Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV

J. Abraham,[1] P. Abreu,[2] M. Aglietta,[3] C. Aguirre,[4] D. Allard,[5] I. Allekotte,[6] J. Allen,[7] P. Allison,[8] J. Alvarez-Muñiz,[9] M. Ambrosio,[10] L. Anchordoqui,[11,12] S. Andringa,[2] A. Anzalone,[13] C. Aramo,[10] S. Argirò,[14] K. Arisaka,[15] E. Armengaud,[5] F. Arneodo,[16] F. Arqueros,[17] T. Asch,[18] H. Asorey,[19] P. Assis,[2] B. S. Atulugama,[20] J. Aublin,[21] M. Ave,[22] G. Avila,[23] T. Bäcker,[24] D. Badagnani,[25] A. F. Barbosa,[26] D. Barnhill,[15] S. L. C. Barroso,[27] B. Baughman,[8] P. Bauleo,[28] J. J. Beatty,[8] T. Beau,[5] B. R. Becker,[29] K. H. Becker,[30] J. A. Bellido,[20] S. BenZvi,[31] C. Berat,[32] T. Bergmann,[33] P. Bernardini,[34] X. Bertou,[19] P. L. Biermann,[35] P. Billoir,[21] O. Blanch-Bigas,[21] F. Blanco,[17] P. Blasi,[36,37,38] C. Bleve,[39] H. Blümer,[33,40] M. Boháčová,[41] C. Bonifazi,[21,26] R. Bonino,[3] J. Brack,[28] P. Brogueira,[2] W. C. Brown,[42] P. Buchholz,[24] A. Bueno,[43] R. E. Burton,[44] N. G. Busca,[5] K. S. Caballero-Mora,[33] B. Cai,[45] D. V. Camin,[46] L. Caramete,[35] R. Caruso,[47] W. Carvalho,[48] A. Castellina,[3] O. Catalano,[13] G. Cataldi,[34] L. Cazon,[22] R. Cester,[14] J. Chauvin,[32] A. Chiavassa,[3] J. A. Chinellato,[49] A. Chou,[7,36] J. Chudoba,[41] J. Chye,[50] P. D. J. Clark,[51] R. W. Clay,[52] E. Colombo,[53] R. Conceição,[2] B. Connolly,[54] F. Contreras,[55] J. Coppens,[56,57] A. Cordier,[58] U. Cotti,[59] S. Coutu,[20] C. E. Covault,[44] A. Creusot,[60] A. Criss,[20] J. Cronin,[22] A. Curutiu,[35] S. Dagoret-Campagne,[58] K. Daumiller,[40] B. R. Dawson,[52] R. M. de Almeida,[49] C. De Donato,[46] S. J. de Jong,[56] G. De La Vega,[61] W. J. M. de Mello Junior,[49] J. R. T. de Mello Neto,[22,62] I. De Mitri,[34] V. de Souza,[33] L. del Peral,[63] O. Deligny,[64] A. Della Selva,[65] C. Delle Fratte,[66] H. Dembinski,[67] C. Di Giulio,[66] J. C. Diaz,[50] P. N. Diep,[68] C. Dobrigkeit,[49] J. C. D'Olivo,[69] P. N. Dong,[68] D. Dornic,[64] A. Dorofeev,[70] J. C. dos Anjos,[26] M. T. Dova,[25] D. D'Urso,[65] I. Dutan,[35] M. A. DuVernois,[71] R. Engel,[40] L. Epele,[25] M. Erdmann,[67] C. O. Escobar,[49] A. Etchegoyen,[72] P. Facal San Luis,[9] H. Falcke,[56,73] G. Farrar,[7] A. C. Fauth,[49] N. Fazzini,[36] F. Ferrer,[44] A. Ferrero,[53] B. Fick,[50] A. Filevich,[53] A. Filipčič,[74,60] I. Fleck,[24] C. E. Fracchiolla,[75] B. García,[1] D. García Gámez,[43] D. Garcia-Pinto,[17] X. Garrido,[58] H. Geenen,[30] G. Gelmini,[15] H. Gemmeke,[18] P. L. Ghia,[64,3] M. Giller,[76] H. Glass,[36] M. S. Gold,[29] G. Golup,[77] F. Gomez Albarracin,[25] M. Gómez Berisso,[77] P. Gonçalves,[2] M. Gonçalves do Amaral,[78] D. Gonzalez,[33] J. G. Gonzalez,[70] M. González,[79] D. Góra,[33,80] A. Gorgi,[3] P. Gouffon,[48] V. Grassi,[46] A. F. Grillo,[16] C. Grunfeld,[25] Y. Guardincerri,[81] F. Guarino,[65] G. P. Guedes,[82] J. Gutiérrez,[63] J. D. Hague,[29] V. Halenka,[41] J. C. Hamilton,[5] P. Hansen,[25] D. Harari,[77] S. Harmsma,[83,57] J. L. Harton,[64,28] A. Haungs,[40] T. Hauschildt,[3] M. D. Healy,[15] T. Hebbeker,[67] G. Hebrero,[63] D. Heck,[40] C. Hojvat,[36] V. C. Holmes,[52] P. Homola,[80] J. R. Hörandel,[56] A. Horneffer,[56] M. Hrabovský,[41] T. Huege,[40] M. Hussain,[60] M. Iarlori,[37] A. Insolia,[47] F. Ionita,[22] A. Italiano,[47] M. Kaducak,[36] K. H. Kampert,[30] T. Karova,[41] P. Kasper,[36] B. Kégl,[58] B. Keilhauer,[33] E. Kemp,[49] R. M. Kieckhafer,[50] H. O. Klages,[40] M. Kleifges,[18] J. Kleinfeller,[40] R. Knapik,[28] J. Knapp,[39] D.-H. Koang,[32] A. Krieger,[53] O. Krömer,[18] D. Kuempel,[30] N. Kunka,[18] A. Kusenko,[15] G. La Rosa,[13] C. Lachaud,[5] B. L. Lago,[62] D. Lebrun,[32] P. Lebrun,[36] J. Lee,[15] M. A. Leigui de Oliveira,[84] A. Letessier-Selvon,[21] M. Leuthold,[67] I. Lhenry-Yvon,[64] R. López,[85] A. Lopez Agüera,[9] J. Lozano Bahilo,[43] A. Lucero,[86] R. Luna García,[79] M. C. Maccarone,[13] C. Macolino,[37] S. Maldera,[3] G. Mancarella,[34] M. E. Manceñido,[25] D. Mandat,[41] P. Mantsch,[36] A. G. Mariazzi,[25] I. C. Maris,[33] H. R. Marquez Falcon,[59] D. Martello,[34] J. Martínez,[79] O. Martínez Bravo,[85] H. J. Mathes,[40] J. Matthews,[70,87] J. A. J. Matthews,[29] G. Matthiae,[66] D. Maurizio,[14] P. O. Mazur,[36] T. McCauley,[12] M. McEwen,[63] R. R. McNeil,[70] M. C. Medina,[72] G. Medina-Tanco,[69] D. Melo,[14,53] E. Menichetti,[14] A. Menschikov,[18] C. Meurer,[40] R. Meyhandan,[83] M. I. Micheletti,[72] G. Miele,[65] W. Miller,[29] S. Mollerach,[77] M. Monasor,[17,63] D. Monnier Ragaigne,[58] F. Montanet,[32] B. Morales,[69] C. Morello,[3] J. C. Moreno,[25] C. Morris,[8] M. Mostafá,[88] M. A. Muller,[49] R. Mussa,[14] G. Navarra,[3] J. L. Navarro,[43] S. Navas,[43] P. Necesal,[41] L. Nellen,[69] C. Newman-Holmes,[36] D. Newton,[39] P. T. Nhung,[68] N. Nierstenhoefer,[30] D. Nitz,[50] D. Nosek,[89] L. Nožka,[41] J. Oehlschläger,[40] T. Ohnuki,[15] A. Olinto,[5,22] V. M. Olmos-Gilbaja,[9] M. Ortiz,[17] F. Ortolani,[66] S. Ostapchenko,[33] L. Otero,[1] N. Pacheco,[63] D. Pakk Selmi-Dei,[49] M. Palatka,[41] J. Pallotta,[90] G. Parente,[9] E. Parizot,[5] S. Parlati,[16] S. Pastor,[91] M. Patel,[39] T. Paul,[12] V. Pavlidou,[22] K. Payet,[32] M. Pech,[41] J. Pękala,[80] R. Pelayo,[79] I. M. Pepe,[92] L. Perrone,[93] R. Pesce,[94,37] S. Petrera,[37] P. Petrinca,[66] Y. Petrov,[28] A. Pichel,[95] R. Piegaia,[81] T. Pierog,[40] M. Pimenta,[2] T. Pinto,[91] V. Pirronello,[47] O. Pisanti,[65] M. Platino,[53] J. Pochon,[19] P. Privitera,[22,66] M. Prouza,[41] E. J. Quel,[90] J. Rautenberg,[30] A. Redondo,[63] S. Reucroft,[12] B. Revenu,[5] F. A. S. Rezende,[26] J. Ridky,[41] S. Riggi,[47] M. Risse,[30] C. Rivière,[32] V. Rizi,[37] M. Roberts,[20] C. Robledo,[85] G. Rodriguez,[9] J. Rodriguez Martino,[47] J. Rodriguez Rojo,[55] I. Rodriguez-Cabo,[9] M. D. Rodríguez-Frías,[63] G. Ros,[17,63] J. Rosado,[17] M. Roth,[40] B. Rouillé-d'Orfeuil,[5] E. Roulet,[77] A. C. Rovero,[95] F. Salamida,[37] H. Salazar,[85] G. Salina,[66] F. Sánchez,[69] M. Santander,[55] C. E. Santo,[2] E. M. Santos,[21] F. Sarazin,[96] S. Sarkar,[97] R. Sato,[55] V. Scherini,[30] H. Schieler,[40] A. Schmidt,[18] F. Schmidt,[22] T. Schmidt,[33] O. Scholten,[83] P. Schovánek,[41] F. Schroeder,[40] S. Schulte,[67] F. Schüssler,[40] S. J. Sciutto,[25] M. Scuderi,[47] A. Segreto,[13] D. Semikoz,[5] M. Settimo,[34] R. C. Shellard,[26,75] I. Sidelnik,[72] B. B. Siffert,[62]

G. Sigl,[5] N. Smetniansky De Grande,[53] A. Smiałkowski,[76] R. Šmída,[41] A. G. K. Smith,[52] B. E. Smith,[39] G. R. Snow,[98]
P. Sokolsky,[88] P. Sommers,[20] J. Sorokin,[52] H. Spinka,[99,36] R. Squartini,[55] E. Strazzeri,[66] A. Stutz,[32] F. Suarez,[3]
T. Suomijärvi,[64] A. D. Supanitsky,[69] M. S. Sutherland,[8] J. Swain,[12] Z. Szadkowski,[76] J. Takahashi,[49] A. Tamashiro,[95]
A. Tamburro,[33] T. Tarutina,[25] O. Taşcău,[30] R. Tcaciuc,[24] N. T. Thao,[68] D. Thomas,[88] R. Ticona,[100] J. Tiffenberg,[81]
C. Timmermans,[57,56] W. Tkaczyk,[76] C. J. Todero Peixoto,[49] B. Tomé,[2] A. Tonachini,[14] I. Torres,[85] P. Travnicek,[41]
A. Tripathi,[15] G. Tristram,[5] D. Tscherniakhovski,[18] V. Tuci,[66] M. Tueros,[25,101] V. Tunnicliffe,[51] R. Ulrich,[40] M. Unger,[40]
M. Urban,[58] J. F. Valdés Galicia,[69] I. Valiño,[9] L. Valore,[65] A. M. van den Berg,[83] V. van Elewyck,[64] R. A. Vázquez,[9]
D. Veberič,[60,74] A. Veiga,[25] A. Velarde,[100] T. Venters,[22] V. Verzi,[66] M. Videla,[61] L. Villaseñor,[59] S. Vorobiov,[60]
L. Voyvodic,[36] H. Wahlberg,[25] P. Wahrlich,[52] O. Wainberg,[86] P. Walker,[51] D. Warner,[28] A. A. Watson,[39] S. Westerhoff,[31]
G. Wieczorek,[76] L. Wiencke,[96] B. Wilczyńska,[80] H. Wilczyński,[80] C. Wileman,[39] M. G. Winnick,[52] H. Wu,[58]
B. Wundheiler,[53] T. Yamamoto,[22] P. Younk,[88] E. Zas,[9] D. Zavrtanik,[60,74] M. Zavrtanik,[60,74] I. Zaw,[7]
A. Zepeda,[79] and M. Ziolkowski[24]

(The Pierre Auger Collaboration)

[1]Universidad Tecnológica Nacional, FR-Mendoza, Argentina
[2]LIP and Instituto Superior Técnico, Lisboa, Portugal
[3]Istituto di Fisica dello Spazio Interplanetario (INAF), Università di Torino and Sezione INFN, Torino, Italy
[4]Universidad Catolica de Bolivia, La Paz, Bolivia
[5]Laboratoire AstroParticule et Cosmologie, Université Paris 7, IN2P3/CNRS, Paris, France
[6]Centro Atómico Bariloche, Comision Nacional de Energía Atómica and Instituto Balseiro (CNEA-UNC),
San Carlos de Bariloche, Argentina
[7]New York University, New York, New York, USA
[8]Ohio State University, Columbus, Ohio, USA
[9]Universidad de Santiago de Compostela, Spain
[10]Sezione INFN di Napoli, Napoli, Italy
[11]University of Wisconsin, Milwaukee, Wisconsin, USA
[12]Northeastern University, Boston, Massachusetts, USA
[13]Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
[14]Università di Torino and Sezione INFN, Torino, Italy
[15]University of California, Los Angeles, California, USA
[16]INFN, Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy
[17]Universidad Complutense de Madrid, Madrid, Spain
[18]Forschungszentrum Karlsruhe, Institut für Prozessdatenverarbeitung und Elektronik, Germany
[19]Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, San Carlos de Bariloche, Argentina
[20]Pennsylvania State University, University Park, Pennsylvania, USA
[21]Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris 6 & 7, IN2P3/CNRS, Paris Cedex 05, France
[22]University of Chicago, Enrico Fermi Institute, Chicago, Illinois, USA
[23]Pierre Auger Southern Observatory and Comisión Nacional de Energía Atómica, Malargüe, Argentina
[24]Universität Siegen, Siegen, Germany
[25]IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[26]Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, RJ, Brazil
[27]Universidade Estadual do Sudoeste da Bahia, Vitoria da Conquista, BA, Brazil
[28]Colorado State University, Fort Collins, Colorado, USA
[29]University of New Mexico, Albuquerque, New Mexico, USA
[30]Bergische Universität Wuppertal, Wuppertal, Germany
[31]University of Wisconsin, Madison, Wisconsin, USA
[32]Laboratoire de Physique Subatomique et de Cosmologie, IN2P3/CNRS, Université Grenoble 1 et INPG, Grenoble, France
[33]Universität Karlsruhe (TH), Institut für Experimentelle Kernphysik (IEKP), Karlsruhe, Germany
[34]Dipartimento di Fisica dell'Università del Salento and Sezione INFN, Lecce, Italy
[35]Max-Planck-Institut für Radioastronomie, Bonn, Germany
[36]Fermilab, Batavia, Illinois, USA
[37]Università dell'Aquila and INFN, L'Aquila, Italy
[38]Osservatorio Astrofisico di Arcetri, Florence, Italy
[39]School of Physics and Astronomy, University of Leeds, United Kingdom
[40]Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany
[41]Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic
[42]Colorado State University, Pueblo, Colorado, USA

[43]Universidad de Granada & C.A.F.P.E., Granada, Spain

[44]Case Western Reserve University, Cleveland, Ohio, USA

[45]University of Minnesota, Minneapolis, Minnesota, USA

[46]Università di Milano and Sezione INFN, Milan, Italy

[47]Università di Catania and Sezione INFN, Catania, Italy

[48]Universidade de Sao Paulo, Instituto de Fisica, Sao Paulo, SP, Brazil

[49]Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil

[50]Michigan Technological University, Houghton, Michigan, USA

[51]Institute of Integrated Information Systems, University of Leeds, United Kingdom

[52]University of Adelaide, Adelaide, S.A., Australia

[53]Laboratorio Tandar, Centro Atómico Constituyentes, CNEA, Buenos Aires, Argentina

[54]University of Pennsylvania, Philadelphia, Pennsylvania, USA

[55]Pierre Auger Southern Observatory, Malargüe, Argentina

[56]IMAPP, Radboud University, Nijmegen, Netherlands

[57]NIKHEF, Amsterdam, Netherlands

[58]Laboratoire de l'Accélérateur Linéaire, Université Paris-Sud, IN2P3/CNRS, Orsay, France

[59]Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Michoacan, Mexico

[60]Laboratory for Astroparticle Physics, University of Nova Gorica, Slovenia

[61]Universidad Tecnológica Nacional, FR-Mendoza and Fundación Universidad Tecnológica Nacional, Argentina

[62]Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil

[63]Universidad de Alcalá, Alcalá de Henares (Madrid), Spain

[64]Institut de Physique Nucléaire, Université Paris- Sud, IN2P3/CNRS, Orsay, France

[65]Università di Napoli "Federico II" and Sezione INFN, Napoli, Italy

[66]Università di Roma II "Tor Vergata" and Sezione INFN, Roma, Italy

[67]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

[68]Institute for Nuclear Science and Technology, Hanoi, Vietnam

[69]Universidad Nacional Autonoma de Mexico, Mexico, D.F., Mexico

[70]Louisiana State University, Baton Rouge, Louisiana, USA

[71]University of Hawaii, Honolulu, Hawaii, USA

[72]Centro Atómico Constituyentes, Comisión Nacional de Energía Atómica and CONICET, Argentina

[73]ASTRON, Dwingeloo, Netherlands

[74]J. Stefan Institute, Ljubljana, Slovenia

[75]Pontifícia Universidade Católica, Rio de Janeiro, RJ, Brazil

[76]University of Łódź, Łódz, Poland

[77]Departamento de Física, Centro Atómico Bariloche, Comisión Nacional de Energía Atómica and CONICET, Argentina

[78]Universidade Federal Fluminense, Instituto de Fisica, Niterói, RJ, Brazil

[79]Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV), México, D.F., Mexico

[80]Institute of Nuclear Physics PAN, Krakow, Poland

[81]Departamento de Física, FCEyN, Universidad de Buenos Aires y CONICET, Argentina

[82]Universidade Estadual de Feira de Santana, Brazil

[83]Kernfysisch Versneller Instituut, University of Groningen, Groningen, Netherlands

[84]Universidade Federal do ABC, Santo André, SP, Brazil

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

[86]Centro Atómico Constituyentes, Comisión Nacional de Energía Atómica and UTN-FRBA, Argentina

[87]Southern University, Baton Rouge, Louisiana, USA

[88]University of Utah, Salt Lake City, Utah, USA

[89]Charles University, Institute of Particle & Nuclear Physics, Prague, Czech Republic

[90]Centro de Investigaciones en Láseres y Aplicaciones, CITEFA and CONICET, Argentina

[91]Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain

[92]Universidade Federal da Bahia, Salvador, BA, Brazil

[93]Dipartimento di Ingegneria dell'Innovazione dell'Università del Salento and Sezione INFN, Lecce, Italy

[94]Università di Genova and Sezione INFN, Genova, Italy

[95]Instituto de Astronomía y Física del Espacio (CONICET), Buenos Aires, Argentina

[96]Colorado School of Mines, Golden, Colorado, USA

[97]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, United Kingdom

[98]University of Nebraska, Lincoln, Nebraska, USA

[99]Argonne National Laboratory, Argonne, Illinois, USA

[100]Universidad Mayor de San Andrés, Bolivia

[101]Departamento de Física, Universidad Nacional de La Plata and Fundación Universidad Tecnológica Nacional, Argentina

The energy spectrum of cosmic rays above 2.5×10^{18} eV, derived from 20 000 events recorded at the Pierre Auger Observatory, is described. The spectral index γ of the particle flux, $J \propto E^{-\gamma}$, at energies between 4×10^{18} eV and 4×10^{19} eV is $2.69 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$, steepening to $4.2 \pm 0.4(\text{stat}) \pm 0.06(\text{syst})$ at higher energies. The hypothesis of a single power law is rejected with a significance greater than 6 standard deviations. The data are consistent with the prediction by Greisen and by Zatsepin and Kuz'min.

We report a measurement of the energy spectrum of cosmic rays showing that the flux is strongly suppressed above 4×10^{19} eV. This is in accord with the 1966 prediction of Greisen [1] and of Zatsepin and Kuz'min [2] (GZK) that the spectrum should steepen around 5×10^{19} eV as cosmic rays from cosmologically distant sources suffer energy losses when propagating through the cosmic microwave radiation. With an exposure twice that of HiRes [3] and 4 times that of AGASA [4], our evidence supports the recent report of the former.

The Pierre Auger Observatory, located near Malargüe (Argentina) at 1400 m a.s.l., is used to measure the properties of extensive air showers (EAS) produced by the highest-energy cosmic rays. At ground level, the electrons, photons, and muons of EAS can be detected using instruments deployed in a large surface array. Additionally, as EAS move through the atmosphere, ultraviolet light is emitted from nitrogen excited by charged particles. This fluorescence light is proportional to the energy deposited by the shower along its path [5]. The Observatory uses 1600 water-Cherenkov detectors, each containing 12 tonnes of water, viewed by three $9''$ photomultipliers, to detect the photons and charged particles. The surface detectors are laid out over 3000 km^2 on a triangular grid of 1.5 km spacing and is overlooked by 4 fluorescence detectors. Each fluorescence detector (FD), located on the perimeter of the area, houses 6 telescopes. EAS detected by both types of detector are hybrid events and play a key role in the analysis. The field of view of each telescope is $30°$ in azimuth, and $1.5° – 30°$ in elevation. Light is focused on a camera containing 440 hexagonal pixels, of 18 cm^2, at the focus of a 11 m^2 mirror. The design and status of the Observatory are described in [6,7]. Between 1 Jan 2004 and 31 Aug 2007, the numbers of telescopes increased from 6 to 24 and of surface detectors from 154 to 1388. The analysis of data from this period is described.

A cosmic ray of 10^{19} eV arriving vertically typically produces signals in 8 surface detectors. Using relative timing, the direction of such an event is reconstructed with an angular accuracy of about $1°$ [8]. Signals are quantified in terms of the response of a surface detector (SD) to a muon travelling vertically and centrally through it (a vertical equivalent muon or VEM). Calibration of each SD is carried out continuously with 2% accuracy [9]. The signals are fitted in each event to find the VEM size at 1000 m, $S(1000)$ [10]. The uncertainty in every $S(1000)$ is found, accounting for statistical fluctuations of the signals, systematic uncertainties in the assumption of the falloff of signal with distance and the shower-to-shower fluctuations [8]. Above 10^{19} eV, the uncertainty in $S(1000)$ is about 10%.

The longitudinal development of EAS in the atmosphere is measured using the fluorescence detectors. The light produced is detected as a line of illuminated pixels in one or more FT cameras. The positions of these pixels and the arrival time of the light determine the shower direction. The signal, after correcting for attenuation due to Rayleigh and aerosol scattering, is proportional to the number of fluorescence photons emitted in the field of view of the pixel. Cherenkov light produced at angles close to the shower axis can be scattered towards the pixels: this contamination is accounted for [11]. A Gaisser-Hillas function [12] is used to reconstruct the shower profile which provides a measurement of the energy of the EAS deposited in the atmosphere. To derive the primary energy, an estimate of the missing energy carried into the ground by muons and neutrinos must be made based on assumptions about the mass of cosmic rays and of the appropriate hadronic model. For a primary beam that is a 50/50 mixture of protons and iron, simulations of showers with the QGSJET01 model indicate a correction of 10% [13]. The systematic uncertainty is 4% [14].

Detailed understanding of the fluorescence emission is needed for accurate energy determination. The absolute fluorescence yield in air at 293 K and 1013 h Pa from the 337 nm band is 5.05 ± 0.71 photons/MeV of energy deposited [15]. The wavelength and pressure dependence of the yield adopted follow [16]. Systematic uncertainties in the FD energy measurement have been estimated. Measurements, made in combination with the fluorescence detectors, are used to measure the quality and transmission properties of the atmosphere. In particular, the vertical aerosol optical depth (VAOD) profile [17] is found every 15 min by observing the light scattered from a centrally located laser of an energy equivalent to a few 10^{19} eV at 355 nm [18] yielding an hourly average. The average correction to E_{FD} from the VAOD measurement is $+5\%$ at 3×10^{18} eV rising to $+18\%$ at 5×10^{19} eV, reflecting the increase of the average distance of such events from an FD. The absolute calibration of the telescopes is measured every few months and is constantly adjusted using relative calibrations [19]. The largest uncertainties are in the absolute fluorescence yield (14%), the absolute calibration of

the telescopes (10%), and the reconstruction method (10%). Systematic uncertainties from atmospheric aerosols, the dependence of the fluorescence spectrum on temperature and on humidity are each at the 5% level [7,20]. These uncertainties are independent and added in quadrature give 22% for E_{FD}.

The fluorescence detectors are operated on clear, moonless nights limiting the duty cycle to 13%. Showers detected by both the surface array and the FD (hybrid events) are more precisely reconstructed than surface array- or FD-only events [7] and are essential to the evaluation of systematic uncertainties. The hybrid events have an angular accuracy that improves from 0.8° at 3×10^{18} eV to 0.5° above 10^{19} eV. The surface array, with its near 100% duty cycle, gives the large sample used here. The comparison of the shower energy, measured using fluorescence, with the $S(1000)$ for a subset of hybrid events is used to calibrate the energy scale for the array.

Only events with zenith angles less than 60° are used here. Candidate showers are selected on the basis of the topology and time compatibility of the triggered detectors [21]. The SD with the highest signal must be enclosed within an active hexagon, in which all six surrounding detectors were operational at the time of the event. Thus, it is guaranteed that the intersection of the axis of the shower with the ground is within the array, and that the shower is sampled sufficiently to make reliable measurements of $S(1000)$ and of the shower axis. From the analysis of hybrid events, using only the fall of the signal size with distance, these criteria result in a combined trigger and reconstruction efficiency greater than 99% for energies above about 3×10^{18} eV; at 2.5×10^{18} eV, it is 90% [22]. The sensitive area has been calculated from the total area of the hexagons active every second.

The decrease of $S(1000)$ with zenith angle arising from the attenuation of the shower and from geometrical effects is quantified by applying the constant integral intensity cut method [23], justified by the approximately isotropic flux of primaries. An energy estimator for each event, independent of θ, is $S_{38°}$, the $S(1000)$ that EAS would have produced had they arrived at the median zenith angle, 38° [24]. Using information from the fluorescence detectors, the energy corresponding to each $S_{38°}$ can be estimated almost entirely from data except for assumptions about the missing energy. The energy calibration is obtained from a subset of high-quality hybrid events, where the geometry of an event is determined from the times recorded at an FD, supplemented by the time at the SD with the highest signal, if it is within 750 m from the shower axis [25,26]. It is also required that a reduced χ^2 is less than 2.5 for the fit of the longitudinal profile and that the depth of shower maximum be within the field of view of the telescopes. The fraction of the signal attributed to Cherenkov light must be less than 50%. Statistical uncertainties in $S_{38°}$ and E_{FD} were assigned to each event:

averaged over the sample, these were 16% and 8%, respectively.

The correlation of $S_{38°}$ with E_{FD} is shown in Fig. 1, together with the least-squares fit of the data to a power-law, $E_{FD} = aS_{38°}^b$. The best fit yields $a = [1.49 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})] \times 10^{17}$ eV and $b = 1.08 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$ with a reduced χ^2 of 1.1. $S_{38°}$ grows approximately linearly with energy. The energy resolution, estimated from the fractional difference between E_{FD} and the derived SD energy, $E = aS_{38°}^b$, is shown inset. The root-mean-square deviation of the distribution is 19%, in good agreement with the quadratic sum of the $S_{38°}$ and E_{FD} statistical uncertainties of 18%. The calibration accuracy at the highest energies is limited by the number of events: the most energetic is $\sim 6 \times 10^{19}$ eV. The calibration at low energies extends below the range of interest.

The energy spectrum based on $\sim 20\,000$ events is shown in Fig. 2. Statistical uncertainties and 84% confidence-level limits are calculated according to [27]. Systematic uncertainties on the energy scale due to the calibration procedure are 7% at 10^{19} eV and 15% at 10^{20} eV, while a 22% systematic uncertainty in the absolute energy scale comes from the FD energy measurement. The possibility of a change in hadronic interactions or in the mean primary mass above 6×10^{19} eV will be addressed with more data. In photon-initiated showers, the value of $S(1000)$ is 2-3 times smaller than for nuclear primaries, so that a large photon flux would change the spectrum. However, a limit to the photon flux of 2% above 10^{19} eV exists [28].

The spectrum is fitted by a smooth transition function with the suppression energy of 4×10^{19} eV defined as that at which the flux falls below an extrapolated power law by 50%. To examine the spectral shape at the highest energies,
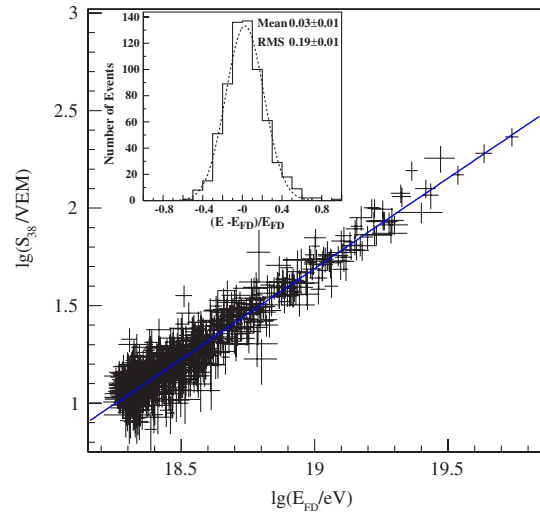

FIG. 1 (color online). Correlation between $\lg S_{38°}$ and $\lg E_{FD}$ for the 661 hybrid events used in the fit. The full line is the best fit to the data. The fractional differences between the two energy estimators are inset.
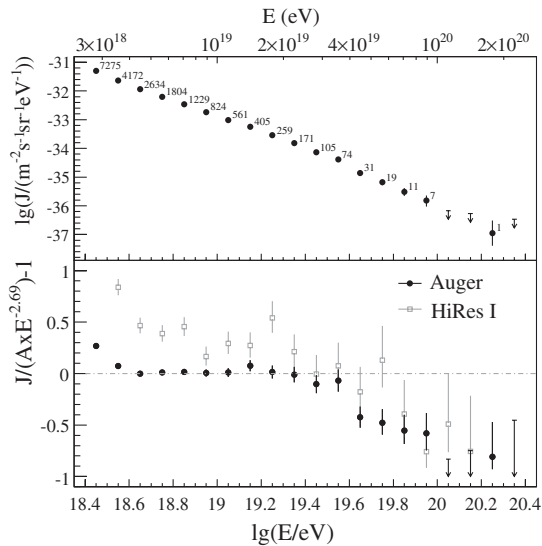
FIG. 2.   Upper panel: The differential flux *J* as a function of energy, with statistical uncertainties. Data are listed at [32]. Lower Panel: The fractional differences between Auger and HiRes I data [3] compared with a spectrum with an index of 2.69.

we fit a power-law function between 4×10^{18} eV and 4×10^{19} eV, $J \propto E^{-\gamma}$, using a binned likelihood method [29]. A power law is a good parameterization: the spectral index obtained is 2.69 ± 0.02(stat) ± 0.06(syst) (reduced $\chi^2 = 1.2$), the systematic uncertainty coming from the calibration curve. The numbers expected if this power law were to hold above 4×10^{19} eV or 10^{20} eV, would be 167 ± 3 and 35 ± 1 while 69 events and 1 event are observed. The spectral index above 4×10^{19} eV is 4.2 ± 0.4(stat) ± 0.06(syst). A method which is independent of the slope of the energy spectrum is used to reject a single power-law hypothesis above 4×10^{18} eV with a significance of more than 6 standard deviations [29], a conclusion independent of the systematic uncertainties currently associated with the energy scale.

In Fig. 2, the fractional differences with respect to an assumed flux $\propto E^{-2.69}$ are shown. HiRes I data [3] show a softer spectrum where our index is 2.69 while the position of suppression agrees within the quoted systematic uncertainties. The AGASA data are not displayed as they are being revised [30]. The change of spectral index indicated below 4×10^{18} eV will be discussed elsewhere.

To summarize, we reject the hypothesis that the cosmic-ray spectrum continues with a constant slope above 4×10^{19} eV, with a significance of 6 standard deviations. In a previous paper [31], we reported that sources of cosmic rays above 5.7×10^{19} eV are extragalactic and lie within 75 Mpc. Taken together, the results suggest that the GZK prediction of spectral steepening may have been verified. A full identification of the reasons for the suppression will come from knowledge of the mass spectrum in the highest-energy region and from reductions of the systematic un-certainties in the energy scale which will allow the derivation of a deconvolved spectrum.

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