Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead–lead collisions at $s_{NN} = 2.76$ TeV with the ATLAS Detector.

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Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead–lead collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

The measurement of collective phenomena in nuclear collisions at high energies has been subject of extensive theoretical and experimental studies. Anisotropic flow, which manifests itself as a large anisotropy in the event-by-event azimuthal angle distribution of produced particles, is generally understood to be a consequence of the spatial anisotropy of the initial energy deposition from nucleon–nucleon collisions in the overlap of the colliding nuclei. Anisotropies in the initial energy density are converted into final state momentum anisotropies via strong rescattering processes which induce pressure gradients, following the laws of relativistic hydrodynamics. Consequently, azimuthal anisotropies are sensitive to the initial state and its subsequent dynamical evolution.

Anisotropic flow is commonly studied by measuring the Fourier coefficients ($v_n$) of the azimuthal angle distributions of emitted particles. The second harmonic, $v_2$, referred to as “elliptic flow”, is the most extensively studied as it most directly relates the anisotropic shape of the overlap of the colliding nuclei to a corresponding anisotropy of the outgoing momentum distribution (for a review, see Ref. [1]). Elliptic flow has been measured over a wide range of energies, collision systems, and collision centralities by all of the RHIC heavy ion experiments [2–5] and recent results from the LHC.

Elliptic flow

Elliptic flow is measured over a wide region in pseudorapidity, $|\eta| < 2.5$, and over a broad range in transverse momentum, $0.5 < p_T < 20$ GeV. The elliptic flow parameter $v_2$ is obtained by correlating individual tracks with the event plane measured using energy deposited in the forward calorimeters. As a function of transverse momentum, $v_2(p_T)$ reaches a maximum at $p_T$ of about 3 GeV, then decreases and becomes weakly dependent on $p_T$ above 7–8 GeV. Over the measured pseudorapidity region, $v_2$ is found to be only weakly dependent on $\eta$, with less variation than observed at lower beam energies. The results are discussed in the context of previous measurements at lower collision energies, as well as recent results from the LHC.

In this Letter, we present a measurement of the elliptic flow of charged particles in lead–lead collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ATLAS detector at the LHC. The elliptic flow is measured in the pseudorapidity region $|\eta| < 2.5$ over the full azimuthal range $0 < \phi < 2\pi$, for transverse momenta $0.5 < p_T < 20$ GeV. This allows stringent tests of the applicability of hydrodynamics in the LHC energy regime, and provides information on the transition between low $p_T$, where hydrodynamics is expected to dominate, and higher $p_T$, where particle production is expected to stem from the fragmentation of jets modified by the hot, dense medium [8].

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.
2. ATLAS detector and trigger

The ATLAS detector [9] is well suited for measurements of azimuthal anisotropies over a large pseudorapidity range. The relevant detectors for this analysis are the inner detector (ID) and forward calorimeter (FCal). The ID is contained within the 2 T field of a superconducting solenoid magnet, and measures the trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$ and over the full azimuthal range. The precision silicon tracking detectors consist of pixel detectors (Pixel) and a semiconductor microstrip tracker (SCT). In the “barrel” region, these are arranged on cylindrical layers surrounding the beam pipe, while in the “end-cap” regions they are mounted on disks perpendicular to the beam axis. A charged particle typically traverses three layers of the Pixel detector and four double-sided layers of the SCT. The silicon detectors are surrounded by a transition radiation tracker (TRT), composed of drift tubes and covering up to $|\eta| = 2$.

The FCal covers a pseudorapidity range $3.2 < |\eta| < 4.9$. It uses tungsten and copper absorbers with liquid argon as the active medium, with a total thickness of about 10 interaction lengths. This analysis uses the energy deposition in the entire FCal for the centrality determination, while for the reaction plane measurement only the energy deposition in the first sampling layer of the FCal (Layer 1) is used, as doing this was found to minimize the effect of fluctuations on the reaction plane measurement.

The trigger system has three stages, the first of which (Level-1) is hardware-based, while the later stages (Level-2 and Event Filter [9]) are based on software algorithms. The minimum-bias Level-1 trigger used for this analysis requires signals in either the two sets of minimum-bias trigger scintillator (MBTS) counters, covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two zero-degree calorimeters (ZDC), each positioned at $|z| = 140$ m relative to the centre of the detector, detecting neutrons and photons with $|\eta| > 8.3$. The ZDC Level-1 trigger thresholds were set just below the single neutron peak on each side. The MBTS trigger was configured to require at least one hit above threshold from each side of the detector. A Level-2 timing requirement on signals from the MBTS was then imposed to remove beam backgrounds, while the ZDC had no further requirements beyond the Level-1 decision. The Event Filter was not needed for the minimum-bias triggering and was run in pass-through mode.

3. Event selection and reconstruction

The lead–lead data set analysed here corresponds to an integrated luminosity of approximately $L_{\text{int}} = 7 \, \mu b^{-1}$. Three main event selection requirements were applied offline to reject both non-collision backgrounds and Coulomb processes, in particular highly-inelastic photonuclear events. First, an offline event selection required a time difference $|\Delta t| < 3$ ns between the positive and negative $\eta$ MBTS counters as well as a reconstructed vertex in order to suppress non-collision backgrounds. Second, a coincidence of the ZDCs at forward and backward pseudorapidities was required in order to reject a variety of background processes, while maintaining high efficiency for non-Coulomb processes. Finally, in this analysis only events with a vertex with $|z_{\text{beam}}| < 10$ cm were used. Simulations show the vertex algorithm to be essentially 100% efficient for the event sample considered here. Pile-up events, defined as additional minimum bias events in the same bunch crossing, are expected to be present at the $10^{-6}$ level and so are negligible. In total, approximately $4 \times 10^7$ events passed the selection criteria.

Tracks were reconstructed within the full acceptance of the inner detector. To improve the reliability of the ID track reconstruction in the tracking environment in heavy ion collisions, the track quality requirements are more stringent than those defined for proton–proton collisions [10]. Tracks are required to have at least eight hits in the SCT, at least two Pixel hits and a hit in the Pixel layer closest to the interaction point. A track must have no missing Pixel hits and at most one missing SCT hit, where such hits are expected. Finally, the transverse and longitudinal impact parameters with respect to the vertex $(|d_{0}|$ and $|z_{0}\sin\theta|)$ were each required to be less than 1 mm. These additional requirements were made to improve the purity of the track sample. The inefficiency of this selection is driven by the loss due to hadronic interactions in the detector material, which increases with $|\eta|$ [10]. This results in an additional inefficiency of approximately 15% at $|\eta| > 1$ compared to the central region of the detector. However, the results shown here are found to be insensitive to the absolute tracking efficiency (discussed below), and the effect of the efficiency decrease at high $|\eta|$ is minimized when measurements are performed in limited transverse momentum and pseudorapidity intervals.

The tracking performance has been studied in detail by comparing data to Monte Carlo simulations based on the HIJING event generator [11] and a full GEANT4 [12] simulation of the detector [13]. In general the simulated distributions of the number of Pixel and SCT hits on tracks describe the data well, particularly after reweighting the simulated momentum distribution to account for the differences in the charged particle spectrum reconstructed in data and HIJING. Monte Carlo calculations show that the tracking efficiency for charged hadrons in this analysis is about 72% near $\eta = 0$ in central collisions, lower than in proton–proton collisions due to the more stringent requirements and the higher occupancy in the SCT. Fake tracks from random combinations of hits are generally negligible, e.g. reaching only 0.1% in $|\eta| < 0.3$ for the highest multiplicity collisions, although the rate of fake tracks increases slightly with increasing $|\eta|$.

4. Data analysis

In order to systematically select various geometries of the initial state, the data were analysed in centrality intervals defined by selections on FCal $\Sigma E_T$, the total transverse energy deposited in the FCal (always stated at the electromagnetic energy scale, which does not correct for the response of the calorimeter to hadrons). These intervals are expressed in percentiles of the total inelastic non-Coulomb lead–lead cross section (0–10%, 10–20%, ..., 70–80%) with the most central interval (0–10%) corresponding to the 10% of events with the largest FCal $\Sigma E_T$. The measured FCal $\Sigma E_T$ distribution for a subset of the data (with $L_{\text{int}}$ approximately 200 mb$^{-1}$), taken with a less restrictive primary trigger than used for the bulk of the data and used for the calibration procedure described below, is shown divided into centrality intervals in Fig. 1.

To establish the fraction $f$ of the total non-Coulomb inelastic cross section selected by our trigger and event selection criteria, we have performed a convolution of FCal $\Sigma E_T$ distributions measured in proton–proton data at $\sqrt{s} = 2.76$ TeV with a full Monte Carlo Glauber calculation [14]. The calculation assumes the number of effective proton–proton collisions per lead–lead event, $N$, scales according to the “two-component model” (from e.g. Ref. [15]). This model combines the number of participants ($N_{\text{part}}$), the number of nucleons which interact inelastically at least once, and the number of binary collisions ($N_{\text{coll}}$) as $N = (1 - x) \frac{N_{\text{int}}}{s} + x N_{\text{coll}}$. In this approach, the only free parameter is $x$, which controls the relative contribution of $N_{\text{part}}$ and $N_{\text{coll}}$. The best description of the data is found to be for $x = 0.088$. The value of $f$ and its uncertainty is estimated by systematically varying the effect of trigger and event selection inefficiencies as well as backgrounds in the most peripheral FCal $\Sigma E_T$ interval to achieve the best agreement between the
measured and simulated distributions. Using this analysis of the FCal $\Sigma E_T$ distribution, the fraction of the total cross section sampled by the trigger and event selection has been estimated to be 98%, with an uncertainty of 2%. This is similar to estimates given in a previous ATLAS publication [16]. The FCal $\Sigma E_T$ ranges defined from this subsample have been found to be stable for the full data set, both by counting the number of events and by measuring the average number of reconstructed tracks in each interval. The 20% of events with the smallest FCal $\Sigma E_T$ are not included in this analysis, due to the relatively large uncertainties in determining the appropriate selection criteria.

The final state momentum anisotropy can be quantified by studying the Fourier decomposition of the azimuthal angle distribution [17]:

$$E \frac{d^3N}{dp^1} = \frac{1}{p_T} \frac{d^3N}{dp_T dp_T dy} = \frac{1}{2\pi p_T} E \frac{d^3N}{dp_T dp_T} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos \left[ n(\phi - \Psi_0) \right] \right).$$

where $y$, $p_T$ and $\phi$ are the rapidity, transverse momentum, and azimuthal angle of final-state charged particle tracks and $\Psi_0$ denotes the azimuthal angle of the $n$-th order reaction plane. In more peripheral events, $\Psi_2$ is close to $\Phi_{BP}$, the reaction plane angle, defined by the impact parameter ($b$, the vector separation of the barycentres of the two nuclei) and the beam axis ($z$). In more central events, $\Psi_2$ primarily reflects fluctuations in the initial-state configurations of colliding nucleons. This analysis was confined to the second Fourier coefficient ($n=2$), $v_2 \equiv \langle \cos[2(\phi - \Phi_{BP})] \rangle$, where angular brackets denote an average first over particles within each event relative to the event-wise reaction plane, and then over events.

In this analysis, the $n=2$ event plane is determined from the data on an event-by-event basis, according to the scheme outlined in Ref. [17]:

$$\Psi_2 = \frac{1}{2} \tan^{-1} \left( \frac{\sum E_{\text{tower}}^\text{lower} \, w_i \sin(2\phi_i)}{\sum E_{\text{tower}}^\text{lower} \, w_i \cos(2\phi_i)} \right).$$

where sums run over tower transverse energies $E_{\text{tower}}^\text{lower}$ as measured in the first sampling layer of the forward calorimeters, with each tower covering $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. The tower weights, $w_i = w_i(\phi_i, \eta_i)$, are used to correct for local variations in detector response. They are calculated in narrow $\Delta \eta$ slices ($\Delta \eta = 0.1$) over the full FCal $\eta$ range in such a way as to remove structures in the uncorrected $\phi$ distributions of $E_{\text{tower}}^\text{lower}$ in every $\Delta \eta$ slice. The final results of this analysis are found to be insensitive to the weighting, and results obtained with all $w_i = 1$ were consistent with those reported here, and well within the systematic uncertainties estimated below.

The correlation of individual track azimuthal angles with the estimated event plane is shown in Fig. 2 for tracks with $p_T = 1-2$ GeV. There is a clear sinusoidal modulation at all centralities. The modulation is largest in the 20–50% centrality intervals, and decreases for the more central and peripheral events. In the central intervals where the correlation is strongest, the correlation does not follow a perfect $1 + \alpha \cos(2\phi)$ form, indicating significant contributions from higher order harmonics. However, in this Letter we rely on the orthogonality of the Fourier expansion and do not extract the other coefficients. To verify that this does not bias the measurement, we have extracted $v_2$ from a fit containing all Fourier components $v_n$ up to $n=6$, and found $v_2$ values consistent with the results extracted below. The odd amplitudes are found to be consistent with zero, as expected when measuring odd harmonic functions relative to $\Psi_2$ [17].

The measured values of $v_2$ are generally underestimated because of the finite experimental resolution in extracting the event plane angle. The event plane resolution correction factor, $R$, was obtained using the subevent technique, also described in Ref. [17]. Two “subevents” are defined in each event, one each in the forward and backward $\eta$ directions. For the measurement of the event plane using the FCal, the first sampling layer on the positive $\eta$ side was selected as subevent “P”, with a corresponding subevent “N” formed for negative $\eta$. The resolution correction for the event...
plane measured by each subevent was calculated as a function of FCal $\Sigma E_T$ according to the formula
\[
R(\Sigma E_T) = \sqrt{\cos(2(\Psi_j^N - \Psi_j^P))},
\]
where angular brackets denote an average over all events in a FCal $\Sigma E_T$ interval. The left panel of Fig. 3 shows the distribution of the difference $\Psi_j^N - \Psi_j^P$. The right panel shows the FCal $\Sigma E_T$ dependence of the resolution correction for the event plane determined using the full FCal Layer 1 as well as a reduced-acceptance version used in the systematic studies discussed below.

The final, resolution-corrected, $v_2$ is calculated in intervals of centrality, $\eta$ and $p_T$ as
\[
v_2(\eta, p_T) = \frac{1}{N_{\text{tot}}^{\text{trk}}} \sum_j \frac{1}{R(\Sigma E_T)} \sum_i c_i \cos[2(\phi_i - \Psi_i^{N/P})],
\]
where $N_{\text{tot}}^{\text{trk}}$ denotes the total number of the reconstructed tracks in a given centrality, $\eta$ and $p_T$ range, and the $c_i$ are weights similar to the $w_i$ for tracks, designed to flatten the $\phi$ distribution in a small $\Delta\eta$ slice. For $\Psi_i^{N/P}$ (the event plane for event $j$) we take the event plane measured in the opposite $\eta$ hemisphere (i.e. “$P$” at positive $\eta$, or “$N$” at negative $\eta$) to each track with azimuthal angle $\phi_i$. Using the track in the opposite hemisphere maximizes the pseudorapidity gap between the reaction plane estimate and the $v_2$ estimate ($|\Delta\eta| > 3.2$), minimizing potential non-flow correlations between them.

The systematic uncertainty on $v_2$ as a function of $p_T$, $\eta$ and centrality was evaluated by varying several different aspects of the analysis procedure.

- The resolution correction was changed by limiting the FCal acceptance to a smaller range in pseudorapidity.
- Tighter tracking requirements were applied (both $|d_0|$ and $|z_0\sin\theta|$ less than 0.5 mm, instead of the nominal 1 mm requirement).
- Results were compared using negatively and positively charged tracks.
- Results were compared between $v_2$ measured at positive and negative pseudorapidities.
- Results were studied as a function of time during the heavy ion run.

Additional sources of systematic uncertainties were examined, including the following: Deviations from zero of $(\sin(2(\phi - v_2)))$, which are sensitive to residual biases in the reaction plane determination and detector non-uniformities, were measured. Monte Carlo studies were performed based on HIJING, with a special procedure applied to the generated particle azimuthal angles so as to simulate elliptic flow (from Ref. [17]), with a magnitude extrapolated from RHIC data. Deviations from the flow induced at the generator level were obtained by applying the same analysis procedure to the simulated data as with real data. The event plane determined from the reconstructed tracks was also investigated as an independent cross-check on the FCal reaction plane. In this case, for the tracks with positive (negative) $\eta$ the event plane determined in the negative (positive) $\eta$ subevent was used. The uncertainty in the fraction of the total inelastic cross section sampled by our trigger and event selection criteria gives an overall scale uncertainty on $v_2$, ranging from 1% in central events up to 5% in peripheral events.

Deviations in individual contributions from the baseline results have been quantified as relative systematic uncertainties on $v_2$ (in percent), which are listed in Table 1 for several centrality and $p_T$ intervals, all for $|\eta| < 1$. The different components have been added in quadrature and expressed as 1σ point-to-point systematic uncertainties. Note that the somewhat large increase in the scale of the uncertainties from moderate to high $p_T$ can be partly attributed to the limited track statistics at high $p_T$. It should also be pointed out that the systematic uncertainties only include those associated with the measurements themselves; no attempt is made to disentangle the potential contributions from non-flow effects, since their nature is not yet fully understood.

5. Results

The top panel of Fig. 4 shows the $v_2$ dependence on $p_T$ for eight 10% centrality intervals and for tracks with $|\eta| < 1$. It is observed that all centrality intervals show a rapid rise in $v_2(p_T)$ up to $p_T = 3$ GeV, a decrease out to 7–8 GeV, and then a weak $p_T$ dependence beyond 9–10 GeV. The same trends are also seen for $1 < |\eta| < 2$ (Fig. 4 middle) and $2 < |\eta| < 2.5$ (Fig. 4 bottom).

The pseudorapidity dependence of $v_2$ is shown in Fig. 5. The top row shows the centrality and $\eta$ dependence of $v_2(\eta, p_T)$ for five $p_T$ intervals, which characterize the trend shown in Fig. 4, and the four most-central intervals. The bottom row shows the same information for the four most peripheral intervals. It is observed that $v_2$ depends very weakly on $\eta$ over the measured pseudorapidity region. In the two lowest $p_T$ intervals, below 1.2 GeV, $v_2$ drops by about 5–10% over the range $|\eta| = 0–2.4$. At higher transverse momenta, a decrease on the order of few percent can be seen, although, due to the large point-to-point errors, a flat
Table 1
Principal systematic uncertainties (stated as a percentage of the value of \(v_2\)) on the \(v_2\) measurement for three \(p_T\) intervals and two centrality intervals, all for \(|\eta| < 1\).

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<th>40–50%</th>
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<td>2.4–2.7</td>
<td>8–10</td>
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<tr>
<td>Total systematic error</td>
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Fig. 4. Elliptic flow \(v_2(p_T)\) as a function of \(p_T\) for eight 10% centrality intervals, for \(p_T\) from 0.5 to 20 GeV, and for three ranges in pseudorapidity (\(|\eta| < 1\), 1 < \(|\eta| < 2\), and 2 < \(|\eta| < 2.5\)). Error bars show statistical and systematic uncertainties added in quadrature. The arrows indicate where the value of \(v_2\) does not fit within the chosen plot scale, due to large statistical fluctuations.
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Fig. 5. Pseudorapidity dependence of $v_2(p_T, \eta)$ for $0.5 < p_T < 20$ GeV in five $p_T$ intervals and 10% centrality intervals. Error bars show statistical and systematic uncertainties added in quadrature.

Fig. 6. $v_2$ vs. $p_T$ at $|\eta| < 1$ in the 40–50% centrality interval, compared to previous experimental data: ALICE $v_2$ [7] for inclusive charged particles, PHENIX [20] $v_2$ for identified $\pi^0$, and STAR data on $v_2(2)$ for inclusive charged particles for the 40–60% interval [19].

$\eta$ dependence cannot be excluded. This is in contrast to the strong variation in $v_2(\eta)$ observed by the PHOBOS experiment at $\sqrt{s_{NN}} = 200$ GeV [18], which drops by approximately 30% between $\eta = 0$ and $\eta = 2.5$.

Fig. 6 shows $v_2(p_T)$ for $|\eta| < 1$ in the 40–50% centrality interval compared to data from the LHC (ALICE, from Ref. [7]) as well as from RHIC (STAR [19] and PHENIX [20]) with a centre-of-mass energy a factor of nearly 14 lower. The ALICE and STAR data are shown for the second cumulant $v_2(2)$, which gives results closest to the event-plane method used in this analysis. The PHENIX data are obtained with a similar method as ATLAS, but with $v_2$ measured only for identified $\pi^0$ hadrons, detected through their two-photon decay mode. It is observed that all of the data sets are quite similar as a function of $p_T$, both at lower $p_T$ (ALICE and STAR) and even at higher $p_T$, within the limited statistical precision of the PHENIX data. The observation of similar $v_2$ at low $p_T$ has been noted recently [7], and has been reproduced using hydrodynamical simulations assuming the same shear viscosity to entropy density ratio but initialized at a higher energy density. However, the similarities at high $p_T$ will require additional theoretical study to see if they are consistent with the differential energy loss of jets in the hot, dense medium.

6. Conclusions

Elliptic flow measurements in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained with the ATLAS detector are presented for an integrated luminosity of approximately 7 $\mu$b$^{-1}$. These results represent the first measurement of $v_2$ over a broad range in $\eta$ and $p_T$ at the LHC energy. As a function of transverse momentum, at all $|\eta|$, $v_2$ rises rapidly up to $p_T = 3$ GeV, decreases somewhat less rapidly out to $p_T = 7–8$ GeV, and then varies weakly out to 20 GeV. Over the measured pseudorapidity region, $|\eta| < 2.5$, $v_2$ is found to be only weakly dependent on $\eta$, with less variation than observed at lower beam energies. Comparison of the 40–50% interval with lower energy data shows little change both at low and high $p_T$. These results provide strong constraints on models which aim to describe the dynamical evolution of the system created in ultra-relativistic heavy ion collisions.

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ATLAS Collaboration


References


123 (a) INHEN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
125 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
127 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
128 Czech Technical University in Prague, Praha, Czech Republic
129 State Research Center Institute for High Energy Physics, Protvino, Russia
130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
131 Physics Department, University of Regina, Regina, SK, Canada
132 (b) Institut de Recherches sur les Lois Fondamentales de l'Univers, CEA Saclay (Commissariat a l'Energie Atomique), GIF-sur-Yvette, France
133 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
134 Department of Physics, University of Washington, Seattle, WA, United States
135 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
136 Physics Department, Tokyo Institute of Technology, Tokyo, Japan
137 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
138 Department of Physics, University of Tokyo, Tokyo, Japan
139 Department of Physics, University of Toronto, Toronto, ON, Canada
140 (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
141 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
142 Science and Technology Center, Tufts University, Medford, MA, United States
143 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
144 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
145 (a) INFN Sezione di Pisa; (b) Laboratoire de Physique Subnucléaire, Université de Cergy-Pontoise, France
146 Department of Physics, University of British Columbia, Vancouver, BC, Canada
147 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
148 Waseda University, Tokyo, Japan
149 (a) Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
150 Department of Physics, University of Wisconsin, Madison, WI, United States
151 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
152 Fachbereich Physik, Universität Siegen, Siegen, Germany
153 Literature Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
154 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
155 Department of Physics, University of Toronto, Toronto, ON, Canada
156 (a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
157 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
158 Science and Technology Center, Tufts University, Medford, MA, United States
159 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
160 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
161 (a) INFN Sezione di Pisa; (b) Laboratoire de Physique Subnucléaire, Université de Cergy-Pontoise, France
162 Department of Physics, University of British Columbia, Vancouver, BC, Canada
163 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
164 Waseda University, Tokyo, Japan
165 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
166 Department of Physics, University of Wisconsin, Madison, WI, United States
167 Institute of Physics, University of Geneva, Geneva, Switzerland
168 Department of Physics, University of Illinois, Urbana, IL, United States
169 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
170 Department of Physics, The University of Tokyo, Tokyo, Japan
171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin, Madison, WI, United States
173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
174 Department of Physics, University of Illinois, Urbana, IL, United States
175 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
176 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
177 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
178 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hauites Energies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Université Cadi Ayad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LITPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
179 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), GIF-sur-Yvette, France
180 Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
181 Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
182 Also at CPPM, Aix-Marseille Université and CERN/IN2P3, Marseille, France.
183 Also at TRIUMF, Vancouver, BC, Canada.
184 Also at Department of Physics, California State University, Fresno, CA, United States.
185 Also at Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland.
186 Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
187 Also at Università di Napoli Parthenope, Napoli, Italy.
188 Also at Institute of Particle Physics (IPP), Canada.
189 Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
190 Also at Louisiana Tech University, Ruston, LA, United States.
191 Also at Department of Physics, University of Montreal, Montreal, QC, Canada.
192 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
193 Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
194 Also at Manhattan College, New York, NY, United States.