ GeV$/c$, leading to a systematic uncertainty on the differential yield of up to 3% at this p_T value.

Due to the different energy per nucleon of the two colliding beams, imposed by the two-in-one magnet design of the LHC, the nucleon-nucleon c.m.s. moves with a rapidity $y_{NN} = 0.465$ in the direction of the proton beam. As a consequence, the detector coverage, $|\eta_{\rm lab}| < 0.8$, implies, for the nucleon-nucleon c.m.s., roughly $-0.3 < \eta_{\rm c.m.s.} < 1.3$. The calculation of $\eta_{\rm c.m.s.} = \eta_{\rm lab} + y_{NN}$ is accurate only for massless particles or at high p_T. Consequently, the differential yield at low p_T suffers from a distortion, which is estimated and corrected for based on the particle composition in the HIJING event generator. For $p_T = 0.5$ GeV$/c$, the correction is 1% for $|\eta_{\rm c.m.s.}| < 0.3$ and reaches 3% for $0.8 < \eta_{\rm c.m.s.} < 1.3$. The systematic uncertainties were estimated by varying the relative particle abundances by factors of 2 around the nominal values. The uncertainty is sizable only at low p_T and is dependent on $\eta_{\rm c.m.s.}$. It is 0.6% for $|\eta_{\rm c.m.s.}| < 0.3$, 4.3% for $0.3 < \eta_{\rm c.m.s.} < 0.8$, and 5.1% for $0.8 < \eta_{\rm c.m.s.} < 1.3$.

The systematic uncertainties on the p_T spectrum are summarized in Table I for $|\eta_{\rm c.m.s.}| < 0.3$. The total uncertainties exhibit a weak p_T and $\eta_{\rm c.m.s.}$ dependence. The total systematic uncertainties range between 5.2% and 5.5% for $|\eta_{\rm c.m.s.}| < 0.3$ and reach between 5.6% and 7.1% for $0.8 < \eta_{\rm c.m.s.} < 1.3$.

In order to quantify nuclear effects in p + Pb collisions, a comparison to a reference p_T spectrum in pp collisions is needed. In the absence of a measurement at $\sqrt{s} = 5.02$ TeV, the reference spectrum is obtained by interpolating or scaling data measured at $\sqrt{s} = 2.76$ and 7 TeV. For $p_T < 5$ GeV$/c$, the measured invariant cross section for charged-particle production in inelastic pp collisions, $d^2\sigma^{pp}_{\rm ch}/d\eta dp_T$, is interpolated bin by bin, assuming a power law dependence as a function of $\sqrt{s}$. For $p_T > 5$ GeV$/c$, the measured data at $\sqrt{s} = 7$ TeV is scaled by a factor obtained from next-to-leading-order (NLO) perturbative QCD calculations [15]. For $p_T < 5$ GeV$/c$, the largest of the relative systematic uncertainties of the spectrum at 2.76 or 7 TeV is assigned as the

TABLE I. Systematic uncertainties on the p_T differential yields in p + Pb and pp collisions for $|\eta_{\rm c.m.s.}| < 0.3$. The quoted ranges span the p_T dependence of the uncertainties.

Uncertainty	Value
Event selection	1.0%–2.0%
Track selection	0.9%–2.7%
Tracking efficiency	3.0%
p_T resolution	0%–3.0%
Particle composition	2.2%–3.1%
Monte Carlo generator used for correction	1.0%
Secondary particle rejection	0.4%–1.1%
Material budget	0%–0.5%
Acceptance (conversion to $\eta_{\rm c.m.s.}$)	0%–0.6%
Total for p + Pb, p_T-dependent	5.2%–5.5%
Normalization p + Pb	3.1%
Total for pp, p_T-dependent	7.7%–8.2%
Normalization pp	3.6%
Nuclear overlap $\langle T_{p\rm Pb}\rangle$	3.6%

systematic uncertainty at the interpolated energy. For $p_T > 5$ GeV/c, the relative difference between the NLO-scaled spectrum for different choices of the renormalization μ_R and factorization μ_F scales ($\mu_R = \mu_F = p_T$, $p_T/2$, $2p_T$) is added to the systematic uncertainties on the spectrum at 7 TeV. In addition, an uncertainty of 2.2% is estimated ny comparing the interpolated and the NLO-scaled data. The total systematic uncertainty ranges from 7.7% to 8.2% for $0.5 < p_T < 20$ GeV/c. The NLO-based scaling of the data at $\sqrt{s} = 2.76$ TeV gives a result well within these uncertainties. More details can be found in Ref. [16].

The final pp reference spectrum is the product of the interpolated invariant cross section and the average nuclear overlap $\langle T_{p+\mathrm{Pb}}\rangle$, calculated employing the Glauber model [17], which gives $\langle T_{p+\mathrm{Pb}}\rangle = \langle N_{\mathrm{coll}}\rangle/\sigma_{NN} = 0.0983 \pm 0.0035\,\mathrm{mb}^{-1}$, with $\langle N_{\mathrm{coll}}\rangle = 6.9 \pm 0.7$ and $\sigma_{NN} = 70 \pm 5$ mb. The uncertainty is obtained by varying the parameters in the Glauber model calculation; see Ref. [11] (the uncertainties on σ_{NN} and $\langle N_{\mathrm{coll}}\rangle$ cancel partially in the calculation of $\langle T_{p\mathrm{Pb}}\rangle$).

The p_T spectra of charged particles measured in minimum bias (0%–100% centrality, NSD) p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 1 together with the

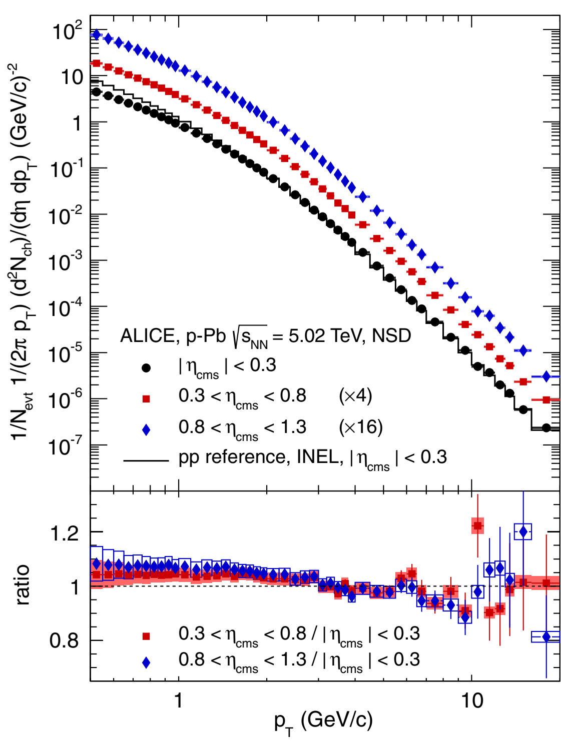

FIG. 1 (color online). Transverse momentum distributions of charged particles in minimum bias (NSD) p + Pb collisions for different pseudorapidity ranges (upper panel). The spectra are scaled by the factors indicated. The histogram represents the reference spectrum in inelastic (INEL) pp collisions (see text). The lower panel shows the ratio of the spectra at forward pseudorapidities to that at $|\eta_{\mathrm{c.m.s.}}| < 0.3$. The vertical bars (boxes) represent the statistical (systematic) errors.

interpolated pp reference spectrum. At high p_T, the p_T distributions in p + Pb collisions are similar to those in pp collisions, as expected in the absence of nuclear effects. There is an indication of a softening of the p_T spectrum when going from central to forward pseudorapidity. This is a small effect, as seen in the ratios of the spectra for forward pseudorapidities to that at $|\eta_{\mathrm{c.m.s.}}| < 0.3$, shown in Fig. 1 (lower panel). We note that several contributions to the systematic uncertainties cancel in the ratios, resulting in systematic uncertainties of 2.2%–5.2% (2.2%–5.9%) for the ratio of the spectrum in $0.3 < \eta_{\mathrm{c.m.s.}} < 0.8$ ($0.8 < \eta_{\mathrm{c.m.s.}} < 1.3$) to that in $|\eta_{\mathrm{c.m.s.}}| < 0.3$. Calculations with the DPMJET event generator [12], which predict well the measured $dN_{\mathrm{ch}}/d\eta_{\mathrm{lab}}$ [11], overpredict the spectra by up to 22% for $p_T < 0.7$ GeV/c and underpredict them by up to 50% for $p_T > 0.7$ GeV/c.

In order to quantify nuclear effects in p + Pb collisions, the p_T differential yield relative to the pp reference, the nuclear modification factor, is calculated as

$$R_{p\mathrm{Pb}}(p_T) = \frac{d^2N_{\mathrm{ch}}^{p\mathrm{Pb}}/d\eta dp_T}{\langle T_{p\mathrm{Pb}}\rangle d^2\sigma_{\mathrm{ch}}^{pp}/d\eta dp_T}, \tag{1}$$

where $N_{\mathrm{ch}}^{p\mathrm{Pb}}$ is the charged-particle yield in p + Pb collisions. The nuclear modification factor is unity for hard processes which are expected to exhibit binary collision scaling. For the region of several tens of GeV, binary collision scaling was experimentally confirmed in Pb + Pb collisions at the LHC by the recent measurements of observables which are not affected by hot QCD matter, direct photon [18], Z^0 [19], and $W^{\pm}$ [20] production. The present measurement in p + Pb collisions extends this important experimental verification down to the GeV scale and to hadronic observables.

The measurement of the nuclear modification factor $R_{p\mathrm{Pb}}$ for charged particles at $|\eta_{\mathrm{c.m.s.}}| < 0.3$ is shown in Fig. 2. The uncertainties of the p + Pb and pp spectra are added in quadrature, separately for the statistical and systematic uncertainties. The total systematic uncertainty on the normalization, the quadratic sum of the uncertainty on $\langle T_{p+\mathrm{Pb}}\rangle$, the normalization of the pp data, and the normalization of the p + Pb data, amounts to 6.0%.

In Fig. 2, we compare the measurement of the nuclear modification factor in p + Pb to that in central (0%–5% centrality) and peripheral (70%–80% centrality) Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8]. $R_{p\mathrm{Pb}}$ is consistent with unity for $p_T \gtrsim 2$ GeV/c, demonstrating that the strong suppression observed in central Pb + Pb collisions at the LHC [6–8] is not due to an initial-state effect but rather to a fingerprint of the hot matter created in collisions of heavy ions.

The so-called Cronin effect [21] (see Ref. [22] for a review), namely, a nuclear modification factor above unity at intermediate p_T, was observed at lower energies

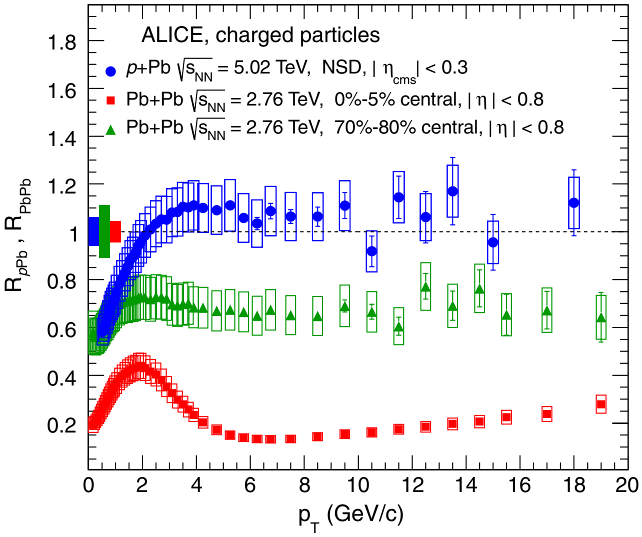

FIG. 2 (color online). The nuclear modification factor of charged particles as a function of transverse momentum in minimum bias (NSD) $p + \mathrm{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data for $|\eta_{\mathrm{c.m.s.}}| < 0.3$ are compared to measurements [8] in central (0%–5% centrality) and peripheral (70%–80%) Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The statistical errors are represented by vertical bars, the systematic errors by (filled) boxes around data points. The relative systematic uncertainties on the normalization are shown as boxes around unity near $p_T = 0$ for $p + \mathrm{Pb}$ (left box), peripheral Pb + Pb (middle box), and central Pb + Pb (right box).

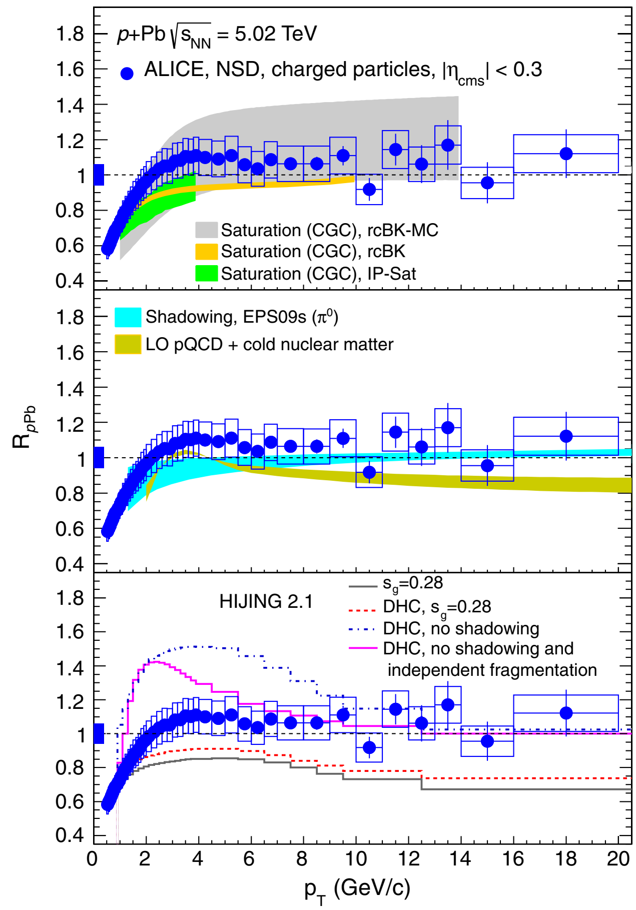

FIG. 3 (color online). Transverse momentum dependence of the nuclear modification factor $R_{p\mathrm{Pb}}$ of charged particles measured in minimum bias (NSD) $p + \mathrm{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The ALICE data in $|\eta_{\mathrm{c.m.s.}}| < 0.3$ (symbols) are compared to model calculations (bands or lines, see text for details). The vertical bars (boxes) show the statistical (systematic) errors. The relative systematic uncertainty on the normalization is shown as a box around unity near $p_T = 0$.

in proton-nucleus collisions. In $d + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV, $R_{d\mathrm{Au}}$ reached values of about 1.4 for charged hadrons in the p_T range of 3 to 5 GeV/c [23–26]. The present measurement clearly indicates a smaller magnitude of the Cronin effect at the LHC; the data are even consistent with no enhancement within systematic uncertainties.

Data in $p + \mathrm{Pb}$ are important also to provide constraints to models. For illustration, in Fig. 3, the measurement of $R_{p\mathrm{Pb}}$ at $|\eta_{\mathrm{c.m.s.}}| < 0.3$ is compared to theoretical predictions. Note that the measurement is performed for NSD collisions. With the HIJING [14] and DPMJET [12] event generators, it is estimated that the inclusion of single-diffractive events would lead to a decrease of $R_{p\mathrm{Pb}}$ by 3%–4%. Several predictions based on the saturation (color glass condensate, CGC) model are available [27–29]. The calculations of Tribedy and Venugopalan [27] are shown for two implementations (running coupling Balitsky-Kovchegov (rcBK) and impact parameter dependent dipole saturation (IP-Sat) models; see Ref. [27] for details). The calculations within IP-Sat are consistent with the data, while those within rcBK slightly underpredict the measurement. The prediction of Albacete *et al.* [28] for the rcBK Monte Carlo model (rcBK-MC) is consistent with the measurement within the rather large uncertainties of the model. The CGC calculations of Rezaeian [29], not included in Fig. 3, are consistent with those of Refs. [27,28]. The shadowing calculations of Helenius *et al.* [30], performed at NLO with the EPS09s parton distribution functions, describe the data well (the calculations are for π^0). The predictions by Kang *et al.* [31], performed within a framework combining leading-order (LO) perturbative QCD (pQCD) and cold nuclear matter effects, show $R_{p\mathrm{Pb}}$ values below unity for $p_T \gtrsim 6$ GeV/c, which is not supported by the data. The prediction from the HIJING 2.1 model [32] describes, with shadowing, the trend seen in the data, although it seems that, with the present shadowing parameter s_g, the model underpredicts the data. The HIJING model implementation of decoherent hard collisions (DHCs) has a small influence on the results; the case of independent fragmentation is included for this model and improves agreement with data at intermediate p_T. The comparisons in Fig. 3 clearly illustrate that the data are crucial for the theoretical understanding of cold nuclear matter as probed in $p + \mathrm{Pb}$ collisions at the LHC.

In summary, we have reported measurements of the charged-particle p_T spectra and the nuclear modification factor in minimum bias (NSD) $p + \mathrm{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data, covering $0.5 < p_T < 20$ GeV/c, show a nuclear modification factor consistent with unity for $p_T \gtrsim 2$ GeV/c. This measurement indicates that the strong suppression of hadron production at high p_T observed at the LHC in Pb + Pb collisions is not due to an initial-state effect but is the fingerprint of jet quenching in hot QCD matter.

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Bán,[44] R. C. Baral,[45] R. Barbera,[46] F. Barile,[23] G. G. Barnaföldi,[8] L. S. Barnby,[47] V. Barret,[41] J. Bartke,[48] M. Basile,[9] N. Bastid,[41] S. Basu,[10] B. Bathen,[29] G. Batigne,[33] B. Batyunya,[49] C. Baumann,[34] I. G. Bearden,[50] H. Beck,[34] N. K. Behera,[51] I. Belikov,[52] F. Bellini,[9] R. Bellwied,[53] E. Belmont-Moreno,[20] G. Bencedi,[8] S. Beole,[54] I. Berceanu,[26] A. Bercuci,[26] Y. Berdnikov,[55] D. Berenyi,[8] A. A. E. Bergognon,[33] D. Berzano,[54,7] L. Betev,[6] A. Bhasin,[42] A. K. Bhati,[5] J. Bhom,[56] L. Bianchi,[54] N. Bianchi,[57] J. Bielčík,[2] J. Bielčíková,[3] A. Bilandzic,[50] S. Bjelogrlic,[58] F. Blanco,[53] F. Blanco,[59] D. Blau,[16] C. Blume,[34] M. Boccioli,[6] S. Böttger,[60] A. Bogdanov,[61] H. Bøggild,[50] M. Bogolyubsky,[62] L. Boldizsár,[8] M. Bombara,[63] J. Book,[34] H. Borel,[43] A. Borissov,[64] F. Bossú,[39] M. Botje,[65] E. Botta,[54] E. Braidot,[66] P. Braun-Munzinger,[27] M. Bregant,[33] T. Breitner,[60] T. A. Browning,[67] M. Broz,[68] R. Brun,[6] E. Bruna,[54,7] G. E. Bruno,[23] D. Budnikov,[69] H. Buesching,[34] S. Bufalino,[54,7] P. Buncic,[6] O. Busch,[28] Z. Buthelezi,[39] D. Caballero Orduna,[4] D. Caffarri,[70,32] X. Cai,[71] H. Caines,[4] E. Calvo Villar,[72] P. Camerini,[73] V. Canoa Roman,[74] G. Cara Romeo,[17] W. Carena,[6] F. Carena,[6] N. Carlin Filho,[75] F. Carminati,[6] A. Casanova Díaz,[57] J. Castillo Castellanos,[43] J. F. Castillo Hernandez,[27] E. A. R. Casula,[76] V. Catanescu,[26] C. Cavicchioli,[6] C. Ceballos Sanchez,[77] J. Cepila,[2] P. Cerello,[7] B. Chang,[38,78] S. Chapeland,[6] J. L. Charvet,[43] S. Chattopadhyay,[79] S. Chattopadhyay,[10] I. Chawla,[5] M. Cherney,[80] C. Cheshkov,[6,81] B. Cheynis,[81] V. Chibante Barroso,[6] D. D. Chinellato,[53] P. Chochula,[6] M. Chojnacki,[50,58] S. Choudhury,[10] P. Christakoglou,[65] C. H. Christensen,[50] P. Christiansen,[82] T. Chujo,[56] S. U. Chung,[83] C. Cicalo,[84] L. Cifarelli,[9,6,18] F. Cindolo,[17] J. Cleymans,[39] F. Coccetti,[18] F. Colamaria,[23] D. Colella,[23] A. Collu,[76] G. Conesa Balbastre,[35] Z. Conesa del Valle,[6] M. E. Connors,[4] G. Contin,[73] J. G. Contreras,[74] T. M. Cormier,[64] Y. Corrales Morales,[54] P. Cortese,[85] I. Cortés Maldonado,[86] M. R. Cosentino,[66] F. Costa,[6] M. E. Cotallo,[59] E. Crescio,[74] P. Crochet,[41] E. Cruz Alaniz,[20] E. Cuautle,[87] L. Cunqueiro,[57] A. Dainese,[70,32] H. H. Dalsgaard,[50] A. Danu,[88] I. Das,[89] D. Das,[79] K. Das,[79] S. Das,[90] A. Dash,[91] S. Dash,[51] S. De,[10] G. O. V. de Barros,[75] A. De Caro,[92,18] G. de Cataldo,[93] J. de Cuveland,[22] A. De Falco,[76] D. De Gruttola,[92] H. Delagrange,[33] A. Deloff,[94] N. De Marco,[7] E. Dénes,[8] S. De Pasquale,[92] A. Deppman,[75] G. D. Erasmo,[23] R. de Rooij,[58] M. A. Diaz Corchero,[59] D. Di Bari,[23] T. Dietel,[29] C. Di Giglio,[23] S. Di Liberto,[95] A. Di Mauro,[6] P. Di Nezza,[57] R. Divià,[6] Ø. Djuvsland,[24] A. Dobrin,[64,82] T. Dobrowolski,[94] B. Dönigus,[27] O. Dordic,[96] O. Driga,[33] A. K. Dubey,[10] A. Dubla,[58] L. Ducroux,[81] P. Dupieux,[41] A. K. Dutta Majumdar,[79] M. R. Dutta Majumdar,[10] D. Elia,[93] D. Emschermann,[29] H. Engel,[60] B. Erazmus,[6,33] H. A. Erdal,[21] B. Espagnon,[89] M. Estienne,[33] S. Esumi,[56] D. Evans,[47] G. Eyyubova,[96] D. Fabris,[70,32] J. Faivre,[35] D. Falchieri,[9] A. Fantoni,[57] M. Fasel,[27,28] R. Fearick,[39] D. Fehlker,[24] L. Feldkamp,[29] D. Felea,[88] A. Feliciello,[7] B. Fenton-Olsen,[66] G. Feofilov,[25] A. Fernández Téllez,[86] A. Ferretti,[54] A. Festanti,[70] J. Figiel,[48] M. A. S. Figueredo,[75] S. Filchagin,[69] D. Finogeev,[97] F. M. Fionda,[23] E. M. Fiore,[23] M. Floris,[6] S. Foertsch,[39] P. Foka,[27] S. Fokin,[16] E. Fragiacomo,[98] A. Francescon,[6,70] U. Frankenfeld,[27] U. Fuchs,[6] C. Furget,[35] M. Fusco Girard,[92] J. J. Gaardhøje,[50] M. Gagliardi,[54] A. Gago,[72] M. Gallio,[54] D. R. Gangadharan,[30] P. Ganoti,[37] C. Garabatos,[27] E. Garcia-Solis,[99] I. Garishvili,[1] J. Gerhard,[22]

M. Germain,[33] C. Geuna,[43] M. Gheata,[88,6] A. Gheata,[6] P. Ghosh,[10] P. Gianotti,[57] M. R. Girard,[100] P. Giubellino,[6] E. Gladysz-Dziadus,[48] P. Glässel,[28] R. Gomez,[101,74] E. G. Ferreiro,[36] L. H. González-Trueba,[20] P. González-Zamora,[59] S. Gorbunov,[22] A. Goswami,[102] S. Gotovac,[103] L. K. Graczykowski,[100] R. Grajcarek,[28] A. Grelli,[58] C. Grigoras,[6] A. Grigoras,[6] V. Grigoriev,[61] S. Grigoryan,[49] A. Grigoryan,[104] B. Grinyov,[19] N. Grion,[98] P. Gros,[82] J. F. Grosse-Oetringhaus,[6] J.-Y. Grossiord,[81] R. Grosso,[6] F. Guber,[97] R. Guernane,[35] C. Guerra Gutierrez,[72] B. Guerzoni,[9] M. Guilbaud,[81] K. Gulbrandsen,[50] H. Gulkanyan,[104] T. Gunji,[105] A. Gupta,[42] R. Gupta,[42] Ø. Haaland,[24] C. Hadjidakis,[89] M. Haiduc,[88] H. Hamagaki,[105] G. Hamar,[8] B. H. Han,[106] L. D. Hanratty,[47] A. Hansen,[50] Z. Harmanová-Tóthová,[63] J. W. Harris,[4] M. Hartig,[34] A. Harton,[99] D. Hasegan,[88] D. Hatzifotiadou,[17] S. Hayashi,[105] A. Hayrapetyan,[6,104] S. T. Heckel,[34] M. Heide,[29] H. Helstrup,[21] A. Herghelegiu,[26] G. Herrera Corral,[74] N. Herrmann,[28] B. A. Hess,[107] K. F. Hetland,[21] B. Hicks,[4] B. Hippolyte,[52] Y. Hori,[105] P. Hristov,[6] I. Hřivnáčová,[89] M. Huang,[24] T. J. Humanic,[30] D. S. Hwang,[106] R. Ichou,[41] R. Ilkaev,[69] I. Ilkiv,[94] M. Inaba,[56] E. Incani,[76] G. M. Innocenti,[54] P. G. Innocenti,[6] M. Ippolitov,[16] M. Irfan,[11] C. Ivan,[27] A. Ivanov,[25] M. Ivanov,[27] V. Ivanov,[55] O. Ivanytskyi,[19] A. Jachołkowski,[46] P. M. Jacobs,[66] H. J. Jang,[12] M. A. Janik,[100] R. Janik,[68] P. H. S. Y. Jayarathna,[53] S. Jena,[51] D. M. Jha,[64] R. T. Jimenez Bustamante,[87] P. G. Jones,[47] H. Jung,[13] A. Jusko,[47] A. B. Kaidalov,[15] S. Kalcher,[22] P. Kaliňák,[44] T. Kalliokoski,[38] A. Kalweit,[108,6] J. H. Kang,[78] V. Kaplin,[61] A. Karasu Uysal,[6,109,110] O. Karavichev,[97] T. Karavicheva,[97] E. Karpechev,[97] A. Kazantsev,[16] U. Kebschull,[60] R. Keidel,[111] S. A. Khan,[10] P. Khan,[79] K. H. Khan,[14] M. M. Khan,[11] A. Khanzadeev,[55] Y. Kharlov,[62] B. Kileng,[21] D. J. Kim,[38] T. Kim,[78] D. W. Kim,[13,12] J. H. Kim,[106] J. S. Kim,[13] M. Kim,[13] M. Kim,[78] S. Kim,[106] B. Kim,[78] S. Kirsch,[22] I. Kisel,[22] S. Kiselev,[15] A. Kisiel,[100] J. L. Klay,[112] J. Klein,[28] C. Klein-Bösing,[29] M. Kliemant,[34] A. Kluge,[6] M. L. Knichel,[27] A. G. Knospe,[113] M. K. Köhler,[27] T. Kollegger,[22] A. Kolojvari,[25] V. Kondratiev,[25] N. Kondratyeva,[61] A. Konevskikh,[97] R. Kour,[47] V. Kovalenko,[25] M. Kowalski,[48] S. Kox,[35] G. Koyithatta Meethaleveedu,[51] J. Kral,[38] I. Králik,[44] F. Kramer,[34] A. Kravčáková,[63] T. Krawutschke,[28,114] M. Krelina,[2] M. Kretz,[22] M. Krivda,[47,44] F. Krizek,[38] M. Krus,[2] E. Kryshen,[55] M. Krzewicki,[27] Y. Kucheriaev,[16] T. Kugathasan,[6] C. Kuhn,[52] P. G. Kuijer,[65] I. Kulakov,[34] J. Kumar,[51] P. Kurashvili,[94] A. Kurepin,[97] A. B. Kurepin,[97] A. Kuryakin,[69] S. Kushpil,[3] V. Kushpil,[3] H. Kvaerno,[96] M. J. Kweon,[28] Y. Kwon,[78] P. Ladrón de Guevara,[87] I. Lakomov,[89] R. Langoy,[24] S. L. La Pointe,[58] C. Lara,[60] A. Lardeux,[33] P. La Rocca,[46] R. Lea,[73] M. Lechman,[6] S. C. Lee,[13] G. R. Lee,[47] K. S. Lee,[13] I. Legrand,[6] J. Lehnert,[34] M. Lenhardt,[27] V. Lenti,[93] H. León,[20] M. Leoncino,[7] I. León Monzón,[101] H. León Vargas,[34] P. Lévai,[8] J. Lien,[24] R. Lietava,[47] S. Lindal,[96] V. Lindenstruth,[22] C. Lippmann,[27,6] M. A. Lisa,[30] H. M. Ljunggren,[82] P. I. Loenne,[24] V. R. Loggins,[64] V. Loginov,[61] D. Lohner,[28] C. Loizides,[66] K. K. Loo,[38] X. Lopez,[41] E. López Torres,[77] G. Løvhøiden,[96] X.-G. Lu,[28] P. Luettig,[34] M. Lunardon,[70] J. Luo,[71] G. Luparello,[58] C. Luzzi,[6] K. Ma,[71] R. Ma,[4] D. M. Madagodahettige-Don,[53] A. Maevskaya,[97] M. Mager,[108,6] D. P. Mahapatra,[45] A. Maire,[28] M. Malaev,[55] I. Maldonado Cervantes,[87] L. Malinina,[49,115] D. Mal'Kevich,[15] P. Malzacher,[27] A. Mamonov,[69] L. Manceau,[7] L. Mangotra,[42] V. Manko,[16] F. Manso,[41] V. Manzari,[93] Y. Mao,[71] M. Marchisone,[41,54] J. Mareš,[116] G. V. Margagliotti,[73,98] A. Margotti,[17] A. Marín,[27] C. Markert,[113] M. Marquard,[34] I. Martashvili,[117] N. A. Martin,[27] P. Martinengo,[6] M. I. Martínez,[86] A. Martínez Davalos,[20] G. Martínez García,[33] Y. Martynov,[19] A. Mas,[33] S. Masciocchi,[27] M. Masera,[54] A. Masoni,[84] L. Massacrier,[33] A. Mastroserio,[23] Z. L. Matthews,[47] A. Matyja,[48,33] C. Mayer,[48] J. Mazer,[117] M. A. Mazzoni,[95] F. Meddi,[118] A. Menchaca-Rocha,[20] J. Mercado Pérez,[28] M. Meres,[68] Y. Miake,[56] L. Milano,[54] J. Milosevic,[96,115] A. Mischke,[58] A. N. Mishra,[102,119] D. Miśkowiec,[27,6] C. Mitu,[88] S. Mizuno,[56] J. Mlynarz,[64] B. Mohanty,[10,120] L. Molnar,[8,6,52] L. Montaño Zetina,[74] M. Monteno,[7] E. Montes,[59] T. Moon,[78] M. Morando,[70] D. A. Moreira De Godoy,[75] S. Moretto,[70] A. Morreale,[38] A. Morsch,[6] V. Muccifora,[57] E. Mudnic,[103] S. Muhuri,[10] M. Mukherjee,[10] H. Müller,[6] M. G. Munhoz,[75] L. Musa,[6] A. Musso,[7] B. K. Nandi,[51] R. Nania,[17] E. Nappi,[93] C. Nattrass,[117] S. Navin,[47] T. K. Nayak,[10] S. Nazarenko,[69] A. Nedosekin,[15] M. Nicassio,[23,27] M. Niculescu,[88,6] B. S. Nielsen,[50] T. Niida,[56] S. Nikolaev,[16] V. Nikolic,[31] S. Nikulin,[16] V. Nikulin,[55] B. S. Nilsen,[80] M. S. Nilsson,[96] F. Noferini,[17,18] P. Nomokonov,[49] G. Nooren,[58] N. Novitzky,[38] A. Nyanin,[16] A. Nyatha,[51] C. Nygaard,[50] J. Nystrand,[24] A. Ochirov,[25] H. Oeschler,[108,6] S. Oh,[4] S. K. Oh,[13] J. Oleniacz,[100] A. C. Oliveira Da Silva,[75] C. Oppedisano,[7] A. Ortiz Velasquez,[82,87] A. Oskarsson,[82] P. Ostrowski,[100] J. Otwinowski,[27] K. Oyama,[28] K. Ozawa,[105] Y. Pachmayer,[28] M. Pachr,[2] F. Padilla,[54] P. Pagano,[92] G. Paić,[87] F. Painke,[22] C. Pajares,[36] S. K. Pal,[10] A. Palaha,[47] A. Palmeri,[40] V. Papikyan,[104] G. S. Pappalardo,[40] W. J. Park,[27] A. Passfeld,[29] B. Pastirčák,[44] D. I. Patalakha,[62] V. Paticchio,[93] B. Paul,[79] A. Pavlinov,[64] T. Pawlak,[100] T. Peitzmann,[58] H. Pereira Da Costa,[43] E. Pereira De Oliveira Filho,[75] D. Peresunko,[16] C. E. Pérez Lara,[65] D. Perini,[6] D. Perrino,[23] W. Peryt,[100] A. Pesci,[17] V. Peskov,[6,87] Y. Pestov,[121] V. Petráček,[2] M. Petran,[2] M. Petris,[26] P. Petrov,[47] M. Petrovici,[26]

C. Petta,[46] S. Piano,[98] A. Piccotti,[7] M. Pikna,[68] P. Pillot,[33] O. Pinazza,[6] L. Pinsky,[53] N. Pitz,[34] D. B. Piyarathna,[53] M. Planinic,[31] M. Płoskoń,[66] J. Pluta,[100] T. Pocheptsov,[49] S. Pochybova,[8] P. L. M. Podesta-Lerma,[101] M. G. Poghosyan,[6] K. Polák,[116] B. Polichtchouk,[62] A. Pop,[26] S. Porteboeuf-Houssais,[41] V. Pospíšil,[2] B. Potukuchi,[42] S. K. Prasad,[64] R. Preghenella,[17,18] F. Prino,[7] C. A. Pruneau,[64] I. Pshenichnov,[97] G. Puddu,[76] V. Punin,[69] M. Putiš,[63] J. Putschke,[64] E. Quercigh,[6] H. Qvigstad,[96] A. Rachevski,[98] A. Rademakers,[6] T. S. Räihä,[38] J. Rak,[38] A. Rakotozafindrabe,[43] L. Ramello,[85] A. Ramírez Reyes,[74] R. Raniwala,[102] S. Raniwala,[102] S. S. Räsänen,[38] B. T. Rascanu,[34] D. Rathee,[5] K. F. Read,[117] J. S. Real,[35] K. Redlich,[94,122] R. J. Reed,[4] A. Rehman,[24] P. Reichelt,[34] M. Reicher,[58] R. Renfordt,[34] A. R. Reolon,[57] A. Reshetin,[97] F. Rettig,[22] J.-P. Revol,[6] K. Reygers,[28] L. Riccati,[7] R. A. Ricci,[123] T. Richert,[82] M. Richter,[96] P. Riedler,[6] W. Riegler,[6] F. Riggi,[46,40] M. Rodríguez Cahuantzi,[86] A. Rodriguez Manso,[65] K. Røed,[24,96] D. Rohr,[22] D. Röhrich,[24] R. Romita,[27,124] F. Ronchetti,[57] P. Rosnet,[41] S. Rossegger,[6] A. Rossi,[6,70] P. Roy,[79] C. Roy,[52] A. J. Rubio Montero,[59] R. Rui,[73] R. Russo,[54] E. Ryabinkin,[16] A. Rybicki,[48] S. Sadovsky,[62] K. Šafařík,[6] R. Sahoo,[119] P. K. Sahu,[45] J. Saini,[10] H. Sakaguchi,[125] S. Sakai,[66] D. Sakata,[56] C. A. Salgado,[36] J. Salzwedel,[30] S. Sambyal,[42] V. Samsonov,[55] X. Sanchez Castro,[52] L. Šándor,[44] A. Sandoval,[20] M. Sano,[56] G. Santagati,[46] R. Santoro,[6,18] J. Sarkamo,[38] E. Scapparone,[17] F. Scarlassara,[70] R. P. Scharenberg,[67] C. Schiaua,[26] R. Schicker,[28] C. Schmidt,[27] H. R. Schmidt,[107] S. Schreiner,[6] S. Schuchmann,[34] J. Schukraft,[6] T. Schuster,[4] Y. Schutz,[6,33] K. Schwarz,[27] K. Schweda,[27] G. Scioli,[9] E. Scomparin,[7] R. Scott,[117] P. A. Scott,[47] G. Segato,[70] I. Selyuzhenkov,[27] S. Senyukov,[52] J. Seo,[83] S. Serci,[76] E. Serradilla,[59,20] A. Sevcenco,[88] A. Shabetai,[33] G. Shabratova,[49] R. Shahoyan,[6] N. Sharma,[5,117] S. Sharma,[42] S. Rohni,[42] K. Shigaki,[125] K. Shtejer,[77] Y. Sibiriak,[16] M. Siciliano,[54] E. Sicking,[29] S. Siddhanta,[84] T. Siemiarczuk,[94] D. Silvermyr,[37] C. Silvestre,[35] G. Simatovic,[87,31] G. Simonetti,[6] R. Singaraju,[10] R. Singh,[42] S. Singha,[10,120] V. Singhal,[10] T. Sinha,[79] B. C. Sinha,[10] B. Sitar,[68] M. Sitta,[85] T. B. Skaali,[96] K. Skjerdal,[24] R. Smakal,[2] N. Smirnov,[4] R. J. M. Snellings,[58] C. Søgaard,[50,82] R. Soltz,[1] H. Son,[106] M. Song,[78] J. Song,[83] C. Soos,[6] F. Soramel,[70] I. Sputowska,[48] M. Spyropoulou-Stassinaki,[126] B. K. Srivastava,[67] J. Stachel,[28] I. Stan,[88] I. Stan,[88] G. Stefanek,[94] M. Steinpreis,[30] E. Stenlund,[82] G. Steyn,[39] J. H. Stiller,[28] D. Stocco,[33] M. Stolpovskiy,[62] P. Strmen,[68] A. A. P. Suaide,[75] M. A. Subieta Vásquez,[54] T. Sugitate,[125] C. Suire,[89] R. Sultanov,[15] M. Šumbera,[3] T. Susa,[31] T. J. M. Symons,[66] A. Szanto de Toledo,[75] I. Szarka,[68] A. Szczepankiewicz,[48,6] A. Szostak,[24] M. Szymański,[100] J. Takahashi,[91] J. D. Tapia Takaki,[89] A. Tarantola Peloni,[34] A. Tarazona Martinez,[6] A. Tauro,[6] G. Tejeda Muñoz,[86] A. Telesca,[6] C. Terrevoli,[23] J. Thäder,[27] D. Thomas,[58] R. Tieulent,[81] A. R. Timmins,[53] D. Tlusty,[2] A. Toia,[22,70,32] H. Torii,[105] L. Toscano,[7] V. Trubnikov,[19] D. Truesdale,[30] W. H. Trzaska,[38] T. Tsuji,[105] A. Tumkin,[69] R. Turrisi,[32] T. S. Tveter,[96] J. Ulery,[34] K. Ullaland,[24] J. Ulrich,[127,60] A. Uras,[81] J. Urbán,[63] G. M. Urciuoli,[95] G. L. Usai,[76] M. Vajzer,[2,3] M. Vala,[49,44] L. Valencia Palomo,[89] S. Vallero,[28] P. Vande Vyvre,[6] M. van Leeuwen,[58] L. Vannucci,[123] A. Vargas,[86] R. Varma,[51] M. Vasileiou,[126] A. Vasiliev,[16] V. Vechernin,[25] M. Veldhoen,[58] M. Venaruzzo,[73] E. Vercellin,[54] S. Vergara,[86] R. Vernet,[127] M. Verweij,[58] L. Vickovic,[103] G. Viesti,[70] Z. Vilakazi,[39] O. Villalobos Baillie,[47] A. Vinogradov,[16] Y. Vinogradov,[69] L. Vinogradov,[25] T. Virgili,[92] Y. P. Viyogi,[10] A. Vodopyanov,[49] K. Voloshin,[15] S. Voloshin,[64] G. Volpe,[6] B. von Haller,[6] I. Vorobyev,[25] D. Vranic,[27] J. Vrláková,[63] B. Vulpescu,[41] A. Vyushin,[69] B. Wagner,[24] V. Wagner,[2] R. Wan,[71] Y. Wang,[28] M. Wang,[71] D. Wang,[71] Y. Wang,[71] K. Watanabe,[56] M. Weber,[53] J. P. Wessels,[6,29] U. Westerhoff,[29] J. Wiechula,[107] J. Wikne,[96] M. Wilde,[29] A. Wilk,[29] G. Wilk,[94] M. C. S. Williams,[17] B. Windelband,[28] L. Xaplanteris Karampatsos,[113] C. G. Yaldo,[64] Y. Yamaguchi,[105] S. Yang,[24] H. Yang,[43,58] S. Yasnopolskiy,[16] J. Yi,[83] Z. Yin,[71] I.-K. Yoo,[83] J. Yoon,[78] W. Yu,[34] X. Yuan,[71] I. Yushmanov,[16] V. Zaccolo,[50] C. Zach,[2] C. Zampolli,[17] S. Zaporozhets,[49] A. 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