Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments

Dennis Soldin\textsuperscript{a,*} for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array Collaborations
(a complete list of authors can be found at the end of the proceedings)

\textsuperscript{a}Bartol Research Institute, Dept. of Physics and Astronomy
University of Delaware, Newark, DE 19716, USA
E-mail: soldin@udel.edu

Over the last two decades, various experiments have measured muon densities in extensive air showers over several orders of magnitude in primary energy. While some experiments observed differences in the muon densities between simulated and experimentally measured air showers, others reported no discrepancies.

We will present an update of the meta-analysis of muon measurements from nine air shower experiments, covering shower energies between a few PeV and tens of EeV and muon threshold energies from a few 100MeV to about 10GeV. In order to compare measurements from different experiments, their energy scale was cross-calibrated and the experimental data has been compared using a universal reference scale based on air shower simulations. Above 10PeV, we find a muon excess with respect to simulations for all hadronic interaction models, which is increasing with shower energy. For EPOS-LHC and QGSJet-II.04 the significance of the slope of the increase is analyzed in detail under different assumptions of the individual experimental uncertainties.
1. Introduction

Cosmic rays enter the Earth’s atmosphere where they produce Extensive Air Showers (EAS) which can be measured at the ground. Although the energy spectrum of cosmic rays has been measured with high precision over many orders of magnitude, the sources of cosmic rays are still unknown, their acceleration mechanism and mass composition are uncertain, and several features observed in the energy spectrum are not well understood [1, 2].

The main challenge lies in the measurements of the muon content in air showers, which have been performed by many experiments over the last 20 years. Various experiments reported discrepancies in the number of muons in simulated and observed air showers, such as the HiRes-MIA [3] and NEVOD-DECOR [4, 5] collaborations, as well as the Pierre Auger Observatory [6, 7] (Auger), Telescope Array [8] (TA), and SUGAR [9]. In contrast, no discrepancies in the average muon densities were observed by EAS-MSU [10], the Yakutsk EAS array [11], and KASCADE-Grande [12]. KASCADE-Grande, however, reported differences in the muon number evolution with the zenith angle with respect to model predictions.

In this article, we present an update of the meta-analysis of global measurements of the lateral muon density by multiple EAS experiments which was previously reported in Refs. [13, 14]. This update includes new data from Auger [15] and its Underground Muon Detectors [16] (UMD), and from the IceCube Neutrino Observatory [17] (IceCube). In addition, data from the AGASA experiment [18] is included for the first time and systematic studies of the energy-dependent trend of the muon discrepancies are discussed in detail. An overview of further measurements of the muon content in EAS is beyond the scope of this work and can be found in Refs. [13, 19].

2. Measurements of the Muon Lateral Density

The lateral density of muons measured at the ground depends on various parameters: cosmic-ray energy, \( E \), zenith angle, \( \theta \), shower age (vertical depth, \( X \), and zenith angle), lateral distance, \( r \), from the shower axis, and energy threshold, \( E_{\mu,\text{min}} \), of the muon detectors. The parameter space covered by the experiments considered in this meta-analysis is shown in Fig. 1. Due to different experimental conditions and analysis techniques, a direct comparison of the muon measurements is not possible. Instead, to compare different results in a meaningful way, the measurements of each

![Figure 1: Phase space of EAS experiments which have reported measurements of the muon density. Points and lines indicate a measurement in a narrow bin of the parameter, while boxes indicate integration over a parameter range. Figure (a) shows the muon energy thresholds, \( E_{\mu,\text{min}} \), (b) the zenith angle range, \( \theta \), and (c) the lateral distances, \( r \), of the muon density measurements, as a function of the EAS energy, \( E \).](image-url)
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Figure 2: Muon density measurements converted to the z-scale, as defined in Eq. (1), for different hadronic interaction models. When corresponding simulations are missing for an experiment, no points can be shown. Error bars show statistical and systematic uncertainties added in quadrature.

Experiment have to be compared to EAS simulations in the same observation conditions in terms of a data/MC ratio. Therefore, the measurements of the muon density from different experiments are converted to the z-scale,

$$z = \frac{\ln \langle N^{\text{det}}_{\mu} \rangle - \ln \langle N^{\text{det}}_{\mu,p} \rangle}{\ln \langle N^{\text{det}}_{\mu,Fe} \rangle - \ln \langle N^{\text{det}}_{\mu,p} \rangle}$$

(1)

where $\langle N^{\text{det}}_{\mu} \rangle$ is the average muon density estimate as seen in the detector, while $\langle N^{\text{det}}_{\mu,p} \rangle$ and $\langle N^{\text{det}}_{\mu,Fe} \rangle$ are the simulated average muon densities for proton and iron showers after a full detector simulation.

The z-scale is constructed such that an observation of the muon density of $z = 0$ is consistent with a simulated proton shower and $z = 1$ for a simulated iron shower. A dedicated discussion on the properties and calculation of the z-scale and its uncertainties can be found in Ref. [18].

The z-values obtained by nine air shower experiments [4–12, 15–18] are shown in Fig. 2. Depending on the experiment, the distributions are given for the post-LHC hadronic interaction models EPOS-LHC [20], QGSJet-II.04 [21], and Sibyll 2.3(d) [22, 23], and for the pre-LHC models QGSJet01 and QGSJet-II.03 [24], and Sibyll 2.1 [25]. For all models the data lies between the expectations for proton and iron showers up to energies of about $10^{17}$ eV. However, at higher energies all data except Yakutsk suggest an unphysical mass composition heavier than iron.

2.1 Energy Scale Offsets and Cross-Calibration

According to the Matthews-Heitler model [26] the number of muons in EAS, $N_{\mu}$, depends on the energy, $E$, and mass, $A$, of the initial cosmic ray as

$$N_{\mu} = A^{1-\beta} \cdot \left(\frac{E}{\xi_C}\right)^{\beta},$$

(2)

with power-law index $\beta \approx 0.9$ and energy constant, $\xi_C$. This causes two experiments with an energy-scale offset of 20%, for example, to have an 18% offset in the data/MC ratios because measurements are compared to EAS simulated at different apparent energies. To compare muon measurements between experiments, energy-scale offsets therefore need to be taken into account.
Assuming that the cosmic ray flux is a universal reference and that all deviations in measured fluxes between different experiments arise from energy scale offsets, a relative scale $E_{\text{data}}/E_{\text{ref}}$ can be determined for each experiment such that the all-particle fluxes match [27]. The relative energy-scale shift between Auger and TA has been found to be 10.4% [28] and the reference energy scale, $E_{\text{ref}}$, used in this work is placed between the two experiments, as shown in Fig. 3. The scaling factors for the other experiments are obtained from the Global Spline Fit (GSF) flux model [27] which also uses cross-calibration internally, with a reference energy scale $E_{\text{ref, GSF}}/E_{\text{ref}} = 0.948/0.880 = 1.08$. Using the adjustment factors from Fig. 3, the $z$-values are energy cross-calibrated as described in detail in Ref. [13] and the individual uncertainties of each experiment are adjusted by removing the contribution from the energy-scale. However, the reference energy-scale, after cross-calibration, has a remaining uncertainty of at least 10%, causing potential shifts of the $z$-values by about ±0.25. No cross-calibration factor can be given for KASCADE-Grande because the cosmic ray flux is computed using a different energy estimator to which this method can not be applied [13]. For EAS-MSU, no all-particle flux is available for cross-calibration.

The resulting $z$-values, after applying the energy-scale cross-calibration, are shown in Fig. 4, where a remarkably consistent picture is obtained. The measurements are in agreement with simulations based on the post-LHC hadronic interaction models, EPOS-LHC and QGSJetII.04, up to about a few $10^{16}$ eV, within the expectation from measurements of the maximum shower depth, $X_{\text{max}}$, and uncertainties. However, at higher energies, an increasing muon excess with respect to simulations is observed for all models, suggesting a mass composition heavier than iron.
2.2 Energy-Dependent Trend

In order to systematically quantify the energy-dependent trend observed in the muon measurements shown in Fig. 4, the mass composition dependence expected from Eq. (2) needs to be taken into account. If the measured \( z \)-values follow \( z_{\text{mass}} \) as expected from \( X_{\text{max}} \) measurements, the model describes the muon density at the ground consistently. Subtracting \( z_{\text{mass}} \) is thus expected to remove the effect of the changing mass composition. The resulting \( \Delta z = z - z_{\text{mass}} \) distributions are shown in Fig. 5 for EPOS-LHC and QGSJet-II.04 with \( z_{\text{mass}} \) determined from the GSF flux model [27]. A simple linear function of the form

\[
\Delta z_{\text{fit}} = a + b \cdot \log_{10}(E/10^{16}\text{eV})
\]  

(3)

is fit to the data, where \( a \) and \( b \) are free parameters. To account for (the unknown) correlated uncertainties in the experimental data, the least-squares method described in Ref. [13] is used. It assumes a correlation factor, \( \alpha \), between data points belonging to the same data set. The fit is repeated for values of \( \alpha \) between 0 and 0.95. To adjust for over/under-estimated uncertainties, the raw result, \( \sigma_{b_{\text{raw}}} \), is re-scaled with the \( \chi^2 \) value and the degrees of freedom, \( n_{\text{dof}} \), of the fit as

\[
\sigma_b = \sigma_{b_{\text{raw}}} \cdot \sqrt{\chi^2 / n_{\text{dof}}},
\]

as described in Ref. [13]. For EPOS-LHC, the resulting slope ranges from...
$b = 0.23 \pm 0.03$ up to $b = 0.29 \pm 0.03$ for $\alpha = 0.95$ and $\alpha = 0.0$, respectively. For QGSJet-II.04, it ranges from $b = 0.22 \pm 0.02$ up to $b = 0.25 \pm 0.03$ for $\alpha = 0.95$ and $\alpha = 0.0$. The significances of the deviations from $b = 0.0$ are around $8\sigma$ for EPOS-LHC and above $10\sigma$ for QGSJet-II.04.

To study the influence of the underlying mass assumption, the fits in $\Delta z = z - z_{\text{mass}}$ are repeated with $z_{\text{mass}}$ obtained from the GST [29] and H4a [30] flux models which are also based on fits to experimental data. The resulting significances for correlations between 0.0 and 0.95 are shown in Fig. 6. While the significances based on the H4a model increase, the GST model always yields smaller significances. However, as shown in Fig. 4, the GST model predicts a heavier cosmic ray mass composition which is in strong tension with measurements of $X_{\text{max}}$ over the vast majority of the energy range considered here. This confirms the choice of the GSF model which shows the best overall agreement with optical measurements of the mass composition. In addition, the effect of the choice of the reference energy scale, $E_{\text{ref}}$ in Fig. 3, was also studied and found to be negligible.

### 2.3 N-1 Tests

To study the contribution from each individual experiment to the significances of the fit slopes to the combined data, systematic $N-1$ tests are performed where data from one experiment at a time is excluded from the fit. The resulting fits for EPOS-LHC are shown in Fig. 7 and the corresponding significances for the models EPOS-LHC and QGSJet-II.04 are depicted in Fig. 8 for systematic correlations $\alpha$ between 0.0 and 0.95. The significances of the fit slopes remain above $5\sigma$ when excluding most experiments. However, lower significances can be observed for EPOS-LHC, for extreme correlations, when removing data from IceCube, and to some extent when removing data from SUGAR. In contrast, excluding the measurements by Yakutsk causes an increase of the significances, in particular towards very small correlations. This indicates that measurements from Yakutsk, which are in strong tension with other data in the same energy region, have a stronger influence on the fit result if data from IceCube is removed. These effects are more pronounced for EPOS-LHC compared to QGSJet-II.04. This is due to a smaller scatter of the data for QGSJet-II.04, which causes smaller uncertainties in the slope, $b$, of the fit through the $\chi^2/n_{\text{dof}}$ re-scaling.
3. Conclusions

An update of the meta-analysis of muon measurements in EAS with energies from PeV up to tens of EeV was presented and a remarkably consistent picture is obtained after cross-calibrating the energy scales of the different experiments. The measurements agree with simulations based on the models EPOS-LHC and QGSJet-II.04, within uncertainties, up to energies of a few $10^{16}$ eV, assuming the GSF flux model. At higher energies, an increasing excess with respect to model predictions is observed. The slope of this increase is between $b = 0.23$ and $b = 0.29$ for EPOS-LHC and between $b = 0.22$ and $b = 0.25$ for QGSJet-II.04, with a significance of the deviations from $b = 0.0$ of around 8σ and 10σ, respectively. A small change of the fits compared to the previous meta-analysis [13, 14] is observed which arises mainly from the updates of the experimental data. Studies of other dependencies, for example the minimum energy of muons at production for each experiment, as described in Ref. [14], have yet been inconclusive due to the limited experimental data. It has been shown that the mass composition model is important for the mass subtraction in $\Delta z = z - z_{mass}$ and should be derived from optical measurements with the least amount of assumptions. The GSF model satisfies this requirement at a certain level, however, the possibility to use data from $X_{\text{max}}$ measurements directly is currently under investigation.

When removing individual data from this meta-analysis, for extreme assumptions of the correlation of uncertainties, the significances for a non-zero slope can decrease to approximately 3σ for EPOS-LHC and around 5σ for QGSJet-II.04. This decrease is mainly due to the data from Yakutsk, which becomes more important when data from IceCube (or to some extent SUGAR) are removed and is in strong tension with other muon measurements. To understand these tensions, further studies of the treatment of systematic uncertainties and relative biases of the individual experiments are necessary. Moreover, additional measurements with high precision are needed, in particular at energies above $10^{17}$ eV. Ongoing EAS detector upgrades and improved analysis methods are expected to reduce the uncertainties of the experimental results and increase the parameter space. This will improve the data accuracy and help to investigate other dependencies of the deviations between simulations and data in future extensions of this meta-analysis.
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Full Author List:

EAS-MSU Collaboration:

Yu. A. Fomin, N. N. Kalmykov, I. S. Karpikov, G. V. Kulikov, M. Yu. Kuznetsov1, G. I. Rubitsov, V. P. Sulakov, V. S. Troitsky2

1 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow 119991, Russia
2 Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
3 Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium

IceCube Collaboration:

R. Abbasi, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahsler, M. Ahrens, A. Alispa, A. A. Alves Jr., N. M. Amin, R. An, K. Andeen, T. Anderson, G. Anton, J. Argüelles, Y. Ashida, S. Axani, X. Bai, B. Alagopalam, V. A. Barbano, S. W. Barwick, B. Bastian, V. Basu, S. Baur, R. Bay, J. J. Beatty, K. -H. Becker, J. Becker Tjus, C. Bellenghi, S. BenZvi, D. Berley, E. Bernardini, D. Z. Besson, G. B. Biely, D. Bindig, E. Blaufuss, S. Blot, M. Boddenberg, F. Bontempi, J. Borowka, S. Bösér, O. Botner, J. Böttcher, E. Bourbeau, F. Bradascio, J. Braun, S. Brons, J. Brosten-Kaiser, S. Browne, A. Burgmann, R. T. Burley, R. S. Busse, M. A. Campana, E. G. Carne-Bronca, C. Chen, D. Chirkin, K. Choi, B. A. Clark, K. Clark, L. Claessens, A. Coleman, G. H. Collini, J. M. Conrad, P. Coppia, P. Correia, D. F. Cowen, R. Cross, C. Dappen, P. Dave, S. De Clercq, J. J. DeLaunay, H. Dembinski, D. Deosarkar, S. De Ridder, A. Desai, P. Desiati, K. D. de Vries, G. de Wasseige, M. de With, T. DeYoung, S. Dharani, A. Diaz, J. C. Díaz-Vélez, D. Dittmer, H. DuJovin, M. Dunkman, M. A. DuVernois, E. Dvorak, T. Elhardt, P. Elmer, R. Engel, M. -S. Eppenbeck, J. Evans, P. A. Evenson, K. L. Fani, A. R. Fazely, S. Fiedlschuster, A. T. Fienberg, K. Filimonov, C. Finley, L. Fischer, D. Fox, A. Franczak, E. Friedmann, A. Fritz, P. Fürst, T. K. Gaisser, J. Gallagher, E. Garster, A. Garcia, S. Garrappa, I. Gerhardt, A. Ghadimi, C. Glaser, T. Glauch, T. Glüsenkamp, A. Goldschmidt, J. G. Gonzalez, S. Goswami, D. Gram, T. Grégoire, S. Griswold, M. Gvendula, N. Gunther, C. Haack, A. Hallgren, R. Halliday, H. Halve, F. Halzen, M. Ha Mink, K. Hanson, J. Hardin, A. A. Harnisch, A. Haungs, S. Hauser, D. Hebecker, K. Helbing, F. Henningsen, E. C. Hettigter, S. Hickford, J. Hignight, C. Hill, C. G. Hill, K. D. Hoffmann, R. Hoffmann, T. Hooka, B. Hokanson-Fasig, K. Hoshiba, F. Huang, M. Huber, T. Huber, K. Hultqvist, M. Hünnefeld, J. K. Hussain, S. In, N. Iovine, A. Ishihara, M. Jansson, G. S. Japaridze, M. Jeong, B. P. Jones, D. Kang, M. Wang, L. Kang, A. Kappes, D. Kappesser, T. Kang, M. Karli, A. Karle, U. Kats, M. Kauer, M. Kellermann, J. L. Kelley, A. Kheirandish, K. Kni, T. Kintschel, J. Kiyuk, S. R. Klein, R. Koirala, H. Kolanoski, J. Kontrimas, L. Köpke, C. Kopper, S. Kopper, D. J. Kossikin, P. Koundal, M. Kovacevich, M. Kowalski, O. 59, T. Kozynets, E. Kuni, N. Kurahashi, N. Lad, C. Lagunas Guada, J. L. Lanfranchi, M. J. Larson, F. Lauber, J. P. Lazar, J. W. Lee, K. Leonard, A. Leszczyńska, Y. Li, M. Lucitelli, Q. R. Liu, M. Liubarska, E. Lohfink, C. J. Lozano Martiscu, L. Lu, F. Lucarelli, A. Ludvig, T. W. Luszczak, Y. Lyu, K. M. L. Ma, J. M. Maden, B. K. M. Maun, Y. Makino, S. Mancina, I. C. Marsili, R. Maruyama, K. Mase, T. McElroy, F. McNally, Y. V. Mead, K. Meagher, A. Medinas, M. Meier, M. Meienberger, J. Micalefer, D. Mockler, T. Montarras, R. W. Moore, R. More, M. Moula, R. Naab, R. Nagai, U. Naumann, J. Neckar, L. V. Nguyen, M. H. Niederhausen, M. U. Nisa, S. C. Nowicki, D. R. Nygren, A. Obertacke Pollmann, M. Oehler, A. O. Olivas, E. O’Sullivan, H. Pandya, D. V. Pankova, N. Park, G. K. Parker, E. N. Paulet, L. Paul, C. Pérez de los Heros, L. Peters, L. J. Petersen, S. Philbin, P. Di Pietro, S. Pieper, M. Pittermann, A. Pizzuto, M. Plum, Y. Popovych, A. Porcelli, M. Prado Rodriguez, P. B. Price, B. Pries, G. T. Przybylski, C. Raar, A. Raissi, M. Ramirez, K. Ramesh, C. Raines, I. R. Real, J. Rehman, P. Reichert, M. -R. Reimann, G. Renzi, E. Resconi, S. Reusch, W. Rhode, M. Richman, B. Riedel, J. O. Roberts, S. Robertson, G. Roe, R. Roehlinghoff, M. Rongen, C. Rot, R. T., T. Ruoho, D. Ryckbosch, D. Rybyszew Canto, J. I. Safa, J. Saffer, E. S. Sanchez Herrera, A. Sandrock, J. Sandros, M. Santander, S. Sarkar, S. Sarkar, K. Satalecka, M. Scharf, M. Schaeufele, D. Schlenker, T. Schmidt, A. Schneider, J. Schneider, F. G. Schröder, J. -S. Schumacher, G. Scheufer, S. Sclafani, D. Seckel, D. Seckel, J. Seidenmanna, A. Sharma, A. Shefi, M. Silva, B. Skrzypek, B. Smithers, R. Smit, J. Soedingekos, D. Soldan, C. Späffele, M. G. Spiczak, C. Spiering, J. Stachurska, M. Stamatikos, T. Stanoe, R. Stein, J. Stettner, A. Steuernagel, T. Stiebel, S. Stierwalt, S. Stuttard, G. W. Sullivan, I. Taboada, F. Tenholt, S. T. Antonyan, S. Tilav, F. Tischbein, K. Tolfort, L. Tomankova, C. Tomnins, S. Toscano, D. Tosi, A. Trettin, M. Tsengidogio, C. F. Tung, A. Turcati, R. Turcotte, C. F. Turley, E. P. Wagner, B. Ty, M. A. Unland Erolleria, N. Valtonen-Mattila, J. Vandenbroucke, N. van Eijndhoven, D. Vannevar, J. van Santen, S. Verpoest, M. Vraeghe, C. Walck, B. P. Watson, C. Weaver, P. Weigel, A. Weindl, M. J. Weiss, J. Weldert, C. Wendt, J. Werthebach, M. Weyrauch, N. Whitehorn, D. R. Williams, M. Wolf, K. Woschnagg, G. Wrede, J. Wulff, X. W. Xu, X. Xu, J. P. Yanecz, S. Yoshida, S. Yu, T. Yuan, Z. Zhang

1 III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
2 Department of Physics, University of Adelaide, Adelaide, 5005, Australia
3 Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK 99508, USA
4 Dept. of Physics, University of Texas at Arlington, 502 Yates St., Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA
5 CTPS, Clark-Atlantic University, Atlanta, GA 30314, USA
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Dennis Soldin

6 School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
7 Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
8 Dept. of Physics, University of California, Berkeley, CA 94720, USA
9 Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
10 Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
11 Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
12 Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
13 Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
14 Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
15 Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
16 Dept. of Physics and Institute for Global Prominent Research, Chiba University, Chiba 263-8522, Japan
17 Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA
18 Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
19 Dept. of Physics, University of Maryland, College Park, MD 20742, USA
20 Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
21 Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
22 Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
23 Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
24 Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
25 Dept. of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
26 Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
27 Physik-department, Technische Universität München, D-85748 Garching, Germany
28 Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
29 Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
30 Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
31 Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
32 Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
33 Dept. of Physics, Engineering Physics, and Astronomy, Queen’s University, Kingston, ON K7L 3N6, Canada
34 Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
35 Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095, USA
36 Department of Physics, Mercer University, Macon, GA 31207-0001, USA
37 Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA
38 Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA
39 Institute of Physics, University of Mainz, Oskar-von-Möllendorff-Platz 1, D-55099 Mainz, Germany
40 Department of Physics, Marquette University, Milwaukee, WI, 53201, USA
41 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
42 Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
43 Dept. of Physics, Yale University, New Haven, CT 06520, USA
44 Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
45 Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
46 Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
47 Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
48 Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
49 Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
50 Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
51 Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
52 Dept. of Physics, Sungkyunkwan University, Suwon 16419, Korea
53 Institute of Basic Science, Sungkyunkwan University, Suwon 16419, Korea
54 Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
55 Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
56 Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
57 Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden
58 Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
59 DESY, D-15738 Zeuthen, Germany
60 Università di Padova, I-35131 Padova, Italy
61 National Research Nuclear University, Moscow Engineering Physics Institute (MEPhI), Moscow 115409, Russia
62 Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

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USA – U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U.S. Na-
Update on the Combined Analysis of Muon Measurements

Dennis Soldin

KASCADE-Grande Collaboration:

W. D. Apel$^1$, I. C. Arteaga-Veláquez$^2$, K. Bekk$^1$, M. Bertain$^3$, J. Blümer$^{1,4}$, H. Bozdog$^1$, E. Canton$^{1,5}$, A. Chiavassa$^1$, F. Cossavella$^1$, K. Daumiller$^1$, V. de Souza$^1$, F. Di Pierro$^1$, P. Doll$^1$, R. Engel$^{1,4}$, D. Fuhrmann$^8$, A. Gherghel-Lascu$^5$, H. J. Gils$^1$, R. Glasstetter$^8$, C. Grupen$^5$, A. Haungs$^1$, J. R. Hörandel$^{10}$, T. Hgue$^1$, K.-H. Kampert$^5$, D. Kang$^1$, H. O. Klages$^1$, K. Link$^1$, P. Łuczak$^{11}$, H. J. Mathes$^1$, H. J. Mayer$^1$, J. Milke$^1$, C. Morello$^8$, J. Oechslin$^1$, S. Ostapchenko$^{12}$, T. Pierog$^1$, H. Rebel$^1$, D. Rivera-Rangel$^2$, M. Roth$^1$, H. Schieler$^1$, S. Schoo$^{11}$, F. G. Schröder$^1$, O. Sima$^{13}$, G. Tomass$^{13}$, G. C. Trinchero$^1$, H. Ulrich$^1$, A. Weindl$^1$, J. Woehle$^1$, J. Zabierowski$^{13}$

1 Karlsruhe Institute of Technology, Institute for Astroparticle Physics, Karlsruhe, Germany
2 Universidad Michoacana, Inst. Fisica y Matematicas, Morelia, Mexico
3 Dipartimento di Fisica, Università degli Studi di Torino, Italy
4 Institut für Experimentelle Teilchenphysik KIT - Karlsruhe Institute of Technology, Germany
5 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
6 Osservatorio Astrofisico di Torino, INAF Torino, Italy
7 Universidade São Paulo, Instituto de Física de São Carlos, Brasil
8 Fachbereich Physik, Universität Wuppertal, Germany
9 Department of Physics, Siegen University, Germany
10 Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
11 National Centre for Nuclear Research, Department of Astrophysics, Lodz, Poland
12 Frankfurt Institute for Advanced Studies (FIAS), Frankfurt am Main, Germany
13 Department of Physics, University of Bucharest, Bucharest, Romania

NEVDOD-DECOR Collaboration:

N. S. Barbashina$^1$, A. G. Bogdanov$^1$, S. S. Kholkov$^1$, V. V. Kindin$^1$, R. P. Kokoulin$^1$, K. G. Kompaniets$^1$, G. Mannocchi$^2$, A. A. Petrukhin$^1$, V. V. Shutenko$^1$, G. Trinchero$^3$, I. I. Yashin$^1$, E. A. Yurina$^1$, E. A. Zadeba$^1$

1 National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
2 Osservatorio Astrofisico di Torino – INAF, Torino, Italy

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Pierre Auger Collaboration:

P. Abreu$^{42}$, M. Aglietta$^{54, 52}$, J. M. Albur$^3$, I. Allekotte$^1$, A. Almeida$^{5, 12}$, J. Alvarez-Muñiz$^{79}$, R. Alves Batista$^{80}$, G. A. Anastass$^{63, 52}$, L. Anchordoqui$^{17}$, B. Andrad$^4$, S. Andringa$^{12}$, C. Aramo$^{50}$, P. R. Araújo Ferreira$^{32}$, J. C. Arteaga Velázquez$^{67}$, H. Asorey$^9$, P. Assis$^{72}$, G. Avila$^{121}$, A. M. Badescu$^{71}$, A. Bakalova$^{32}$, A. Balaceanu$^{32}$, F. Barbato$^{45, 46}$, R. J. Barreiro Luiz$^{72}$, K. H. Becker$^{18}$, J. A. Bellido$^{13, 69}$, C. Beral$^{36}$, M. E. Bertain$^{63, 52}$, X. Bertou$^{1}$, P. L. Biermann$^{32}$, V. Binet$^{42}$, K. Bismarck$^{39, 8}$, T. Bister$^{32}$, J. Biteau$^{37}$, J. Blazek$^{32}$, C. Bleve$^{46}$, M. Boháčová$^{20}$, D. Boncioli$^{121}$, C. Bonfazi$^{44}$, L. Bonneau Arbeletche$^{21}$, N. Bordoloi$^{70}$, A. M. Botti$^{3}$, J. Brack$^{4}$, T. Bretz$^{42}$, D. Briggs$^{32}$, S. A. Britsch$^{41}$, F. L. Briere$^{42}$, P. Buchholz$^{40}$, A. Bueno$^{79}$, S. Buitink$^{15}$, M. Buscemi$^{37}$, M. Büsken$^{59, 8}$, K. S. Caballero-Mora$^{8}$, L. Caccianiga$^{59, 49}$, F. Canfora$^{30, 8}$, I. Caracas$^{38}$, J. M. Carceller$^{78}$, R. Caruso$^{58, 87}$, A. Castellana$^{54, 52}$, F. Cataldi$^{19}$,
Update on the Combined Analysis of Muon Measurements

DennisSoldin
Update on the Combined Analysis of Muon Measurements

Dennis Soldin

19 Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
20 Universidade de São Paulo, Instituto de Física de São Carlos, São Carlos, SP, Brazil
21 Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
22 Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
23 Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
24 Universidade Federal do ABC, Santo André, SP, Brazil
25 Universidade Federal do Paraná, Setor Palotina, Palotina, Brazil
26 Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
27 Universidade Federal do Rio de Janeiro (UFRJ), Observatório do Valongo, Rio de Janeiro, RJ, Brazil
28 Universidade Federal Fluminense, EEMVR, Volta Redonda, RJ, Brazil
29 Universidad de Medellín, Medellín, Colombia
30 Universidade Industrial de Santander, Bucaramanga, Colombia
31 Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
32 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
33 Palacky University, RCPTM, Olomouc, Czech Republic
34 CNRS/IN2P3, IJCLab, Université Paris-Saclay, Orsay, France
35 Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, Université de Paris, CNRS-IN2P3, Paris, France
36 Univ. Grenoble Alpes, CNRS, Grenoble Institute of Engineering Univ. Grenoble Alpes, LPSC-IN2P3, 38000 Grenoble, France
37 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
38 Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
39 Karlsruhe Institute of Technology (KIT), Institute for Experimental Particle Physics, Karlsruhe, Germany
40 Karlsruhe Institute of Technology (KIT), Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany
41 Karlsruhe Institute of Technology (KIT), Institute for Astroparticle Physics, Karlsruhe, Germany
42 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
43 Universität Hamburg, II. Institut für Theoretische Physik, Hamburg, Germany
44 Universität Siegen, Department Physik – Experimentelle Teilchenphysik, Siegen, Germany
45 Gran Sasso Science Institute, L'Aquila, Italy
46 INFN Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy
47 INFN, Sezione di Catania, Catania, Italy
48 INFN, Sezione di Lecce, Lecce, Italy
49 INFN, Sezione di Milano, Milano, Italy
50 INFN, Sezione di Napoli, Napoli, Italy
51 INFN, Sezione di Roma “Tor Vergata”, Roma, Italy
52 INFN, Sezione di Torino, Torino, Italy
53 Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
54 Osservatorio Astrofisico di Torino (INAF), Torino, Italy
55 Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy
56 Università del Salento, Dipartimento di Matematica e Fisica “E. De Giorgi”, Lecce, Italy
57 Università dell’Aquila, Dipartimento di Scienze Fisiche e Chimiche, L’Aquila, Italy
58 Università di Catania, Dipartimento di Fisica e Astronomia, Catania, Italy
59 Università di Milano, Dipartimento di Fisica, Milano, Italy
60 Università di Napoli “Federico II”, Dipartimento di Fisica “Ettore Pancini”, Napoli, Italy
61 Università di Palermo, Dipartimento di Fisica e Chimica “E. Segrè”, Palermo, Italy
62 Università di Roma “Tor Vergata”, Dipartimento di Fisica, Roma, Italy
63 Università Torino, Dipartimento di Fisica, Torino, Italy
64 Benemérita Universidad Autónoma de Puebla, Puebla, México
65 Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas del Instituto Politécnico Nacional (UPIITA-IPN), México, D.F., México
66 Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México
67 Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
68 Universidad Nacional Autónoma de México, México, D.F., México
69 Universidad Nacional de San Agustín de Arequipa, Facultad de Ciencias Naturales y Formales, Arequipa, Peru
70 Institute of Nuclear Physics PAN, Krakow, Poland
71 University of Łódź, Faculty of High-Energy Astrophysics, Łódź, Poland
72 Laboratório de Instrumentação e Física Experimental de Partículas – LIP and Instituto Superior Técnico – IST, Universidade de Lisboa – UL, Lisboa, Portugal
73 “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
74 Institute of Space Science, Bucharest-Magurele, Romania
75 University of Bucharest, Bucharest, Romania
76 Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
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SUGAR Collaboration:

N. N. Kalmeykov\textsuperscript{1}, I. S. Karpinkov\textsuperscript{2}, G. I. Rubtsov\textsuperscript{3}, S. V. Troitsky\textsuperscript{3}, J. Ulrichs\textsuperscript{3}

\textsuperscript{1} D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow 119991, Russia
\textsuperscript{2} Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
\textsuperscript{3} jusyd19@gmail.com

Telescope Array Collaboration:

R. U. Abbasi\textsuperscript{1}, M. Abe\textsuperscript{2}, T. Abu-Zayyad\textsuperscript{1,3}, M. Allen\textsuperscript{3}, Y. Ara\textsuperscript{4}, E. Barcikowski\textsuperscript{3}, J. W. Belz\textsuperscript{2}, D. R. Bergman\textsuperscript{3}, S. A. Blake\textsuperscript{3}, I. Buckland\textsuperscript{3}, R. Cady\textsuperscript{2}, B. G. Cheon\textsuperscript{2}, J. Chiba\textsuperscript{2}, M. Chikawa\textsuperscript{7}, T. Fujii\textsuperscript{2}, K. Fujisue\textsuperscript{2}, K. Fujita\textsuperscript{2}, R. Fujiwara\textsuperscript{1}, M. Fukushima\textsuperscript{2,9}, R. Fukushina\textsuperscript{8}, G. Furitch\textsuperscript{3}, R. Gonzalez\textsuperscript{3}, W. Hanlon\textsuperscript{3}, M. Hayashi\textsuperscript{10}, N. Hayashida\textsuperscript{11}, K. Hibino\textsuperscript{11}, R. Higuchi\textsuperscript{2}, K. Honda\textsuperscript{12}, D. Ikeda\textsuperscript{11}, T. Inadomi\textsuperscript{13}, N. Inoue\textsuperscript{2}, T. Ishii\textsuperscript{11}, H. Ito\textsuperscript{14}, D. Ivanov\textsuperscript{3}, H. Iwakura\textsuperscript{13}, H. M. Jeong\textsuperscript{15}, S. Jeong\textsuperscript{13}, C. C. H. Jui\textsuperscript{3}, K. Kadota\textsuperscript{16}, F. Kakimoto\textsuperscript{11}, O. Kalashin\textsuperscript{17}, K. Kasahara\textsuperscript{18}, S. Kasami\textsuperscript{19}, H. Kawai\textsuperscript{20}, S. Kawakami\textsuperscript{1}, S. Kawana\textsuperscript{2}, K. Kawata\textsuperscript{2}, E. Kido\textsuperscript{13}, H. B. Kim\textsuperscript{3}, J. H. Kim\textsuperscript{3}, M. H. Kim\textsuperscript{15}, S. W. Kim\textsuperscript{15}, Y. Kimura\textsuperscript{4}, S. Kishigami\textsuperscript{4}, Y. Kubota\textsuperscript{13}, S. Kurisu\textsuperscript{13}, V. Kuzmin\textsuperscript{7}, M. Kuznetsov\textsuperscript{17,21}, Y. J. Kwon\textsuperscript{22}, K. H. Lee\textsuperscript{15}, B. Lubandsorzhie\textsuperscript{17}, J. P. Lundquist\textsuperscript{13,23}, K. Machida\textsuperscript{12}, H. Matsumiya\textsuperscript{4}, T. Matsuyma\textsuperscript{4}, J. N. Matthews\textsuperscript{3}, R. Maya\textsuperscript{2}, M. Minamino\textsuperscript{4}, K. Mukai\textsuperscript{12}, I. Myers\textsuperscript{5}, S. Nagataki\textsuperscript{14}, K. Nakai\textsuperscript{4}, R. Nakamura\textsuperscript{13}, T. Nakamura\textsuperscript{24}, T. Nakamura\textsuperscript{13}, Y. Nakamura\textsuperscript{13}, A. Nakazawa\textsuperscript{13}, T. Nonaka\textsuperscript{7}, H. Oda\textsuperscript{3}, S. Ogio\textsuperscript{2,25}, M. Ohnishi\textsuperscript{7}, H. Ohoka\textsuperscript{7}, Y. Oku\textsuperscript{15}, T. Okuda\textsuperscript{26}, Y. Omura\textsuperscript{2}, M. Ono\textsuperscript{15}, R. Onogi\textsuperscript{2}, A. Oshima\textsuperscript{2}, S. Ozawa\textsuperscript{27}, I. Park\textsuperscript{15}, M. Potts\textsuperscript{3}, M. S. Pshirkov\textsuperscript{17,28}, J. Remington\textsuperscript{3}, D. C. Rodriguez\textsuperscript{1}, G. I. Rubtsov\textsuperscript{17}, D. Ryu\textsuperscript{29}, H. Sagawa\textsuperscript{1}, R. Sahara\textsuperscript{1}, Y. Saito\textsuperscript{30}, N. Sakaki\textsuperscript{1}, T. Sakai\textsuperscript{2}, N. Sakurai\textsuperscript{2}, K. Sano\textsuperscript{13}, K. Sato\textsuperscript{3}, T. Seki\textsuperscript{13}, K. Sekino\textsuperscript{2}, P.D. Shah\textsuperscript{1}, Y. Shibasaki\textsuperscript{13}, F. Shibata\textsuperscript{12}, N. Shibata\textsuperscript{19}, T. Shibata\textsuperscript{1}, H. Shimodaira\textsuperscript{2}, B. K. Shin\textsuperscript{29}, H. S. Shin\textsuperscript{1}, D. Shinoh\textsuperscript{19}, D. J. Smith\textsuperscript{2}, P. Sokolsky\textsuperscript{1}, N. Sone\textsuperscript{13}, B. T. Stokes\textsuperscript{1}, T. A. Stroman\textsuperscript{1}, T. Suzawa\textsuperscript{1}, Y. Takagi\textsuperscript{14}, Y. Takahashi\textsuperscript{1}, M. Takamura\textsuperscript{2}, M. Takeda\textsuperscript{1}, R. Takeishi\textsuperscript{1}, A. Taketa\textsuperscript{30}, M. Takita\textsuperscript{1}, Y. Tameda\textsuperscript{1}, H. Tanaka\textsuperscript{1}, K. Tanaka\textsuperscript{1}, M. Tanaka\textsuperscript{32}, Y. Tanno\textsuperscript{3}, S. B. Thomas\textsuperscript{2}, G. B. Thompson\textsuperscript{1}, P. Tnyakov\textsuperscript{17,21}, I. Tkachev\textsuperscript{27}, H. Tokuno\textsuperscript{13}, T. Tomida\textsuperscript{17}, S. Troitsky\textsuperscript{7}, R. Tsuda\textsuperscript{1}, Y. Tsumedasi\textsuperscript{14,24}, Y. Uchihori\textsuperscript{13}, S. Udo\textsuperscript{13}, T. Uehama\textsuperscript{13}, F. Urban\textsuperscript{15}, T. Wong\textsuperscript{1}, K. Yada\textsuperscript{1}, M. Yamamoto\textsuperscript{31}, K. Yamazaki\textsuperscript{11}, J. Yang\textsuperscript{26}, K. Yashiro\textsuperscript{2}, F. Yoshida\textsuperscript{9}, Y. Yoshioda\textsuperscript{3}, Y. Zhuzher\textsuperscript{17,19}, and Z. Zandel\textsuperscript{25}

1 Department of Physics, Loyola University Chicago, Chicago, Illinois, USA
2 The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan
3 High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA
4 Graduate School of Science, Osaka City University, Osaka, Osaka, Japan
5 Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea
6 Department of Physics, Tokyo University of Science, Noda, Chiba, Japan
7 Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan
8 The Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto, Japan
9 Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan
10 Information Engineering Graduate School of Science and Technology, Shinshu University, Nagano, Nagano, Japan
11 Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan
12 Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan
13 Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan
14 Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan
15 Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea
16 Department of Physics, Tokyo University of Science, Setagaya-ku, Tokyo, Japan
17 Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
18 Faculty of Systems Engineering and Science, Shibaura Institute of Technology, Minato-ku, Tokyo, Japan
19 Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan
20 Department of Physics, Chiba University, Chiba, Chiba, Japan
21 Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium
22 Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea
23 Center for Astrophysics and Cosmology, University of Nova Gorica, Nova Gorica, Slovenia
24 Faculty of Science, Kocsi University, Kocsi, Kochi, Japan
25 Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka City University, Osaka, Osaka, Japan
26 Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan
27 Quantum ICT Advanced Development Center, National Institute for Information and Communications Technology, Koganei, Tokyo, Japan
28 Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia
29 Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, Ulsan, Korea
30 Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan
31 Graduate School of Physical Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan
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Yakutsk EAS Array Collaboration:
E. A. Atlasov1, N. G. Bolotnikov1, N. A. Dyachkovskiy1, N. S. Gerasimova1, A. V. Glushkov1, A. A. Ivanov1, O. N. Ivanov1, I. A. Kellarev1, S. P. Knurenko1, A. D. Krasilnikov1, I. V. Ksenofontov1, L. T. Ksenofontov1, K. G. Lebedev1, S. V. Matarkin1, V. P. Mokhnachevskaya1, N. I. Neustreov1, I. S. Petrov1, A. S. Proshutinsky1, A. V. Sabourov1, I. Ye. Sleptsov1, G. G. Struchkov1, L. V. Timofeev1, B. B. Yakovlev1

1 Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS 677980 Yakutsk, Russia

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