Flow Dominance and Factorization of Transverse Momentum Correlations in Pb-Pb Collisions at the LHC

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We present the first measurement of the two-particle transverse momentum differential correlation function, $P_2 \equiv \langle \Delta p_T \Delta p_T \rangle / \langle p_T \rangle^2$, in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Results for P_2 are reported as a function of the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\varphi$) between two particles for different collision centralities. The $\Delta\phi$ dependence is found to be largely independent of $\Delta\eta$ for $|\Delta\eta| \geq 0.9$. In the 5% most central Pb-Pb collisions, the two-particle transverse momentum correlation function exhibits a clear double-hump structure around $\Delta\varphi = \pi$ (i.e., on the away side), which is not observed in number correlations in the same centrality range, and thus provides an indication of the dominance of triangular flow in this collision centrality. Fourier decompositions of P_2, studied as a function of the collision centrality, show that correlations at $|\Delta\eta| \geq 0.9$ can be well reproduced by a flow ansatz based on the notion that measured transverse momentum correlations are strictly determined by the collective motion of the system.

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Measurements of particle production and their correlations in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have provided very compelling evidence that the produced matter is characterized by extremely high temperatures and energy densities consistent with a deconfined, but strongly interacting quark-gluon plasma (sQGP). Evidence for the production of the sQGP is provided by observations of a large suppression of particle production at momenta $p_T \gtrsim 3$ GeV/c relative to that observed in pp collisions and a strong suppression of away-side particles observed in two-particle number correlations, as well as by anisotropic flow studies (anisotropies in particle azimuthal distributions relative to the reaction plane defined by the beam axis and a line connecting the centers of colliding nuclei) [1–11]. The comparison of measured flow coefficients, v_n, with predictions from hydrodynamical models indicates that the sQGP has a vanishingly small shear viscosity over entropy density ratio [12]. Furthermore, the observation of an approximate number of constituent quark scaling of flow coefficients in the $2 < p_T < 4$ GeV/c range, suggested as a signature of a deconfined medium [13], was reported by RHIC and LHC experiments [14,15]. These results imply that the two-particle number correlations observed in the region of low p_T (< 2 GeV/c), corresponding to the bulk of particle production, are largely determined by anisotropic flow. Such flow dominance is manifested, in particular, by an approximate factorization of the measured flow coefficients, $V_{n\Delta}(\eta_1, p_{T,1}, \eta_2, p_{T,2}) = \langle \cos(n\Delta\varphi) \rangle = \langle v_n(\eta_1, p_{T,1}) v_n(\eta_2, p_{T,2}) \rangle$, observed for pairs of particles at relative pseudorapidity $\Delta\eta > 0.8$, in different transverse momentum bins up to $p_T \approx 3$–5 GeV/c [16].

Two-particle transverse momentum correlations [17–21] provide additional insights into the dynamics of multiparticle production and can be used to further examine the flow dominance of two-particle correlation functions. One expects, in particular, that in the presence of anisotropic flow the differential transverse momentum correlator $\langle \Delta p_T \Delta p_T \rangle$ should feature azimuthal Fourier decomposition coefficients calculable with a simple formula, hereafter called the *flow ansatz*, in terms of the regular and p_T weighted flow coefficients [17]. Such a simple relation, discussed in more detail below, is not expected for particle production arising from processes not related to the common symmetry plane, known as nonflow, such as jets or resonance decays. An agreement between the Fourier coefficients of the $\langle \Delta p_T \Delta p_T \rangle$ correlator and those calculated with the flow ansatz should thus provide additional evidence of the dominance of collective flow effects.

In this Letter, we present the first measurements of the differential transverse momentum correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in terms of the dimensionless correlator P_2 defined as

$$P_2 = \frac{\langle \Delta p_T \Delta p_T \rangle (\Delta\eta, \Delta\varphi)}{\langle p_T \rangle^2} = \frac{1}{\langle p_T \rangle^2} \frac{\int_{p_{T,\min}}^{p_{T,\max}} \rho_2(\vec{p}_1, \vec{p}_2) \Delta p_{T,1} \Delta p_{T,2} dp_{T,1} dp_{T,2}}{\int_{p_{T,\min}}^{p_{T,\max}} \rho_2(\vec{p}_1, \vec{p}_2) dp_{T,1} dp_{T,2}}, \quad (1)$$

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where $\Delta p_{T,i} = p_{T,i} - \langle p_T \rangle$, with $\langle p_T \rangle = \int \rho_1 p_T dp_T / \int \rho_1 dp_T$, the inclusive average transverse momentum of particles observed in the $p_{T,\min} \leq p_T \leq p_{T,\max}$ range. The quantities ρ_1 and ρ_2 represent single- and two-particle densities, respectively. For particle correlations induced strictly by anisotropic emission relative to the reaction plane, the Fourier coefficients of P_2, $v_n[P_2]$, should be determined by regular and the p_T weighted flow coefficients defined according to the following *flow ansatz* [17]:

$$v_n[P_2] \cong v_n^{p_T} / \langle p_T \rangle - v_n, \qquad (2)$$

where v_n and $v_n^{p_T} = \int \rho_1 v_n(p_T) p_T dp_T / \int \rho_1 dp_T$ are the regular and p_T weighted coefficients, respectively [17,22]. Thus, we shall compare the Fourier coefficients of the P_2 correlator to values expected from this ansatz based on coefficients v_n and $v_n^{p_T}$ measured with traditional flow methods, e.g., the scalar product method [22].

This study is based on an analysis of a 14×10^6 events subset of a sample of minimum bias trigger events recorded with the ALICE detector during the LHC run 1 in 2010. Detailed descriptions of the ALICE detector, its subsystems, and their respective performance have been reported in Refs. [23–26]. For this study, the inner tracking system and the time projection chamber (TPC) were used to reconstruct charged-particle tracks, while the V0 detector and the silicon pixel detector formed the basis of the online minimum bias trigger used to acquire the data, as described in Refs. [5,6].

The ALICE solenoidal magnet was operated with a field of 0.5 T with both positive and negative polarities. Events included in this analysis were required to have a single reconstructed primary vertex within 10 cm of the nominal interaction point along the beam axis, hereafter taken to be the z axis. The fraction of pileup events in the analysis sample is found to be negligible after applying dedicated pileup removal criteria [26].

Correlation functions reported in this Letter are based on charged-particle tracks measured in the pseudorapidity range $|\eta| < 1.0$ and with full azimuthal coverage $0 \leq \varphi < 2\pi$. The analysis was limited to particles produced with $0.2 < p_T < 2.0$ GeV/c corresponding largely to particles emerging from the bulk of the matter. Only tracks with a minimum of 70 reconstructed space points in the TPC, out of a maximum of 159, were included in the analysis. Contributions from photon conversions into e^+e^- pairs were suppressed based on an electron rejection criterion relying on the truncated average of the specific ionization energy loss $\langle dE/dx \rangle$ measured in the TPC. Tracks with $\langle dE/dx \rangle$ lying within $3\sigma_{dE/dx}$ of the Bethe-Bloch parametrization of the dE/dx expectation value for electrons and at least $3\sigma_{dE/dx}$ away from the relevant parameterizations for π, K, and p were removed. In addition, the suppression of the contamination from secondary particles originating from weak decays and from the interaction of particles with the detector material was accomplished by imposing upper limits of 3.2 and 2.4 cm (rms ~0.36 cm) for the distance of closest approach (DCA) of a track to the reconstructed vertex in the longitudinal (DCA$_z$) and radial (DCA$_{xy}$) directions, respectively. These criteria lead to a reconstruction efficiency of about 80% for primary particles and contamination from secondaries of about 5% at $p_T = 1$ GeV/c [27]. No filters were used to suppress like-sign (LS) particle correlations resulting from Hanbury Brown–Twiss effects, which produce a strong and narrow peak centered at $\Delta\eta, \Delta\varphi = 0$ in LS correlation functions. Corrections for single track losses were carried out using the weight technique described in Ref. [28] with weights calculated separately for positively and negatively charged tracks, positive and negative solenoidal magnetic fields, and with 40 vertex position bins in the fiducial range $|z| \leq 10$ cm. Pair inefficiencies associated with track merging or crossing (e.g., two tracks being partly or entirely reconstructed as a single track) within the TPC were corrected for based on track charge and momentum ordering techniques [29]. The P_2 correlators were measured separately for charge pair combinations $++$, $+-$, and $--$ and were combined with equal weights to produce the charge-independent correlation functions reported in this Letter.

Systematic uncertainties were investigated by repeating the analysis for different operational and analysis conditions including two solenoidal magnetic field polarities and different event and track selection criteria, as well as different track reconstruction methods. Track selection criteria, most particularly the maximum value of the distance of closest approach to the primary vertex, dominate systematic effects. The systematic uncertainties assigned to the measurements of v_n coefficients are the quadratic sums of individual contributions and range from 4% in the central 0%–10% collisions to 14% in the peripheral 70%–80% collisions.

Figure 1(a) presents the correlator P_2 measured as a function of $\Delta\eta$ and $\Delta\varphi$ in the 5% most central Pb-Pb collisions. The central range around $\Delta\eta \sim 0$ and $\Delta\varphi \sim 0$(rad) is left undercorrected by the weight correction procedure mainly due to track merging effects. It is thus not considered in this analysis. [The central range around $\Delta\eta \sim 0$ and $\Delta\varphi \sim 0$(rad) is considered, however, in a related ALICE analysis carried out with a mixed event technique [30]]. The correlator P_2 features a prominent near-side ridge centered at $\Delta\varphi = 0$, extending across the full pseudorapidity range of the measurement. It also features two distinct away-side humps at $|\Delta\varphi - \pi| \approx 60°$ separated by a weak dip centered at $\Delta\varphi = \pi$ and also extending across the full pseudorapidity range of the acceptance. Such an away-side correlation feature, which indicates the presence of a strong third harmonic, was previously reported in ultracentral (0%–2%) Pb-Pb collisions at the LHC [16,31,32] as well as in central Au-Au

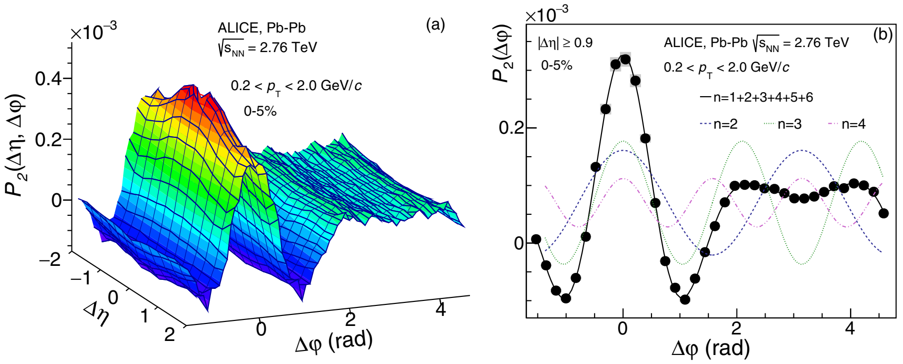

FIG. 1. (a) $P_2(\Delta\eta, \Delta\varphi)$ in the 5% most central Pb-Pb collisions. The region $|\Delta\eta| < 0.15$ and $|\Delta\varphi| < 0.13$ rad, where the weight technique used in this analysis does not provide a reliable efficiency correction, is excluded. (b) $P_2(\Delta\varphi)$ for $|\Delta\eta| \geq 0.9$. Systematic errors are shown as gray boxes. Note the statistically significant dip at $\Delta\varphi \sim \pi$.

collisions at the RHIC but for the latter case only after the subtraction of a correlated component whose shape was exclusively attributed to elliptic flow [33–35].

To further study the azimuthal angle dependence of transverse momentum correlations, projections of the measured P_2 correlation function are fitted with an unconstrained sixth-order Fourier decomposition in $\Delta\varphi$ according to $F(\Delta\varphi) = b_0 + 2\sum_{n=1}^{6} b_n \cos(n\Delta\varphi)$, as illustrated in Fig. 1(b). We verified that higher-order contributions, with $n > 6$, do not significantly improve the fits for $|\Delta\eta| \geq 0.9$. Coefficients b_5 and b_6 feature large relative errors and are thus not reported in this Letter. The double hump at $|\Delta\varphi - \pi| \approx 60°$ implies the presence of a strong third harmonic, v_3, in the Fourier decompositions of the correlation functions. The large v_3 likely originates from fluctuations in the initial density profile of colliding nuclei [36].

The flow coefficients obtained from two-particle transverse momentum correlations, $v_n[P_2]$, calculated according to $v_n = \sqrt{b_n/(b_0 + 1)}$, are plotted in Fig. 2 as a function of centrality for central (0%–5%) up to peripheral collisions (70%–80%). The $v_n[P_2]$ coefficients exhibit a collision centrality dependence qualitatively similar to that of regular flow coefficients obtained from standard flow measurement

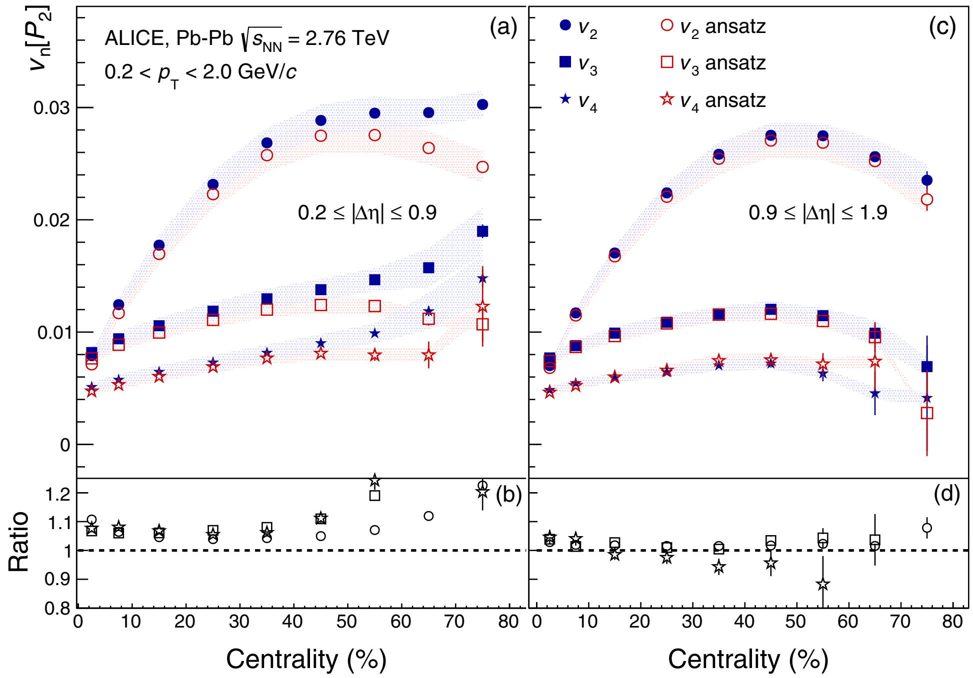

FIG. 2. v_n coefficients, where $n = 2, 3, 4$ in the range (a) $0.2 \leq |\Delta\eta| \leq 0.9$ and (c) $0.9 \leq |\Delta\eta| \leq 1.9$ obtained from the P_2 correlation function. The coefficients are compared with the expectations from the flow ansatz calculated in their respective $\Delta\eta$ ranges in Pb-Pb collisions. Statistical errors are shown as vertical solid lines, whereas systematic errors are displayed as colored bands. Ratios of the v_n coefficients and their corresponding flow ansatz values are shown in (b) and (d). The errors on the ratios are only statistical.

methods [22]. In addition, they feature a hierarchy such that $v_2 > v_3 > v_4$ at all centralities except in the 5% most central Pb-Pb collisions, where the third is slightly larger than the second harmonic, thereby explaining the presence of the away-side double hump seen in Fig. 1. This is at variance with the dependence of the regular flow coefficients which, even in the centrality range 0%–5%, exhibit the basic hierarchy $v_2 > v_3 > v_4$. The observed higher value of $v_3[P_2]$ relative to $v_2[P_2]$ implies that v_3 should rise faster with increasing p_T than v_2, in agreement with explicit measurements of the flow coefficient dependence on p_T [37].

We next consider the possible role of nonflow correlations on the correlator P_2 by comparing, in Fig. 2, the $v_n[P_2]$ coefficients obtained in the ranges $0.2 \leq |\Delta\eta| \leq 0.9$ and $0.9 \leq |\Delta\eta| \leq 1.9$ with values predicted by the flow ansatz, introduced above. In the range $0.9 \leq |\Delta\eta| \leq 1.9$ [see Fig. 2(c)], one observes that the coefficients $v_n[P_2]$ are in very good agreement, at all measured collision centralities, with expectations from the flow ansatz. This agreement provides additional evidence that two-particle correlations in this relative pseudorapidity range are predominantly determined by the collective nature of particle emission at low p_T, which motivates the factorization hypothesis used to derive Eq. (2). It also suggests that away-side jets, that might be associated with the near-side peak, are significantly suppressed and contribute minimally to the away-side correlated yield in that η range. In contrast, in the range $0.2 \leq |\Delta\eta| \leq 0.9$ [see Fig. 2(a)], the $v_n[P_2]$ coefficients exhibit a stronger and monotonic centrality evolution. In particular, the $v_n[P_2]$ deviate significantly from the flow ansatz for collision centralities larger than 40%, where one expects the largest nonflow contributions associated with the presence of the correlation function near-side peak.

Using the same measurement technique, we further compare features of the P_2 correlation function to that of the number correlation function R_2, defined as

$$R_2 + 1 = \int_{p_{T,\mathrm{min}}}^{p_{T,\mathrm{max}}} \rho_2(\vec{p}_1, \vec{p}_2) dp_{T,1} dp_{T,2} \bigg/ \int_{p_{T,\mathrm{min}}}^{p_{T,\mathrm{max}}} \rho_1(\vec{p}_1)\rho_1(\vec{p}_2) dp_{T,1} dp_{T,2}. \tag{3}$$

Figure 3 presents the $\Delta\eta$ dependence of v_n, $n = 2$, 3, and 4, coefficients obtained from these correlation functions for the 5% most central collisions. In this centrality interval, one finds that the hierarchies $v_3[P_2] > v_2[P_2]$ and $v_2[R_2] > v_3[R_2]$ indeed hold for all measured $\Delta\eta$. The dominance of $v_3[P_2]$ across all $\Delta\eta$ is likely a consequence of the third harmonic's (triangular flow) stronger dependence on p_T relative to that of the second harmonic (elliptic flow). The v_2, v_3, and v_4 dependencies on $\Delta\eta$ reveal additional interesting features. In the case of the R_2 correlation, the coefficients v_2 and v_3 monotonically decrease over the entire $\Delta\eta$ range, whereas coefficients extracted from P_2 exhibit a more pronounced decrease for $|\Delta\eta| \leq 0.9$. From $|\Delta\eta| \sim 1.0$ to ~ 2.0, the relative decrease of v_2 is about 5%

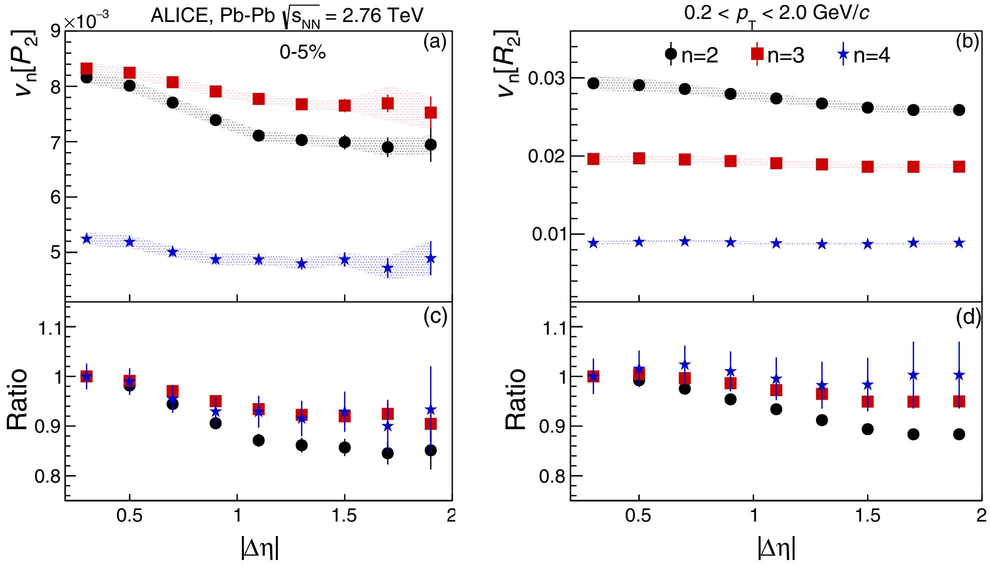

FIG. 3. v_n coefficients, $n = 2$, 3, 4, obtained from (a) P_2 and (b) R_2 correlators, as a function of $|\Delta\eta|$ in the 5% most central Pb-Pb collisions. Statistical errors are shown as vertical solid lines, whereas systematic uncertainties are displayed as shaded bands. (c),(d) Ratios of the v_n, $n = 2$, 3, 4, by the corresponding values of v_n measured at $\Delta\eta = 0.3$.

for both correlators and somewhat smaller for v_3. These contrasting dependencies reflect the different shapes of the near-side peaks of the two correlation functions. The narrower shape of the near-side peak of the P_2 distribution suggests that the near-side peak of R_2 might involve two components, one of which is characterized by a vanishing $\langle \Delta p_T \Delta p_T \rangle$ for pairs with $|\Delta\eta| \leq 0.9$. While the origin of this behavior is not fully understood, it offers the benefit of enabling the determination of flow coefficients with smaller nonflow effects using a narrower $\Delta\eta$ gap.

In summary, we presented the first measurements of the two-particle transverse momentum differential correlation function P_2 from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In the 5% most central Pb-Pb collisions, P_2 has a shape qualitatively different to that observed in measurements of the number density correlations, with a relatively narrow near-side peak near $|\Delta\eta|, |\Delta\varphi| < 0.5$, and a longitudinally broad and double-hump structure on the away side. The double-hump structure in the 5% most central P_2 correlation indicates that this observable is more sensitive to the presence of a triangular flow component than the number correlations R_2 and consequently provides an indication that triangular flow features a stronger dependence on p_T than elliptic flow does. Comparison of the Fourier decompositions of the R_2 and P_2 correlators, calculated as a function of $|\Delta\eta|$, suggests that the v_2, v_3, and v_4 coefficients extracted from P_2 reach approximately constant values beyond $|\Delta\eta| \sim 0.9$, while coefficients v_2 and v_3 obtained from R_2 decrease monotonically for increasing $|\Delta\eta|$. The observed agreement between the flow coefficients measured from P_2 correlations, at $|\Delta\eta| > 0.9$, and the values predicted from the flow ansatz provide new and independent support to the notion that the observed long-range correlations are largely due to the initial collision geometry. These results may be used to further constrain particle production models. This agreement to the flow ansatz also provides further evidence for flow coefficient factorization in heavy-ion collisions.

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J. Adam,[38] D. Adamová,[87] M. M. Aggarwal,[91] G. Aglieri Rinella,[34] M. Agnello,[30,113] N. Agrawal,[47] Z. Ahammed,[137]
S. Ahmad,[17] S. U. Ahn,[70] S. Aiola,[141] A. Akindinov,[54] S. N. Alam,[137] D. S. D. Albuquerque,[124] D. Aleksandrov,[83]
B. Alessandro,[113] D. Alexandre,[104] R. Alfaro Molina,[64] A. Alici,[12,107] A. Alkin,[3] J. Alme,[21,36] T. Alt,[41] S. Altinpinar,[21]
I. Altsybeev,[136] C. Alves Garcia Prado,[123] M. An,[7] C. Andrei,[81] H. A. Andrews,[104] A. Andronic,[100] V. Anguelov,[96]
C. Anson,[90] T. Antičić,[101] F. Antinori,[110] P. Antonioli,[107] R. Anwar,[126] L. Aphecetche,[116] H. Appelshäuser,[60] S. Arcelli,[26]
R. Arnaldi,[113] O. W. Arnold,[97,35] I. C. Arsene,[20] M. Arslandok,[60] B. Audurier,[116] A. Augustinus,[34] R. Averbeck,[100]
M. D. Azmi,[17] A. Badalà,[109] Y. W. Baek,[69] S. Bagnasco,[113] R. Bailhache,[60] R. Bala,[93] A. Baldisseri,[66] R. C. Baral,[57]
A. M. Barbano,[25] R. Barbera,[27] F. Barile,[32] L. Barioglio,[25] G. G. Barnaföldi,[140] L. S. Barnby,[104,34] V. Barret,[72] P. Bartalini,[7]
K. Barth,[34] J. Bartke,[120,†] E. Bartsch,[60] M. Basile,[26] N. Bastid,[72] S. Basu,[137] B. Bathen,[61] G. Batigne,[116] A. Batista Camejo,[72]
B. Batyunya,[68] P. C. Batzing,[20] I. G. Bearden,[84] H. Beck,[96] C. Bedda,[30] N. K. Behera,[50] I. Belikov,[65] F. Bellini,[26]
H. Bello Martinez,[2] R. Bellwied,[126] L. G. E. Beltran,[122] V. Belyaev,[77] G. Bencedi,[140] S. Beole,[25] A. Bercuci,[81]
Y. Berdnikov,[89] D. Berenyi,[140] R. A. Bertens,[53,129] D. Berzano,[34] L. Betev,[34] A. Bhasin,[93] I. R. Bhat,[93] A. K. Bhati,[91]
B. Bhattacharjee,[43] J. Bhom,[120] L. Bianchi,[126] N. Bianchi,[74] C. Bianchin,[139] J. Bielčík,[38] J. Bielčíková,[87] A. Bilandzic,[35,97]
G. Biro,[140] R. Biswas,[4] S. Biswas,[4] J. T. Blair,[121] D. Blau,[83] C. Blume,[60] F. Bock,[76,96] A. Bogdanov,[77] L. Boldizsár,[140]
M. Bombara,[39] M. Bonora,[34] J. Book,[60] H. Borel,[66] A. Borissov,[99] M. Borri,[128] E. Botta,[25] C. Bourjau,[84]
P. Braun-Munzinger,[100] M. Bregant,[123] T. A. Broker,[60] T. A. Browning,[98] M. Broz,[38] E. J. Brucken,[45] E. Bruna,[113]
G. E. Bruno,[32] D. Budnikov,[102] H. Buesching,[60] S. Bufalino,[30,25] P. Buhler,[115] S. A. I. Buitron,[62] P. Buncic,[34] O. Busch,[132]
Z. Buthelezi,[67] J. B. Butt,[15] J. T. Buxton,[18] J. Cabala,[118] D. Caffarri,[34] H. Caines,[141] A. Caliva,[53] E. Calvo Villar,[105]
P. Camerini,[24] A. A. Capon,[115] F. Carena,[34] W. Carena,[34] F. Carnesecchi,[26,12] J. Castillo Castellanos,[66] A. J. Castro,[129]
E. A. R. Casula,[23,108] C. Ceballos Sanchez,[9] P. Cerello,[113] J. Cerkala,[118] B. Chang,[127] S. Chapeland,[34] M. Chartier,[128]
J. L. Charvet,[66] S. Chattopadhyay,[137] S. Chattopadhyay,[103] A. Chauvin,[97,35] M. Cherney,[90] C. Cheshkov,[134] B. Cheynis,[134]
V. Chibante Barroso,[34] D. D. Chinellato,[124] S. Cho,[50] P. Chochula,[34] K. Choi,[99] M. Chojnacki,[84] S. Choudhury,[137]
P. Christakoglou,[85] C. H. Christensen,[84] P. Christiansen,[33] T. Chujo,[132] S. U. Chung,[99] C. Cicalo,[108] L. Cifarelli,[12,26]
F. Cindolo,[107] J. Cleymans,[92] F. Colamaria,[32] D. Colella,[55,34] A. Collu,[76] M. Colocci,[26] G. Conesa Balbastre,[73]
Z. Conesa del Valle,[51] M. E. Connors,[141,‡] J. G. Contreras,[38] T. M. Cormier,[88] Y. Corrales Morales,[113] I. Cortés Maldonado,[2]
P. Cortese,[31] M. R. Cosentino,[123,125] F. Costa,[34] J. Crkovská,[51] P. Crochet,[72] R. Cruz Albino,[11] E. Cuautle,[62] L. Cunqueiro,[61]
T. Dahms,[35,97] A. Dainese,[110] M. C. Danisch,[96] A. Danu,[58] D. Das,[103] I. Das,[103] S. Das,[4] A. Dash,[82] S. Dash,[47] S. De,[48,123]
A. De Caro,[29] G. de Cataldo,[106] C. de Conti,[123] J. de Cuveland,[41] A. De Falco,[23] D. De Gruttola,[12,29] N. De Marco,[113]
S. De Pasquale,[29] R. D. De Souza,[124] H. F. Degenhardt,[123] A. Deisting,[100,96] A. Deloff,[80] C. Deplano,[85] P. Dhankher,[47]
D. Di Bari,[32] A. Di Mauro,[34] P. Di Nezza,[74] B. Di Ruzza,[110] M. A. Diaz Corchero,[10] T. Dietel,[92] P. Dillenseger,[60] R. Divià,[34]
Ø. Djuvsland,[21] A. Dobrin,[58,34] D. Domenicis Gimenez,[123] B. Dönigus,[60] O. Dordic,[20] T. Drozhzhova,[60] A. K. Dubey,[137]
A. Dubla,[100] L. Ducroux,[134] A. K. Duggal,[91] P. Dupieux,[72] R. J. Ehlers,[141] D. Elia,[106] E. Endress,[105] H. Engel,[59] E. Epple,[141]
B. Erazmus,[116] F. Erhardt,[133] B. Espagnon,[51] S. Esumi,[132] G. Eulisse,[34] J. Eum,[99] D. Evans,[104] S. Evdokimov,[114]

L. Fabbietti,[35,97] D. Fabris,[110] J. Faivre,[73] A. Fantoni,[74] M. Fasel,[88,76] L. Feldkamp,[61] A. Feliciello,[113] G. Feofilov,[136]
J. Ferencei,[87] A. Fernández Téllez,[2] E. G. Ferreiro,[16] A. Ferretti,[25] A. Festanti,[28] V. J. G. Feuillard,[72,66] J. Figiel,[120]
M. A. S. Figueredo,[123] S. Filchagin,[102] D. Finogeev,[52] F. M. Fionda,[23] E. M. Fiore,[32] M. Floris,[34] S. Foertsch,[67] P. Foka,[100]
S. Fokin,[83] E. Fragiacomo,[112] A. Francescon,[34] A. Francisco,[116] U. Frankenfeld,[100] G. G. Fronze,[25] U. Fuchs,[34] C. Furget,[73]
A. Furs,[52] M. Fusco Girard,[29] J. J. Gaardhøje,[84] M. Gagliardi,[25] A. M. Gago,[105] K. Gajdosova,[84] M. Gallio,[25]
C. D. Galvan,[122] D. R. Gangadharan,[76] P. Ganoti,[79] C. Gao,[7] C. Garabatos,[100] E. Garcia-Solis,[13] K. Garg,[27] P. Garg,[48]
C. Gargiulo,[34] P. Gasik,[35,97] E. F. Gauger,[121] M. B. Gay Ducati,[63] M. Germain,[116] P. Ghosh,[137] S. K. Ghosh,[4] P. Gianotti,[74]
P. Giubellino,[34,113] P. Giubilato,[28] E. Gladysz-Dziadus,[120] P. Glässel,[96] D. M. Goméz Coral,[64] A. Gomez Ramirez,[59]
A. S. Gonzalez,[34] V. Gonzalez,[10] P. González-Zamora,[10] S. Gorbunov,[41] L. Görlich,[120] S. Gotovac,[119] V. Grabski,[64]
L. K. Graczykowski,[138] K. L. Graham,[104] L. Greiner,[76] A. Grelli,[53] C. Grigoras,[34] V. Grigoriev,[77] A. Grigoryan,[1]
S. Grigoryan,[68] N. Grion,[112] J. M. Gronefeld,[100] F. Grosa,[30] J. F. Grosse-Oetringhaus,[34] R. Grosso,[100] L. Gruber,[115]
F. R. Grull,[59] F. Guber,[52] R. Guernane,[34,73] B. Guerzoni,[26] K. Gulbrandsen,[84] T. Gunji,[131] A. Gupta,[93] R. Gupta,[93]
I. B. Guzman,[2] R. Haake,[34,61] C. Hadjidakis,[51] H. Hamagaki,[78,131] G. Hamar,[140] J. C. Hamon,[65] J. W. Harris,[141] A. Harton,[13]
D. Hatzifotiadou,[107] S. Hayashi,[131] S. T. Heckel,[60] E. Hellbär,[60] H. Helstrup,[36] A. Herghelegiu,[81] G. Herrera Corral,[11]
F. Herrmann,[61] B. A. Hess,[95] K. F. Hetland,[36] H. Hillemanns,[34] B. Hippolyte,[65] J. Hladky,[56] D. Horak,[38] R. Hosokawa,[132]
P. Hristov,[34] C. Hughes,[129] T. J. Humanic,[18] N. Hussain,[43] T. Hussain,[17] D. Hutter,[41] D. S. Hwang,[19] R. Ilkaev,[102]
M. Inaba,[132] M. Ippolitov,[83,77] M. Irfan,[17] V. Isakov,[52] M. S. Islam,[48] M. Ivanov,[34,100] V. Ivanov,[89] V. Izucheev,[114] B. Jacak,[76]
N. Jacazio,[26] P. M. Jacobs,[76] M. B. Jadhav,[47] S. Jadlovska,[118] J. Jadlovsky,[118] C. Jahnke,[35] M. J. Jakubowska,[138]
M. A. Janik,[138] P. H. S. Y. Jayarathna,[126] C. Jena,[82] S. Jena,[126] M. Jercic,[133] R. T. Jimenez Bustamante,[100] P. G. Jones,[104]
A. Jusko,[104] P. Kalinak,[55] A. Kalweit,[34] J. H. Kang,[142] V. Kaplin,[77] S. Kar,[137] A. Karasu Uysal,[71] O. Karavichev,[52]
T. Karavicheva,[52] L. Karayan,[100,96] E. Karpechev,[52] U. Kebschull,[59] R. Keidel,[143] D. L. D. Keijdener,[53] M. Keil,[34]
M. Mohisin Khan,[17,§] P. Khan,[103] S. A. Khan,[137] A. Khanzadeev,[89] Y. Kharlov,[114] A. Khatun,[17] A. Khuntia,[48]
M. M. Kielbowicz,[120] B. Kileng,[36] D. W. Kim,[42] D. J. Kim,[127] D. Kim,[142] H. Kim,[142] J. S. Kim,[42] J. Kim,[96] M. Kim,[50]
M. Kim,[142] S. Kim,[19] T. Kim,[142] S. Kirsch,[41] I. Kisel,[41] S. Kiselev,[54] A. Kisiel,[138] G. Kiss,[140] J. L. Klay,[6] C. Klein,[60]
J. Klein,[34] C. Klein-Bösing,[61] S. Klewin,[96] A. Kluge,[34] M. L. Knichel,[96] A. G. Knospe,[126] C. Kobdaj,[117] M. Kofarago,[34]
T. Kollegger,[100] A. Kolojvari,[136] V. Kondratiev,[136] N. Kondratyeva,[77] E. Kondratyuk,[114] A. Konevskikh,[52] M. Kopcik,[118]
M. Kour,[93] C. Kouzinopoulos,[34] O. Kovalenko,[80] V. Kovalenko,[136] M. Kowalski,[120] G. Koyithatta Meethaleveedu,[47]
I. Králik,[55] A. Kravčáková,[39] M. Krivda,[55,104] F. Krizek,[87] E. Kryshen,[89] M. Krzewicki,[41] A. M. Kubera,[18] V. Kučera,[87]
C. Kuhn,[65] P. G. Kuijer,[85] A. Kumar,[93] J. Kumar,[47] L. Kumar,[91] S. Kumar,[47] S. Kundu,[82] P. Kurashvili,[80] A. Kurepin,[52]
A. B. Kurepin,[52] A. Kuryakin,[102] S. Kushpil,[87] M. J. Kweon,[50] Y. Kwon,[142] S. L. La Pointe,[41] P. La Rocca,[27]
C. Lagana Fernandes,[123] I. Lakomov,[34] R. Langoy,[40] K. Lapidus,[141] C. Lara,[59] A. Lardeux,[66,20] A. Lattuca,[25] E. Laudi,[34]
R. Lavicka,[38] L. Lazaridis,[34] R. Lea,[24] L. Leardini,[96] S. Lee,[142] F. Lehas,[85] S. Lehner,[115] J. Lehrbach,[41] R. C. Lemmon,[86]
V. Lenti,[106] E. Leogrande,[53] I. León Monzón,[122] P. Lévai,[140] S. Li,[7] X. Li,[14] J. Lien,[40] R. Lietava,[104] S. Lindal,[20]
V. Lindenstruth,[41] C. Lippmann,[100] M. A. Lisa,[18] V. Litichevskyi,[45] H. M. Ljunggren,[33] W. J. Llope,[139] D. F. Lodato,[53]
P. I. Loenne,[21] V. Loginov,[77] C. Loizides,[76] P. Loncar,[119] X. Lopez,[72] E. López Torres,[9] A. Lowe,[140] P. Luettig,[60]
M. Lunardon,[28] G. Luparello,[24] M. Lupi,[34] T. H. Lutz,[141] A. Maevskaya,[52] M. Mager,[34] S. Mahajan,[93] S. M. Mahmood,[20]
A. Maire,[65] R. D. Majka,[141] M. Malaev,[89] I. Maldonado Cervantes,[62] L. Malinina,[68,¶] D. Mal'Kevich,[54] P. Malzacher,[100]
A. Mamonov,[102] V. Manko,[83] F. Manso,[72] V. Manzari,[106] Y. Mao,[7] M. Marchisone,[67,130] J. Mareš,[56] G. V. Margagliotti,[24]
A. Margotti,[107] J. Margutti,[53] A. Marín,[100] C. Markert,[121] M. Marquard,[60] N. A. Martin,[100] P. Martinengo,[34]
J. A. L. Martinez,[59] M. I. Martínez,[2] G. Martínez García,[116] M. Martinez Pedreira,[34] A. Mas,[123] S. Masciocchi,[100]
M. Masera,[25] A. Masoni,[108] A. Mastroserio,[32] A. M. Mathis,[97,35] A. Matyja,[129,120] C. Mayer,[120] J. Mazer,[129] M. Mazzilli,[32]
M. A. Mazzoni,[111] F. Meddi,[22] Y. Melikyan,[77] A. Menchaca-Rocha,[64] E. Meninno,[29] J. Mercado Pérez,[96] M. Meres,[37]
S. Mhlanga,[92] Y. Miake,[132] M. M. Mieskolainen,[45] D. Mihaylov,[97] K. Mikhaylov,[54,68] L. Milano,[76] J. Milosevic,[20]
A. Mischke,[53] A. N. Mishra,[48] T. Mishra,[57] D. Miśkowiec,[100] J. Mitra,[137] C. M. Mitu,[58] N. Mohammadi,[53] B. Mohanty,[82]
E. Montes,[10] D. A. Moreira De Godoy,[61] L. A. P. Moreno,[2] S. Moretto,[28] A. Morreale,[116] A. Morsch,[34] V. Muccifora,[74]
E. Mudnic,[119] D. Mühlheim,[61] S. Muhuri,[137] M. Mukherjee,[137] J. D. Mulligan,[141] M. G. Munhoz,[123] K. Münning,[44]
R. H. Munzer,[35,60,97] H. Murakami,[131] S. Murray,[67] L. Musa,[34] J. Musinsky,[55] C. J. Myers,[126] B. Naik,[47] R. Nair,[80]
B. K. Nandi,[47] R. Nania,[107] E. Nappi,[106] M. U. Naru,[15] H. Natal da Luz,[123] C. Nattrass,[129] S. R. Navarro,[2] K. Nayak,[82]
R. Nayak,[47] T. K. Nayak,[137] S. Nazarenko,[102] A. Nedosekin,[54] R. A. Negrao De Oliveira,[34] L. Nellen,[62] S. V. Nesbo,[36]

F. Ng,[126] M. Nicassio,[100] M. Niculescu,[58] J. Niedziela,[34] B. S. Nielsen,[84] S. Nikolaev,[83] S. Nikulin,[83] V. Nikulin,[89]
F. Noferini,[107,12] P. Nomokonov,[68] G. Nooren,[53] J. C. C. Noris,[2] J. Norman,[128] A. Nyanin,[83] J. Nystrand,[21] H. Oeschler,[96]
S. Oh,[141] A. Ohlson,[96,34] T. Okubo,[46] L. Olah,[140] J. Oleniacz,[138] A. C. Oliveira Da Silva,[123] M. H. Oliver,[141]
J. Onderwaater,[100] C. Oppedisano,[113] R. Orava,[45] M. Oravec,[118] A. Ortiz Velasquez,[62] A. Oskarsson,[33] J. Otwinowski,[120]
K. Oyama,[78] M. Ozdemir,[60] Y. Pachmayer,[96] V. Pacik,[84] D. Pagano,[135,25] P. Pagano,[29] G. Paić,[62] S. K. Pal,[137] P. Palni,[7]
J. Pan,[139] A. K. Pandey,[47] S. Panebianco,[66] V. Papikyan,[1] G. S. Pappalardo,[109] P. Pareek,[48] J. Park,[50] W. J. Park,[100]
S. Parmar,[91] A. Passfeld,[61] V. Paticchio,[106] R. N. Patra,[137] B. Paul,[113] H. Pei,[7] T. Peitzmann,[53] X. Peng,[7] L. G. Pereira,[63]
H. Pereira Da Costa,[66] D. Peresunko,[83,77] E. Perez Lezama,[60] V. Peskov,[60] Y. Pestov,[5] V. Petráček,[38] V. Petrov,[114]
M. Petrovici,[81] C. Petta,[27] R. P. Pezzi,[63] S. Piano,[112] M. Pikna,[37] P. Pillot,[116] L. O. D. L. Pimentel,[84] O. Pinazza,[107,34]
L. Pinsky,[126] D. B. Piyarathna,[126] M. Płoskoń,[76] M. Planinic,[133] J. Pluta,[138] S. Pochybova,[140] P. L. M. Podesta-Lerma,[122]
M. G. Poghosyan,[88] B. Polichtchouk,[114] N. Poljak,[133] W. Poonsawat,[117] A. Pop,[81] H. Poppenborg,[61]
S. Porteboeuf-Houssais,[72] J. Porter,[76] J. Pospisil,[87] V. Pozdniakov,[68] S. K. Prasad,[4] R. Preghenella,[34,107] F. Prino,[113]
C. A. Pruneau,[139] I. Pshenichnov,[52] M. Puccio,[25] G. Puddu,[23] P. Pujahari,[139] V. Punin,[102] J. Putschke,[139] H. Qvigstad,[20]
A. Rachevski,[112] S. Raha,[4] S. Rajput,[93] J. Rak,[127] A. Rakotozafindrabe,[66] L. Ramello,[31] F. Rami,[65] D. B. Rana,[126]
R. Raniwala,[94] S. Raniwala,[94] S. S. Räsänen,[45] B. T. Rascanu,[60] D. Rathee,[91] V. Ratza,[44] I. Ravasenga,[30] K. F. Read,[88,129]
K. Redlich,[80] A. Rehman,[21] P. Reichelt,[60] F. Reidt,[34] X. Ren,[7] R. Renfordt,[60] A. R. Reolon,[74] A. Reshetin,[52] K. Reygers,[96]
V. Riabov,[89] R. A. Ricci,[75] T. Richert,[53,33] M. Richter,[20] P. Riedler,[34] W. Riegler,[34] F. Riggi,[27] C. Ristea,[58]
M. Rodríguez Cahuantzi,[2] K. Røed,[20] E. Rogochaya,[68] D. Rohr,[41] D. Röhrich,[21] F. Ronchetti,[74,34] L. Ronflette,[116]
P. Rosnet,[72] A. Rossi,[28] F. Roukoutakis,[79] A. Roy,[48] C. Roy,[65] P. Roy,[103] A. J. Rubio Montero,[10] R. Rui,[24] R. Russo,[25]
E. Ryabinkin,[83] Y. Ryabov,[89] A. Rybicki,[120] S. Saarinen,[45] S. Sadhu,[137] S. Sadovsky,[114] K. Šafařík,[34] B. Sahlmuller,[60]
B. Sahoo,[47] P. Sahoo,[48] R. Sahoo,[48] S. Sahoo,[57] P. K. Sahu,[57] J. Saini,[137] S. Sakai,[74,132] M. A. Saleh,[139] J. Salzwedel,[18]
S. Sambyal,[93] V. Samsonov,[77,89] A. Sandoval,[64] D. Sarkar,[137] N. Sarkar,[137] P. Sarma,[43] M. H. P. Sas,[53] E. Scapparone,[107]
F. Scarlassara,[28] R. P. Scharenberg,[98] C. Schiaua,[81] R. Schicker,[96] C. Schmidt,[100] H. R. Schmidt,[95] M. O. Schmidt,[96]
M. Schmidt,[95] J. Schukraft,[34] Y. Schutz,[116,34,65] K. Schwarz,[100] K. Schweda,[100] G. Scioli,[26] E. Scomparin,[113] R. Scott,[129]
M. Šefčík,[39] J. E. Seger,[90] Y. Sekiguchi,[131] D. Sekihata,[46] I. Selyuzhenkov,[77,100] K. Senosi,[67] S. Senyukov,[3,65,34]
E. Serradilla,[64,10] P. Sett,[47] A. Sevcenco,[58] A. Shabanov,[52] A. Shabetai,[116] O. Shadura,[3] R. Shahoyan,[34] A. Shangaraev,[114]
A. Sharma,[93] A. Sharma,[91] M. Sharma,[93] M. Sharma,[93] N. Sharma,[129,91] A. I. Sheikh,[137] K. Shigaki,[46] Q. Shou,[7]
K. Shtejer,[25,9] Y. Sibiriak,[83] S. Siddhanta,[108] K. M. Sielewicz,[34] T. Siemiarczuk,[80] D. Silvermyr,[33] C. Silvestre,[73]
G. Simatovic,[133] G. Simonetti,[34] R. Singaraju,[137] R. Singh,[82] V. Singhal,[137] T. Sinha,[103] B. Sitar,[37] M. Sitta,[31] T. B. Skaali,[20]
M. Slupecki,[127] N. Smirnov,[141] R. J. M. Snellings,[53] T. W. Snellman,[127] J. Song,[99] M. Song,[142] F. Soramel,[28] S. Sorensen,[129]
F. Sozzi,[100] E. Spiriti,[74] I. Sputowska,[120] B. K. Srivastava,[98] J. Stachel,[96] I. Stan,[58] P. Stankus,[88] E. Stenlund,[33] J. H. Stiller,[96]
D. Stocco,[116] P. Strmen,[37] A. A. P. Suaide,[123] T. Sugitate,[46] C. Suire,[51] M. Suleymanov,[15] M. Suljic,[24] R. Sultanov,[54]
M. Šumbera,[87] S. Sumowidagdo,[49] K. Suzuki,[115] S. Swain,[57] A. Szabo,[37] I. Szarka,[37] A. Szczepankiewicz,[138]
M. Szymanski,[138] U. Tabassam,[15] J. Takahashi,[124] G. J. Tambave,[21] N. Tanaka,[132] M. Tarhini,[51] M. Tariq,[17] M. G. Tarzila,[81]
A. Tauro,[34] G. Tejeda Muñoz,[2] A. Telesca,[34] K. Terasaki,[131] C. Terrevoli,[28] B. Teyssier,[134] D. Thakur,[48] D. Thomas,[121]
R. Tieulent,[134] A. Tikhonov,[52] A. R. Timmins,[126] A. Toia,[60] S. Tripathy,[48] S. Trogolo,[25] G. Trombetta,[32] V. Trubnikov,[3]
W. H. Trzaska,[127] B. A. Trzeciak,[53] T. Tsuji,[131] A. Tumkin,[102] R. Turrisi,[110] T. S. Tveter,[20] K. Ullaland,[21] E. N. Umaka,[126]
A. Uras,[134] G. L. Usai,[23] A. Utrobicic,[133] M. Vala,[118,55] J. Van Der Maarel,[53] J. W. Van Hoorne,[34] M. van Leeuwen,[53]
T. Vanat,[87] P. Vande Vyvre,[34] D. Varga,[140] A. Vargas,[2] M. Vargyas,[127] R. Varma,[47] M. Vasileiou,[79] A. Vasiliev,[83]
A. Vauthier,[73] O. Vázquez Doce,[97,35] V. Vechernin,[136] A. M. Veen,[53] A. Velure,[21] E. Vercellin,[25] S. Vergara Limón,[2]
R. Vernet,[8] R. Vértesi,[140] L. Vickovic,[119] S. Vigolo,[53] J. Viinikainen,[127] Z. Vilakazi,[130] O. Villalobos Baillie,[104]
A. Villatoro Tello,[2] A. Vinogradov,[83] L. Vinogradov,[136] T. Virgili,[29] V. Vislavicius,[33] A. Vodopyanov,[68] M. A. Völkl,[96]
K. Voloshin,[54] S. A. Voloshin,[139] G. Volpe,[32] B. von Haller,[34] I. Vorobyev,[97,35] D. Voscek,[118] D. Vranic,[34,100] J. Vrláková,[39]
B. Wagner,[21] J. Wagner,[100] H. Wang,[53] M. Wang,[7] D. Watanabe,[132] Y. Watanabe,[131] M. Weber,[115] S. G. Weber,[100]
D. F. Weiser,[96] J. P. Wessels,[61] U. Westerhoff,[61] A. M. Whitehead,[92] J. Wiechula,[60] J. Wikne,[20] G. Wilk,[80] J. Wilkinson,[96]
G. A. Willems,[61] M. C. S. Williams,[107] B. Windelband,[96] W. E. Witt,[129] S. Yalcin,[71] P. Yang,[7] S. Yano,[46] Z. Yin,[7]
H. Yokoyama,[132,73] I.-K. Yoo,[34,99] J. H. Yoon,[50] V. Yurchenko,[3] V. Zaccolo,[84,113] A. Zaman,[15] C. Zampolli,[34]
H. J. C. Zanoli,[123] S. Zaporozhets,[68] N. Zardoshti,[104] A. Zarochentsev,[136] P. Závada,[56] N. Zaviyalov,[102] H. Zbroszczyk,[138]
M. Zhalov,[89] H. Zhang,[7,21] X. Zhang,[76,7] Y. Zhang,[7] C. Zhang,[53] Z. Zhang,[7] C. Zhao,[20] N. Zhigareva,[54] D. Zhou,[7] Y. Zhou,[84]

Z. Zhou,[21] H. Zhu,[21,7] J. Zhu,[7,116] X. Zhu,[7] A. Zichichi,[12,26] A. Zimmermann,[96] M. B. Zimmermann,[34,61] S. Zimmermann,[115] G. Zinovjev,[3] and J. Zmeskal[115]

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