PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Cosmic Ray Indirect Rapporteur Report (37$^{\text{th}}$ ICRC)

Tareq AbuZayyad[a,b,*]

[a] *Loyola University Chicago, Chicago, Illinois, United States*
[b] *University of Utah, Salt Lake City, Utah, United States*
E-mail: tareq@cosmic.utah.edu

This report summarizes the physics results presented as part of the cosmic-ray indirect (CRI) session of the 37$^{\text{th}}$ICRC conference. Updated measurements on cosmic-ray energy spectrum, mass composition, and arrival direction distributions were presented by several collaborations, spanning the energy range of a few TeV up to the highest observed energies. We select some of the results which were highlighted by the respective discussion leaders or which presented new results at this conference. Results on atmospheric phenomena, including TGFs and thunderstorms are also presented.
We see a few interesting trends in the presented data. Among these are, the increased use of IACT's to study cosmic-rays among experiments primarily intended for gamma-ray measurements. Another, is the continued development of radio detection of air showers. Multi-component detectors are becoming the preferred detection mode, as the knowledge of how to integrate the different information about an air shower collected by the different detector components improves.
The main physics questions about the origins of cosmic rays, both galactic and extra-galactic, remain open. Increased statistics and improved analyses allow for refining and better constraining theoretical models, but no definitive answers can be claimed thus far. Looking forward, the field is moving at a rapid pace; Several detectors upgrades are underway, data is continually coming in and analyzed, old data being made public for a wider audience and a new generation of scientists to examine, with new tools and approaches that will hopefully result in new insights to help solve the open questions on cosmic-rays.

37$^{\text{th}}$ International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

Contents

1. Introduction

The 37$^{\text{th}}$ International Cosmic Ray Conference (ICRC 2021) included many contributions that were grouped under the "Cosmic Rays Indirect" track. These contributions were divided among 13 discussion sessions that focused on more specific topics. In the following section, a short description is given for each discussion session, with references to some of the contributions that stood out during the discussion. After the overview of the CRI contributions in section 2, we discuss some results on cosmic-ray energy spectrum and mass composition measurements in section 3 and cosmic-ray anisotropy results in section 4. Lastly we look at results related to atmospheric and geophysical phenomena in section 5. We close with a short summary.

2. Sessions Summaries

A short description of the cosmic-ray indirect sessions follows:

Magnetic fields and CR propagation

The following is the executive summary from the session conveners[1]. References to some of the highlighted presentations were inserted by the author of this report: "Since magnetic fields affect a huge variety of processes, this session was quite diverse, including contributions from the first cosmological fields [1], to small-scale MHD turbulence [2] and everything in between. Common themes included: the coherence length of the magnetic field, how to generate it theoretically, model it numerically [3, 4], or measure it observationally; the utility of multi-messenger information [5, 6] and tools like CRPropa [7] that can model all the processes self-consistently; amazing new data such as polarized radio surveys of the halos of external galaxies and high-energy CR anisotropies probing magnetic field turbulence near the Sun [8]."

[1]Glennys Farrar, Tess Jaffe

Galactic Particle Acceleration, including PIC

Not covered by this report. Please see the report for Cosmic Ray Direct [9].

UHECR Acceleration

From the session conveners[2]: "This session will focus on the accelerator source environment, and how this environment in the context of high velocity outflows can give rise to efficient particle acceleration up to the ultra high energy scale. The general challenges that any ultra high energy accelerator must overcome will be one of the key focuses of the discussion. Additionally, the session will query what new insights that can be provided by recent very high energy observations of powerful outflows." Four presentations [10–13] were selected for the discussion session.

Muon Puzzle and EAS modeling

Session conveners[3] were kind enough to provide the author with a summary of their thoughts and observations about the presentations in their discussion session. The following is based in part on that summary. The session was divided into three topics:

1. Muon Measurements in Air Shower Experiments
2. Shower Modifications and Muon Puzzle
3. Air Shower Modeling and LHC Forward Experiments

The progress reported by the many ongoing efforts dealing with the above topics indicate that the field is moving forward toward a better understanding of air shower development and eventually resolving the "Muon Puzzle". The following efforts, among others, are noteworthy:

1. An updated measurement of the proton-air and p-p cross section was presented by the Telescope Array collaboration [14]. By using a hybrid observations from two FD's and the SD, the updated measurement increased its data sample size by four times relative to the previous study. The update also incorporated the latest hadronic interaction models available at the time.
2. The combined analysis of muon measurements from nine experiments by the Working Group for Hadronic Interactions and Shower Physics (WHISP) which represents a systematic effort by many experiments to understand the experimental data in the context of the muon puzzle, finding significant discrepancies between data and simulations, increasing with cosmic ray energy. This contribution also includes many data updates from various experiments which have also been presented during the session [15].
3. The development of CORSIKA 8 [16] was a big topic during the sessions. CORSIKA is, probably, the primary tool for the UHECR field's modeling of air showers. The upgraded version of this simulation package is likely to play this role in the coming decade or more.

[2]Damiano Caprioli, Andrew Taylor
[3]Hans Dembinski, Anatoli Fedynitch, Dennis Soldin

4. During the discussion session the importance of oxygen collisions at LHC became obvious. The LHC council recently approved the plan for p-O collisions for Run 3 in 2023/2024 [17]. These results will be very important to understand multi-particle production in the forward direction of collisions including heavy nuclei which is crucial for EAS development; as discussed in detail in the invited talk by H. Dmbinski *et al.* [18]. A status update of the LHCf and RHICf experiments can be found in [19].
5. Finally, a somewhat technical topic, the importance of the hadronization for the description of the air shower development in current models represented an important aspect of the discussions [20].

EAS reconstruction and analyses

Experiments employ various types of detectors to observe Extensive Air Showers. The recorded data for an observed EAS will depend on the type of detector; e.g. a Water-Cherenkov, IACT, fluorescence telescope, or Radio. The reconstruction of the EAS parameters from the observed signals is a major undertaking in any experiment. This session dealt with topics related to detector data reconstruction, including detector calibration, and analysis techniques to extract physics information from observations. The discussion centered on the following topics (contributions):

- Detector Calibration: (LHAASO) Using the Moon Shadow for energy scale calibration [21].
- Muon reconstruction: (HAWC) Reconstruction of Nearly-Horizontal Muons [22], and (MuTe) Muography for the Colombian Volcanoes [23].
- Air shower reconstruction: (IceCube-Gen2) Surface Array [24], and (Auger) Water-Cherenkov and Scintillator Surface Detectors [25].
- Air Shower Simulation: Neutron production in extensive air showers [26].
- Machine Learning and physics driven analysis: Mainly application to Surface Detector Arrays; (Auger) Detector Signal Model [27], $X_{\rm max}$ reconstruction [28], and (TA) Shower energy and arrival direction [29].

Where to go in UHECR observations

A number of collaborations reported on ongoing detector expansions and upgrades. The main drivers for the upgrades were increased statistics at the highest energies, e.g. TAx4 [30], lowering the energy-reach of the detectors, e.g. Auger's SD-433 [31], TALE-infill [32], or improving the quality of collected data by adding new detection channels. e.g. Auger Scintillator SD's [33], IceCube-Gen2 surface array [34, 35]. Last but not least, space-borne cosmic ray detectors: JEM-EUSO [36] represents an active multi-national effort ("25 contributions at this conference") aiming at a $\times 10$ larger annual exposure at the highest energies than the ground based observatories. TUS [37] reported some of its findings.

New Instrumentation and Tools for EAS Detection

Among the topics covered were:

- The Electron-Neutron Detector Array (ENDA).
- Upgrades and R&D at Auger and TA.
- Various research and development efforts for the JEM-EUSO program.
- Bring up and calibration of the multiple the components of LHAASO.
- Radio detection of cosmic rays.
- CORSIKA-8 development.

Radio Observations of Cosmic Rays

The conveners[4] organized the session following five themes, described below:

Simulation & signal processing: New simulation codes and signal processing techniques, and their application to increasingly complex radio experiments.

Highly inclined showers: As a strategy to reach ultra-high energies or to search for showers from the direction of mountain ranges.

From the knee to the ankle: Extending the reach of radio to lower energies, and reports from some operational experiments.

Interferometry: Feasibility of use for cosmic-ray observation.

Cosmic rays in dense media Ongoing investigations of radio detection of cosmic rays in dense media.

CR Energy Spectrum

Cosmic-ray energy spectrum results will be presented in a separate section. Main observations by the session conveners[5] can be summarized as:

- All the low-energy experiments presented mass-resolved energy spectra.
- Waiting for LHAASO results [On the Energy Spectrum].
- Data being accumulated at mid-energies by Auger&TA low-energy extensions.
- UHE spectroscopy: fine structures in the energy spectrum at the highest energies were reported.
- The "instep" feature in the energy spectrum should be mentioned.

CR Mass Composition

Cosmic-ray mass composition results will be presented in a separate section. Main highlights according to the session conveners[6] can be summarized as:

- The Auger composition anisotropy result.
- The overlap of air shower and direct measurements.

[4]Stijn Buitink,Frank Schröder, João Torres de Mello Neto
[5]Ioana Maris, Yoshiki Tsunesada
[6]Michael Unger, Tom Gaisser

- The progress (and problems) with radio-Xmax. The low energy $X_{\max}$ measurements with TALE-Cherenkov and TALE-hybrid.

CR Anisotropies

Cosmic-ray anisotropy results will be presented in a separate section. That said, the session summary provided by the conveners[7] was quite detailed and informative. I will include it here with some minor edits for clarity and with added citations to the conference contributions being referenced:

"The arrival directions of cosmic rays show weak anisotropies on various angular and energy scales. In our session we discussed results of recent analyses based on GeV-TeV (AMS-02), TeV-PeV (GRAPES-3, IceCube & LHAASO), and 1-100 EeV (Pierre Auger & Telescope Array) cosmic ray observations. Cosmic ray anisotropies carry information about the distribution of nearby Galactic and extragalactic sources as well as the structure of Galactic and extragalactic magnetic fields. We discussed recent work on the calculation, simulation and interpretation of cosmic ray anisotropies.

We list here some "highlights" of our session:

Wei Gao presented first results on the dipole anisotropy with the partially constructed LHAASO detector[73]. The amplitude agrees qualitatively with earlier observations by IceCube (Frank McNally) [72] of a phase flip in the energy region of around 100 TeV.

Test-particle simulations in synthetic turbulent magnetic fields allow us to predict CR anisotropies in the TeV-PeV energy range. Simulations presented by Gwenael Giacinti [3] and Marco Kuhlen [2] support the idea that small-scale anisotropies can arise by CR transport in local turbulence.

The dipole anisotropy above 8 EeV with 17 years of data from the Pierre Auger Observatory reaches 6.6σ (Rogerio de Almeida) [75]. The data above 32 EeV shows evidence for correlation with catalogues of nearby sources (Jonathan Biteau) [76], with the strongest excess found in the data above 38 EeV in the direction of starburst galaxies.

Telescope Array observers a spectral anisotropy within 30° along the supergalactic plane (Toshiyuki Nonaka) [77] with a post-trial significance of 3.2σ. With 12 years of data the TA hotspot (>57 EeV) near the constellation Ursa Major persists but has a reduced a post-trial significance of now 3.2σ (Jihyun Kim) [79]. A new hot spot is observed in the data above an energy of 32 EeV in the vicinity of the Perseus-Pisces supercluster. Assuming PP supercluster is the source, the significance of the excess is 3.6σ [79].

Joint studies by Pierre Auger and Telescope allow us to study UHE CR anisotropies with a 4pi sky coverage, improving the reconstruction of dipole and quadrupole features (Peter Tinyakov) [80] and reducing bias of cross-correlations with candidate sources (Amando di Matteo) [81].

Chen Ding shows that PAOs finding of large-scale dipole features and the CR arrival directions above 38 EeV are consistent with UHE CR acceleration in sources following

[7] Markus Ahlers, Peter Tinyakov

the local large-scale structure and accounting for UHE CR deflections in Galactic magnetic fields [38]."

Constraining UHECR SOURCES

This summary relies heavily on the conveners[8] after-session summary that was kindly provided to the author. Some noteworthy contributions to this session are listed below.

- Rodrigues et al [39] examine what it takes for AGN to fit the UHECR data. A dominant contribution from low luminosity BL Lac objects can describe the energy spectrum above the ankle. A smaller contribution from high-luminosity is required to fit the mass composition reported by Auger. The implications for PeV and EeV neutrino fluxes are discussed.
- Farrar et al [40] showed that a Galactic source can explain component B, the tail of the Galactic cosmic ray spectrum, with a single bursting source. They associate the transient source (due to its location) with a particular supernova remnant, namely SNR G65.3+5.7.
- Merten [41] showed that FR0 galaxies, a newly discovered type of low-luminosity AGN can in principle accelerate UHECRs to the highest energies.
- Samuelsson [42] showed that low luminosity GRBs are constrained as the sources of UHECRs as the acceleration of UHECRs is inconsistent with the observed radio spectrum of one particular source that they used as a benchmark ("the archetypical low-luminosity GRB 060218").
- The work of Bister [43] shows that the combined fit to UHECR data is sensitive to separating source populations if one includes arrival directions which has never been done before.
- The work of Bakalova [44] shows that in principle a single source can be responsible for the end of the UHECR spectrum and fit the Auger composition. The motivation for such work is to assess whether the difference in the Auger/TA energy spectra can be explained by the existence of a dominant nearby source only seen by one of the two instruments.
- The contribution of Biteau [45] showed a new source catalogue, much more detailed than any existing all sky nearby galaxy catalogues, relevant for UHECR studies of arrival directions.
- The work of Muzio [46] is also very interesting and showed a combined fit to UHECR and neutrino data, showing what it takes for such a combined fit. They basically find that the data are more compatible with photon dominated environments as the source environments if we insist on a combined fit.
- The results of Condorelli [48] are in a similar direction to those of Muzio. They performed a combined fit to UHECR data only, assuming UHECRs originate in starburst galaxies, and find, like Muzio that they end up with a very hard neutrino spectrum which doesn't describe the IceCube data well.

[8]Foteini Oikonomou,Kohta Murase

- The contribution of Eichmann [47] demonstrated how to infer non-thermal elemental abundances starting about what we know about thermal abundances. This is quite fundamental but so far it only applies to low energy cosmic rays, as we generally have very little idea about cosmic ray abundances and just assume something when modeling.
- The contribution of Rudolph [49] showed what it take for GRBs to be the sources of UHECRs and fit the UHECR spectrum and composition.
- The contribution of Morejon [50] is an interesting work in progress as to the possible origin of the gamma-ray emission of Cen A as gamma-ray emission from high-energy nuclei (as opposed to protons).
- The contribution of Das [51] showed that in principle extreme BL Lac objects (those with energy peaks at very high energies with respect to the rest of the BL Lac population) can be sources of UHECRs and that the UHECR contribution can help fit the source spectra nicely. But in general one does not expect neutrinos from these sources (there are too few).

Atmospheric and geophysical phenomena

An alternative title for this session is "Interdisciplinary science with Cosmic Ray Detector Facilities". As is well known in the field by now, it is possible to use cosmic-ray detectors to observe some atmospheric and weather phenomena, such as lightning. CR detectors have also been augmented with specialized atmospheric monitoring equipment to improve their capability for atmospheric studies. On the other hand, weather affects CR observations, and atmospheric modeling and monitoring is a major part of detector calibration that is required for the reconstruction of CR data.

This session covered atmospheric phenomena such as ELVES and TGFs, thunderstorms, lightning, atmospheric monitoring, and "exotic events". Some of these results will be presented in a separate section.

3. CR Energy Spectrum and Mass Composition

A number of collaborations presented updated results on the energy spectrum, composition, and various anisotropy studies. In the following, we highlight some of these results starting with energy spectrum and composition and then follow with results on anisotropy. We start at lower energies then work our way to the highest energies.

The MAGIC telescope, an Imaging Air Cherenkov Telescope (IACT), was used to measure the protons energy spectrum from 1 TeV to 500 TeV, left panel of Figure 1. It is noteworthy that the *background* cosmic rays events collected by the detector were used as the data for this measurement. The presented analysis was based on using artificial neural network for event reconstruction and classification. The same method can be used for further measurements of other primaries [52]. Results from a similar study using the HAWC's Eye telescopes, right panel of Figure 1, was presented on behalf of the HAWC collaboration [53].

Pushing beyond 1 PeV in energy, the HAWC collaboration presented results on the all particle cosmic-ray energy spectrum [54], and those of three elemental mass groups, namely protons,

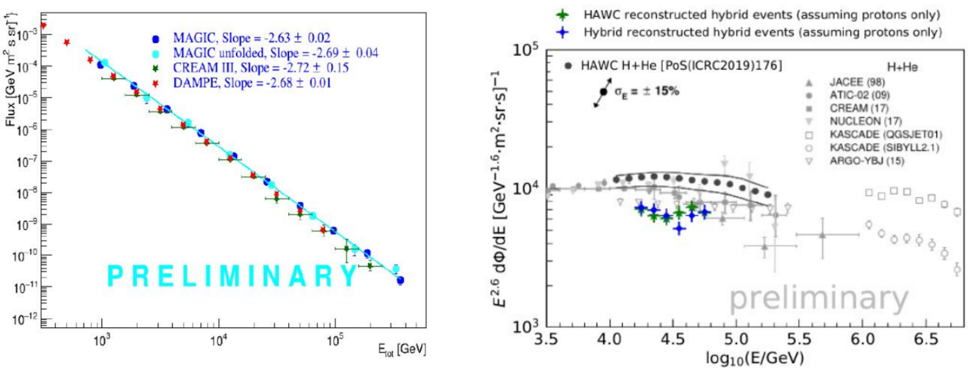

Figure 1: (left) The protons energy spectrum obtained from MAGIC telescope background cosmic-rays data [52]. (right) Results on the cosmic-ray energy spectrum from the HAWC's Eye telescopes operated in hybrid mode [53].

Helium, and heavy nuclei [55]. Results are shown in Figure 2. The updated all-particle energy spectrum confirms the presence of a knee-like structure in the TeV range, with a reported break energy of 69.1 ± 7.5 TeV.

For the resolved mass groups, the fluxes show features such as softenings whose energy positions increase with the primary mass. We quote from the proceeding [55]: "The observation of softenings in the spectra of H and He with HAWC, close to (14.06 ± 0.02 (stat) $^{+2.2}_{-0.4}$ (sys)) TeV and (25.30 ± 0.01 (stat) $^{+1.1}_{-0.8}$ (sys)) TeV, respectively, confirms the recent detections with the DAMPE satellite of similar features in the intensity of protons [*ref*], at around ($13.6^{+4.1}_{-4.8}$) TeV, and helium [*ref*], at approximately ($34.4^{+6.7}_{-9.8}$) TeV."

Further observations regarding the features in the spectra, comparisons to previous observations (including references), and to the expectations based on theory can be found in the same proceeding.

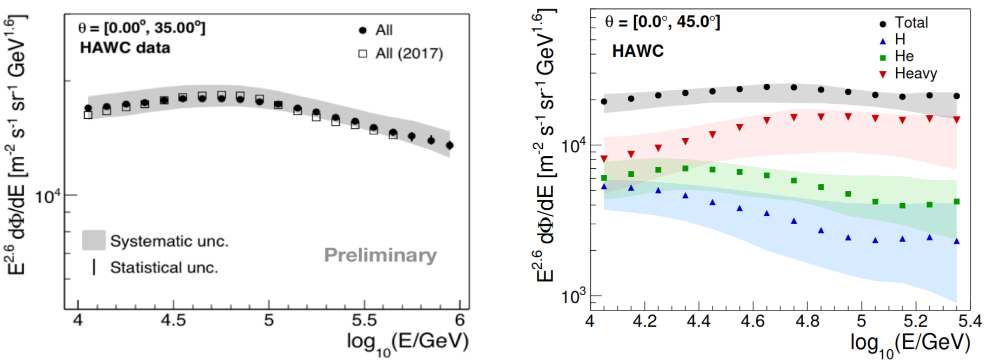

Figure 2: (left) The unfolded all-particle cosmic-ray energy spectrum obtained from HAWC. The gray error band corresponds to the systematic uncertainties, while the error bars represent the statistical uncertainties on the flux. For comparison HAWC results from 2017 are also shown. (right) Unfolded protons, Helium, and heavy components of the flux.

Another measurement, proclaimed as a bridge between direct and indirect measurements, was presented by the GRAPES-3 collaboration. The proton and Helium energy spectra in the energy range of 50 TeV to 1 PeV was shown [56]. Reproduced in Figure 3, the results show good agreement with experimental results at the low and high energy ranges made by different experiments. Primary fractions at different energies were also presented for mass grouping of: H, He, N, and Al+Fe, also in [56].

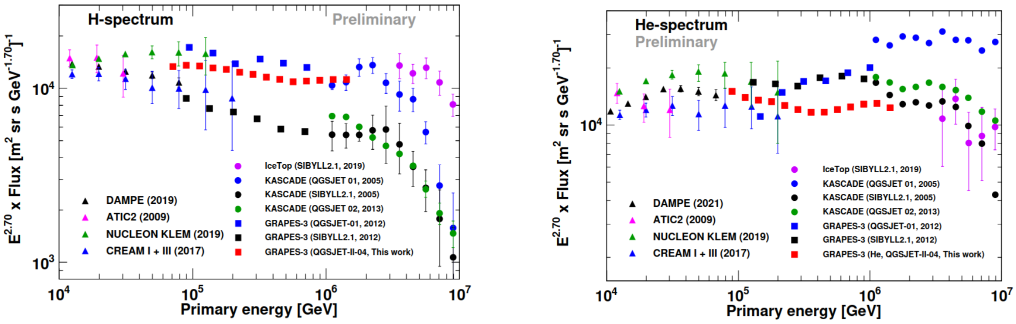

Figure 3: (left) Proton spectrum from Grapes-3. (right) Helium spectrum from Grapes-3

Several contributions by the LHAASO collaboration showed progress in understanding the detector(s) and the collected data, and in the various data characterization and analysis related to the study of high energy cosmic-rays. In [57], for example, the authors presented energy resolution estimates of 15% for protons and Helium with shower energies greater than 300 TeV using LHAASO's Cherenkov telescopes, in addition to methods for primary mass discrimination.

Above PeV energies the Telescope Array (TA) collaboration presented preliminary results from the NICHE non-imaging Cherenkov array [58]. The measurement of the cosmic-ray energy spectrum and shower $X_{\max}$ distributions were shown. The NICHE array lies in the field of view of the TALE fluorescence telescopes and in the future the detector components should be able to collect data in hybrid mode. The TALE FD's are currently operated either in monocular mode [59, 60], or in hybrid mode with the TALE SD [61, 62].

Results from the TALE FD measurements of the cosmic-rays flux and mass composition are shown in Figure 4. TALE-Hybrid mean $X_{\max}$ results show a clear break in the elongation rate at about $10^{17.1}$ EeV [62], indicating the start of a transition from heavy to light composition.

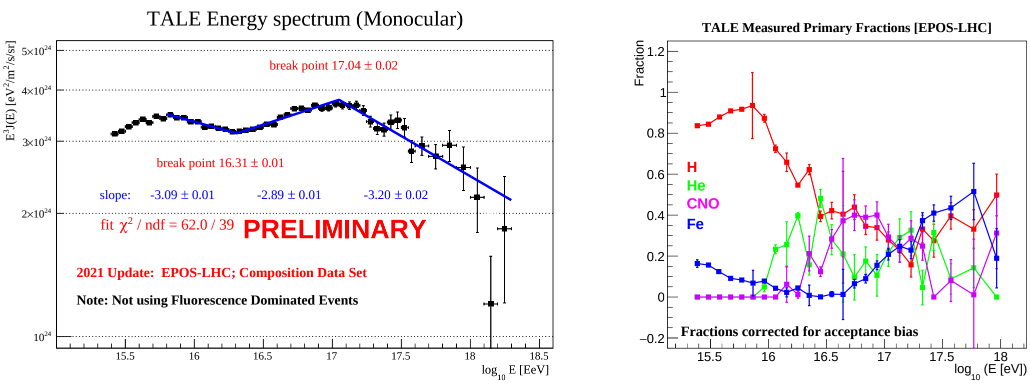

Figure 4: (left) All-particle energy spectrum by TALE FD. (right) Primary fractions based on fit of data $X_{\max}$ distributions.

Efforts on updating the IceTop cosmic-ray composition results were also discussed during the meeting [?]. The detector itself is being upgraded as part of the IceCube-Gen2 upgrade and is expected to be an invaluable instrument for the study of the PeV-EeV energy region [?].

KASCADE and KASCADE-Grande data now made public has allowed new analyses by outside groups. Mass composition using KASCADE data was shown in [?], and the energy spectra for different mass groups were reconstructed using post-LHC hadronic models [?].

Mass composition measurements were presented by LOFAR [63], significant for the fact that this is a radio detector and signifies the maturing of the radio detection technique for measuring air shower properties. A similar effort by AERA [64] at higher but overlapping energies was presented and compared to LOFAR. The results for the mean X_{max} dependence on shower energy are shown in Figure 5.

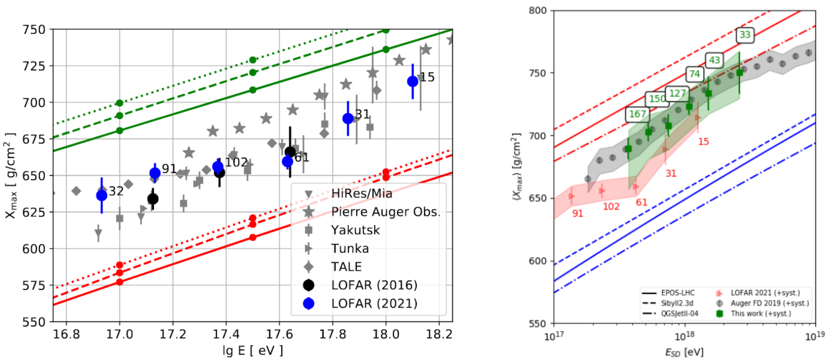

Figure 5: Mean X_{max} versus energy: (left) LOFAR, (right) AERA.

At ultra-high energies, both Auger and the Telescope Array collaborations presented several updates to ongoing analyses, and some new results. An updated energy spectrum using 10 years of FD data, Figure 6, was shown by TA [65]. The Auger energy spectrum was extended down in energy to 6 PeV, Figure 7, using observations by the HEAT telescopes of Cherenkov dominated events [66]. Efforts to use surface detectors for mass composition are continuing. An update from TA using 12 years of data [71] favors a mixed composition above 1 EeV, it is however systematically "heavier" than reported observations by the TA hybrid (Fluorescence) results, Figure 6, 6. Auger's mass composition result, Figure 7, shown at the conference demonstrates a statistically significant difference in the mean X_{max} values observed from different parts of the sky, namely the regions near and far from the galactic plane [69]. A search for mass composition anisotropy by TA looking at the "hotspot" region did not find any significant signal in 11 years of TA SD data [70].

Efforts to understand the differences in the cosmic-ray energy spectrum at the highest energies are also continuing with the joint analysis [67], reporting on energy scale shifts required to bring the two spectra into agreement, Figure 8. The analysis focuses on the spectra measured using data from a common declination band. As can be seen in Figure 9, the "instep" feature has been confirmed by both detectors [67, 68].

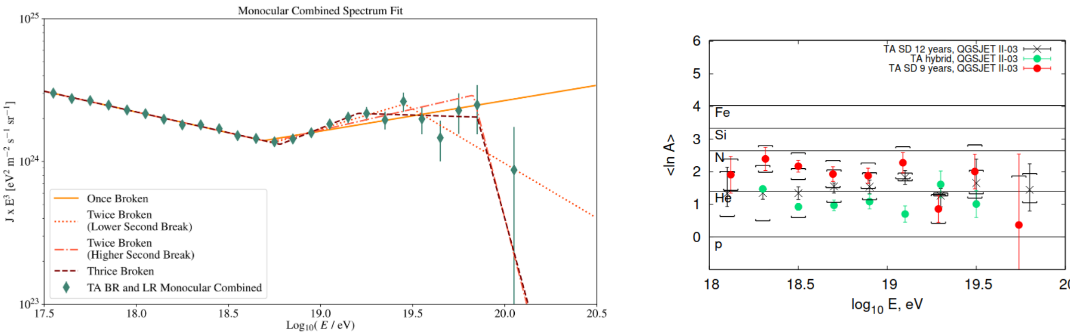

Figure 6: (left) Cosmic-ray energy spectrum using the Black Rock and Long Ridge fluorescence detectors of TA. (right) A composition measurement using the TA SD data.

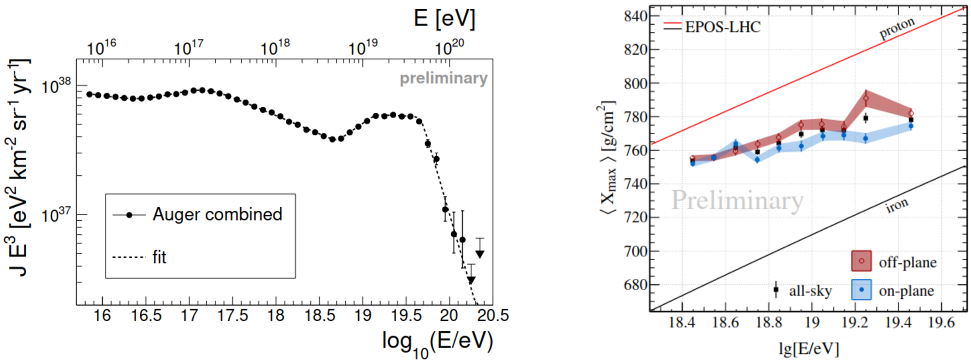

Figure 7: (left) All-particle energy spectrum by AUGER. (right) Mean X_{max} values from different regions of the sky.

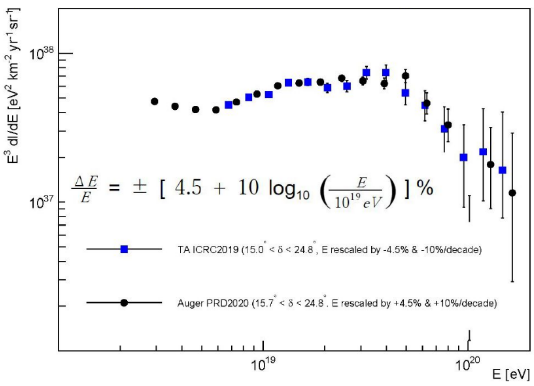

Figure 8: Auger and TA energy spectra in a common declination band brought into agreement by applying energy scale shifts as indicated in the figure.

4. CR Anisotropies

An update on IceCube anisotropy using a 9-year data set with 577 billion events was presented in [72]. The results confirm earlier published results but with higher significance; achieving a pre-trial significance of over 3σ in the highest energy map ($E > 3$ PeV). LHAASO-KM2A data

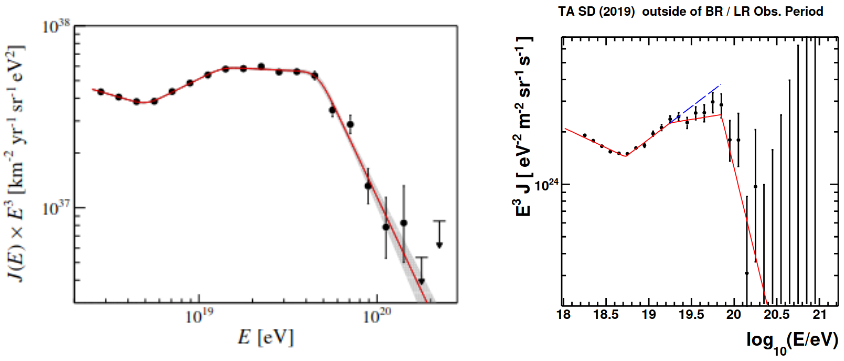

Figure 9: The “instep” feature in the Auger (left) and TA (right) energy spectra.

was used to study the large-scale anisotropy of cosmic rays [73]. data was split into energy bins with mean energy in the range of 23 TeV - 985 TeV, and the energy dependence of the anisotropy was examined. In particular, it was found that the amplitudes and phases of first harmonic of the intensity of sidereal large-scale anisotropy (right Ascension) are energy dependent, with an "inverse" anisotropy observed with the significance of 5σ. Another study of cosmic-ray anisotropy measured by GRAPES-3 reported the observation of small scale structures consistent with observations by other experiments, but was unable to observe large scale structures as seen by others [74]. The authors suspect this could be due to various systematic effects, and will update their results as they make progress in understanding these effects [74].

In an update to the large scale anisotropy search, the Auger collaboration reports that “The statistical significance of the large-scale dipolar modulation observed above 8 EeV has increased to $6.6\sigma \ldots$ All other multipoles are not significant.” [75]. The updated result is shown in Figure 10. At energies above 32 EeV, Auger reports a $\sim 4\sigma$ excess in the direction of the Centaurus region [76].

The TA collaboration searched, using 12 years of data, but did not see a significant dipole structure [78]. This result was still consistent with Auger, due to the lower event statistics. A study of the correlation of the TA SD data with matter distribution was updated from a previous result based on 5-year data to 12-year data. Observed Events with energies above 10^{19} eV obtained by TA surface detectors were divided based on their arrival direction as being within 30° from the super galactic plane (*on source*), or not (*off source*). The results of the 12-year analysis are consistent with the 5-year, and expectations (lower break energy and lower event fraction) [77].

TA also provided an update on the Hotspot analysis; Events with energies, $E > 57$ EeV. With 12-years of data, the post-trial probability of the excess is estimated to be 3.2σ [79]. In addition, a new excess region was identified for lower-energy events, $E > 10^{19.5}$ eV. The chance probability of the excess is estimated to be at the 3.6σ level. The newly identified region sits in front of the Perseus-Pisces supercluster and further analysis is underway [79].

Joint analysis of Auger and TA data was also presented at the conference. In [80], the authors examine the dipole and quadropole outcomes for a “full sky” data-set formed by Auger and TA combined data. The advantage of using the combined data is summarized by the authors as: “We find that the full-sky coverage achieved by combining Auger and TA data reduces the uncertainties on the north-south components of the dipole and quadrupole in half compared to Auger-only

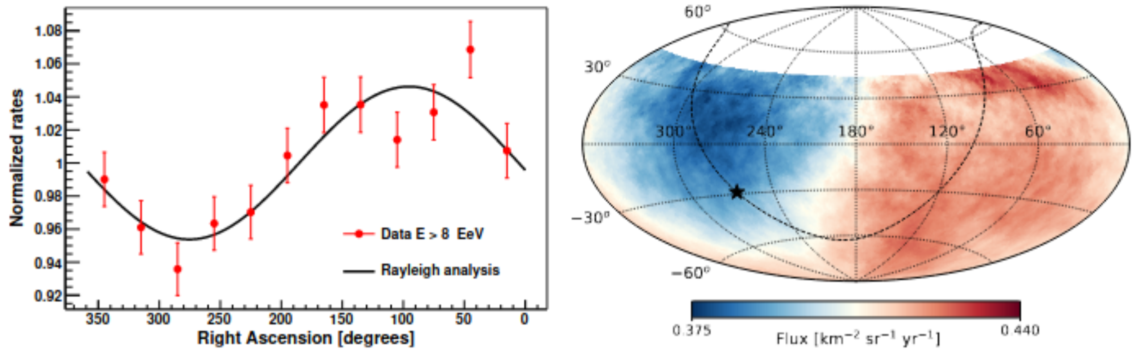

Figure 10: (left) Distribution of the normalized rate of events with $E > 8$ EeV. (right) Map of the flux of cosmic rays, $E > 8$ EeV, in equatorial coordinates.

results." [80]. A cross correlation study of the arrival direction with nearby galaxies is presented in [81]. The use of the combined data in this study resulted in finding a higher significance of the correlation between cosmic-ray arrival directions and starburst galaxies than was observed using Auger only data. However, the significance of correlation will all galaxies was reduced [81].

5. Atmospheric and geophysical phenomena

Two contributions described the observation of ELVES; These show up with a distinctive pixel trigger pattern in fluorescence detector telescopes. Auger reported [82] on a long term study of multi-ELVES (time separation $\Delta t > 80\mu s$. "Many" events were recorded in the period of 2014-2020. The frequency of events was compared to EMP ground reflection mechanism candidates (out of 144 ELVES events, one ground reflection candidate and 33 multi-ELVES with $\Delta t > 80\mu s$), and their relations to thunderstorms and lightning was also discussed (128 ELVES out of 144 correlated with ENTLN and WWLLN data). Mini-EUSO recorded 17 ELVES in the first year of data [83], "including three double-ringed ELVEs and one three-ringed ELVE". At this stage in the detector development, the observation serves as a verification of the correct functioning of the instrument.

Terrestrial Gamma-ray Flashes (TGF) observations at the Telescope Array have led to the identification of the relation between these events and the lightning initiation process in Thunderstorms [84]. An example of such an event is shown in Figure 11. Auger has been conducting TGF searches as well [85]. Events believed to be related to thunderstorms have been detected and are considered TGF candidate events. To confirm the nature of the observed events and enhance the capability of the surface detector for atmospheric electricity and related studies, the collaboration has "developed a strategy for a dedicated trigger". Newly installed instruments and some being or planned to be installed will be used for these studies. Lastly, The ASEC collaboration presented an overview of their research in high-energy physics in the atmosphere (HEPA) and in particular the analysis of TGE events and comparisons to CORSIKA simulations [90].

Another area of interest in atmospheric phenomena is the measurement of the electric fields generated in thunderstorms. Two reports on the subject were given by the Grapes-3 collaboration [86] and the TA collaboration [87]. Grapes-3 looked at the azimuthal distribution of thunderstorm events over a ~10 years of data and found an azimuthal asymmetry that can be attributed to the ratio of μ_+/μ_- observed in Monte Carlo simulations. TA reported on the first observation of the effect of thunderstorms on the development of cosmic ray showers. They used the variation in cosmic-ray shower rates across the 700 km^2 surface detector, Figure 11 and Monte Carlo simulations to estimate the strength and polarity of the electric field inside thunderstorms.

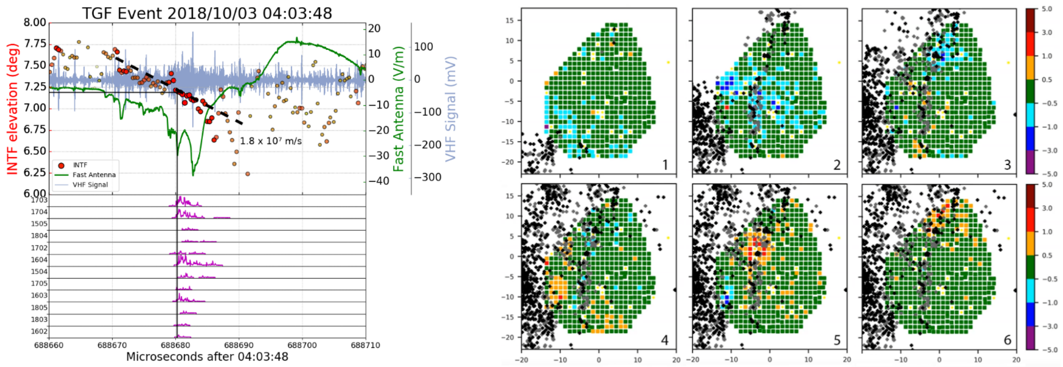

Figure 11: Telescope Array atmospheric studies. (left) Source determination for a TGF. Black vertical and horizontal bars show the solution of the TGF source resulting from the iterative analysis method [84]. (right) Cosmic-ray rate variation across the TA SD at 10 minute intervals as a thunderstorm passes overhead [87].

The presence of clouds in the atmosphere affects the efficiency of fluorescence and Cherenkov telescopes to detect air-showers. Detecting clouds in the FOV of the telescopes is challenging. Towards this goal, Mini-EUSO presented a study to measure the UV emission from clouds [88], while Auger discussed their use of satellite data for atmospheric monitoring; both for clouds detection and aerosols optical depth estimation [89]

6. Summary and Conclusions

We reviewed some of the measurements updates given at the conference. These were the physics results based on data collected by the larger operating experiments. A large number of contributions dealing with cosmic-ray theory, simulations, measurement techniques, or the status of the field and future direction were briefly mentioned but not discussed in this review.

References

[1] Y. Ohira, *Magnetic field generation by the first cosmic rays*, PoS **ICRC2021**, 458 (2021) doi:10.22323/1.395.0458

[2] M. Kuhlen, P. Mertsch and V. H. M. Phan, *Cosmic Ray Small-Scale Anisotropies in Slab Turbulence*, PoS **ICRC2021**, 164 (2021) doi:10.22323/1.395.0164 [arXiv:2107.02094 [astro-ph.HE]].

[3] G. Giacinti and B. Reville, *Simulations of the cosmic-ray anisotropy down to TeV energies*, PoS **ICRC2021**, 455 (2021) doi:10.22323/1.395.0455

[4] Y. Génolini and M. Ahlers, *Local Turbulence and the Dipole Anisotropy of Galactic Cosmic Rays*, PoS **ICRC2021**, 160 (2021) doi:10.22323/1.395.0160

[5] A. Saveliev and R. A. Batista, *Multimessenger Constraints on Intergalactic Magnetic Fields from Flaring Objects*, PoS **ICRC2021**, 994 (2021) doi:10.22323/1.395.0994 [arXiv:2106.16041 [astro-ph.HE]].

[6] A. van Vliet, A. Palladino, W. Winter, A. Taylor and A. Franckowiak, *Extragalactic magnetic fields and directional correlations of ultra-high-energy cosmic rays with local galaxies and neutrinos*, PoS **ICRC2021**, 470 (2021) doi:10.22323/1.395.0470

[7] R. Alves Batista, J. Becker Tjus, J. Dörner, A. Dundovic, B. Eichmann, A. Frie, C. Heiter, M. R. Hoerbe, K. H. Kampert and L. Merten, *et al. CRPropa 3.2: a framework for high-energy astroparticle propagation*, PoS **ICRC2021**, 978 (2021) doi:10.22323/1.395.0978 [arXiv:2107.01631 [astro-ph.HE]].

[8] T. Fitoussi, G. Medina-Tanco and J. C. D'Olivo, *Faraday rotation constraints on large scale Halo model*, PoS **ICRC2021**, 451 (2021) doi:10.22323/1.395.0451

[9] P. Mertsch, *Rapporteur Talk: Cosmic Ray Direct*, PoS **ICRC2021**, 044 (2021) doi:10.22323/1.395.0044 [arXiv:2110.03325 [astro-ph.HE]].

[10] S. O'Sullivan, A. Taylor and B. Reville, *Particle acceleration at the discontinuous flow boundary of collimated cylindrical jets*, PoS **ICRC2021**, 491 (2021) doi:10.22323/1.395.0491

[11] R. Mbarek, D. Caprioli and K. Murase, *Ultra-High-Energy Cosmic Rays and Neutrinos from Relativistic Jets of Active Galactic Nuclei*, PoS **ICRC2021**, 481 (2021) doi:10.22323/1.395.0481

[12] E. De Gouveia Dal Pino, T. E. Medina-Torrejon, L. H. S. Kadowaki, G. Kowal and J. C. Rodriguez-Ramirez, *Ultra-high-energy cosmic ray acceleration by magnetic reconnection in relativistic jets and the origin of very high energy emission*, PoS **ICRC2021**, 454 (2021) doi:10.22323/1.395.0454

[13] Z. L. Zhang, R. Y. Liu and X. Y. Wang, *Acceleration of ultrahigh-energy cosmic rays in the early afterglows of gamma-ray bursts*, PoS **ICRC2021**, 423 (2021) doi:10.22323/1.395.0423

[14] R. Abbasi and W. Hanlon, *Measurement of the Proton-Air Cross Section with Telescope Arrays Black Rock, Long Ridge, and Surface Array in Hybrid Mode*, PoS **ICRC2021** (2021), 296 doi:10.22323/1.395.0296

[15] D. Soldin [EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array], *Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments*, PoS **ICRC2021**, 349 (2021) doi:10.22323/1.395.0349 [arXiv:2108.08341 [astro-ph.HE]].

[16] A. A. Alves, Junior *et al.* [CORSIKA 8], *Status of the novel CORSIKA 8 air shower simulation framework*, PoS **ICRC2021**, 284 (2021) doi:10.22323/1.395.0284

PoS(ICRC2021)043

[17] O. Adriani *et al.* [LHCf], *LHCf plan for proton-oxygen collisions at LHC*, PoS **ICRC2021**, 348 (2021) doi:10.22323/1.395.0348

[18] H. Dembinski, J. Albrecht, L. Cazon, A. Fedynitch, K. H. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan and R. Ulrich, *et al. The Muon Puzzle in air showers and its connection to the LHC*, PoS **ICRC2021**, 037 (2021) doi:10.22323/1.395.0037 [arXiv:2105.06148 [astro-ph.HE]].

[19] H. Menjo *et al.* [LHCf and RHICf], *Status and Prospects of the LHCf and RHICf experiments*, PoS **ICRC2021**, 301 (2021) doi:10.22323/1.395.0301

[20] T. Pierog, S. Baur, H. Dembinski, M. Perlin, R. Ulrich and K. Werner, *When heavy ions meet cosmic rays: potential impact of QGP formation on the muon puzzle*, PoS **ICRC2021**, 469 (2021) doi:10.22323/1.395.0469

[21] Y. Wang *et al.* [LHAASO], *The Energy Scale Calibration using the Moon Shadow of LHAASO-WCDA Detector*, PoS **ICRC2021**, 356 (2021) doi:10.22323/1.395.0356

[22] A. U. Abeysekara *et al.* [HAWC], *Reconstruction of Nearly-Horizontal Muons in the HAWC Observatory*, PoS **ICRC2021**, 254 (2021) doi:10.22323/1.395.0254

[23] R. de Leon-Barrios, J. Peña-Rodríguez, J. Sanabria-Gómez, A. Vásquez-Ramírez, R. Calderón-Ardila, C. Sarmiento-Cano, A. Vesga-Ramirez, D. Sierra-Porta, M. Suárez-Durán and H. Asorey, *et al. Muography for the Colombian Volcanoes*, PoS **ICRC2021**, 280 (2021) doi:10.22323/1.395.0280

[24] R. Abbasi *et al.* [IceCube-Gen2], *Simulation study for the future IceCube-Gen2 surface array*, PoS **ICRC2021**, 411 (2021) doi:10.22323/1.395.0411 [arXiv:2108.04307 [astro-ph.HE]].

[25] P. Abreu *et al.* [Pierre Auger], *Reconstruction of Events Recorded with the Water-Cherenkov and Scintillator Surface Detectors of the Pierre Auger Observatory*, PoS **ICRC2021**, 218 (2021) doi:10.22323/1.395.0218

[26] R. Engel, A. Ferrari, M. Roth, M. Schimassek, D. Schmidt and D. Veberic, *Neutron production in extensive air showers*, PoS **ICRC2021**, 492 (2021) doi:10.22323/1.395.0492

[27] M. Stadelmaier, M. Roth, D. Schmidt and D. Veberic, *A complete model of the signal in surface detector arrays and its application for the reconstruction of mass-sensitive observables*, PoS **ICRC2021**, 432 (2021) doi:10.22323/1.395.0432

[28] P. Abreu *et al.* [Pierre Auger], *Event-by-event reconstruction of the shower maximum* $X_{\max}$ *with the Surface Detector of the Pierre Auger Observatory using deep learning*, PoS **ICRC2021**, 359 (2021) doi:10.22323/1.395.0359

[29] O. Kalashev *et al.* [Telescope Array], *TA SD energy and arrival direction estimation using deep learning*, PoS **ICRC2021**, 252 (2021) doi:10.22323/1.395.0252

[30] R. Abbasi *et al.* [Telescope Array], *Current status and prospects of surface detector of the TAx4 experiment*, PoS **ICRC2021** (2021), 203 doi:10.22323/1.395.0203

[31] P. Abreu *et al.* [Pierre Auger], *Performance of the 433 m surface array of the Pierre Auger Observatory*, PoS **ICRC2021** (2021), 224 doi:10.22323/1.395.0224

[32] R. Abbasi *et al.* [Telescope Array], *The status of the TALE surface detector array and TALE infill project*, PoS **ICRC2021** (2021), 255 doi:10.22323/1.395.0255

[33] G. Cataldi *et al.* [Pierre Auger], *The upgrade of the Pierre Auger Observatory with the Scintillator Surface Detector*, PoS **ICRC2021** (2021), 251 doi:10.22323/1.395.0251

[34] F. G. Schroeder *et al.* [IceCube-Gen2], *The Surface Array planned for IceCube-Gen2*, PoS **ICRC2021** (2021), 407 doi:10.22323/1.395.0407 [arXiv:2108.00364 [astro-ph.HE]].

[35] R. Abbasi *et al.* [IceCube], *First air-shower measurements with the prototype station of the IceCube surface enhancement*, PoS **ICRC2021** (2021), 314 doi:10.22323/1.395.0314 [arXiv:2107.08750 [astro-ph.HE]].

[36] M. E. Bertaina [JEM-EUSO], *An overview of the JEM-EUSO program and results*, PoS **ICRC2021** (2021), 406 doi:10.22323/1.395.0406

[37] P. Klimov *et al.* [Lomonosov-UHECR/TLE], *Main results of the TUS experiment on board the Lomonosov satellite*, PoS **ICRC2021** (2021), 316 doi:10.22323/1.395.0316 [arXiv:2108.07022 [astro-ph.HE]].

[38] C. Ding, N. Globus and G. R. Farrar, *The Imprint of Large Scale Structure on the Ultra-High-Energy Cosmic Ray Sky*, Astrophys. J. Lett. **913** (2021) no.1, L13 doi:10.3847/2041-8213/abf11e [arXiv:2101.04564 [astro-ph.HE]].

[39] X. Rodrigues, J. Heinze, A. Palladino, A. van Vliet and W. Winter, *Active Galactic Nuclei Jets as the Origin of Ultrahigh-Energy Cosmic Rays and Perspectives for the Detection of Astrophysical Source Neutrinos at EeV Energies*, Phys. Rev. Lett. **126** (2021) no.19, 191101 doi:10.1103/PhysRevLett.126.191101 [arXiv:2003.08392 [astro-ph.HE]].

[40] G. R. Farrar and C. Ding, *Transient Source for the Highest Energy Galactic Cosmic Rays*, PoS **ICRC2021** (2021), 488 doi:10.22323/1.395.0488

[41] L. Merten, M. Boughelilba, A. Reimer, P. Da Vela, S. Vorobiov, F. Tavecchio, G. Bonnoli, J. P. Lundquist and C. Righi, *FR-0 jetted active galaxies: extending the zoo of candidate sites for UHECR acceleration*, PoS **ICRC2021** (2021), 986 doi:10.22323/1.395.0986 [arXiv:2107.13278 [astro-ph.HE]].

[42] F. Samuelsson, D. Begue, F. Ryde, A. Pe'er and K. Murase, *The problematic connection between low-luminosity gamma-ray bursts and ultra-high-energy cosmic rays*, PoS **ICRC2021** (2021), 467 doi:10.22323/1.395.0467

[43] P. Abreu *et al.* [Pierre Auger], *A combined fit of energy spectrum, shower depth distribution and arrival directions to constrain astrophysical models of UHECR sources*, PoS **ICRC2021** (2021), 368 doi:10.22323/1.395.0368

[44] A. Bakalova, J. Vicha and P. Travnicek, *Features of a single source describing the very end of the energy spectrum of cosmic rays*, PoS **ICRC2021** (2021), 363 doi:10.22323/1.395.0363

[45] J. Biteau, S. Marafico, Y. Kerfis and O. Deligny, *Cosmographic model of the astroparticle skies*, PoS **ICRC2021** (2021), 1012 doi:10.22323/1.395.1012 [arXiv:2108.10775 [astro-ph.HE]].

[46] M. S. Muzio, G. R. Farrar and M. Unger, *Constraining the origin of UHECRs and astrophysical neutrinos*, PoS **ICRC2021** (2021), 1021 doi:10.22323/1.395.1021

[47] B. Eichmann and J. P. Rachen, *Thermal-to-nonthermal element abundances in different Galactic environments*, PoS **ICRC2021** (2021), 466 doi:10.22323/1.395.0466 [arXiv:2108.06985 [astro-ph.HE]].

[48] A. Condorelli, D. Boncioli, E. Peretti and S. Petrera, *Starburst Galaxies as possible sources of UHECRs and neutrinos*, PoS **ICRC2021** (2021), 959 doi:10.22323/1.395.0959

[49] A. Rudolph, J. Heinze, D. Biehl, A. Fedynitch, D. Boncioli, Ž. Bošnjak, I. Sadeh, A. Palladino and W. Winter, *UHECR from high- and low-luminosity Gamma-Ray Bursts*, PoS **ICRC2021** (2021), 1000 doi:10.22323/1.395.1000

[50] H. Abdalla, R. Adam, F. Aharonian, F. A. Benkhali, E. O. Angüner, M. Arakawa, C. Arcaro, C. Armand, H. Ashkar and M. Backes, *et al. Resolving acceleration to very high energies along the jet of Centaurus A*, Nature **582** (2020) no.7812, 356-359 [erratum: Nature **583** (2020) no.7815, E23] doi:10.1038/s41586-020-2354-1 [arXiv:2007.04823 [astro-ph.HE]].

[51] S. Das, N. Gupta and S. Razzaque, *Ultrahigh-energy cosmic ray interactions as the origin of very high energy $\gamma-$rays from BL Lacs*, Astrophys. J. **889** (2020), 149 doi:10.3847/1538-4357/ab6131 [arXiv:1911.06011 [astro-ph.HE]].

[52] P. Temnikov *et al.* [MAGIC], *Protons Spectrum from MAGIC Telescopes data*, PoS **ICRC2021**, 231 (2021) doi:10.22323/1.395.0231

[53] F. Rehbein, R. Alfaro, J. Audehm, T. Bretz, O. Chaparro-Amaro, G. Do, F. J. Gonzalez, M. M. Gonzalez, A. Iriarte and J. Martínez-Castro, *et al. Preliminary Cosmic Ray Results from the HAWC's Eye Telescopes*, PoS **ICRC2021**, 397 (2021) doi:10.22323/1.395.0397

[54] J. A. Morales-Soto *et al.* [HAWC], *The all-particle cosmic ray energy spectrum measured with HAWC*, PoS **ICRC2021**, 330 (2021) doi:10.22323/1.395.0330 [arXiv:2108.04748 [astro-ph.HE]].

[55] A. U. Abeysekara *et al.* [HAWC], *HAWC measurements of the energy spectra of cosmic ray protons, helium and heavy nuclei in the TeV range*, PoS **ICRC2021**, 374 (2021) doi:10.22323/1.395.0374 [arXiv:2108.03208 [astro-ph.HE]].

[56] F. Varsi *et al.* [GRAPES-3], *Cosmic ray energy spectrum and composition measurements from the GRAPES-3 experiment: Latest results*, PoS **ICRC2021**, 388 (2021) doi:10.22323/1.395.0388

[57] L. Ma *et al.* [LHAASO], *The Energy Spectrum of Cosmic Ray Proton and Helium above 100TeV Measured by LHAASO Experiment*, PoS **ICRC2021**, 377 (2021) doi:10.22323/1.395.0377

[58] Y. Omura, R. Tsuda, Y. Tsunesada, D. R. Bergman and J. F. Krizmanic, *Energy spectrum and the shower maxima of cosmic rays above the knee region measured with the NICHE detectors at the TA site*, PoS **ICRC2021**, 329 (2021) doi:10.22323/1.395.0329

[59] T. AbuZayyad *et al.* [Telescope Array], *Cosmic Ray Energy Spectrum measured by the TALE Fluorescence Detector*, PoS **ICRC2021**, 347 (2021) doi:10.22323/1.395.0347

[60] T. AbuZayyad *et al.* [Telescope Array], *Cosmic Ray Composition between 2 PeV and 2 EeV measured by the TALE Fluorescence Detector*, PoS **ICRC2021**, 346 (2021) doi:10.22323/1.395.0346

[61] R. Abbasi *et al.* [Telescope Array], *Cosmic ray energy spectrum in the 2nd knee region measured by the TALE-SD array*, PoS **ICRC2021**, 362 (2021) doi:10.22323/1.395.0362

[62] R. Abbasi *et al.* [Telescope Array], *Cosmic Ray Composition in the Second Knee Region as Measured by the TALE Hybrid Detector*, PoS **ICRC2021**, 353 (2021) doi:10.22323/1.395.0353

[63] A. Corstanje, S. Buitink, H. Falcke, B. M. Hare, J. Hörandel, T. Huege, G. Krampah, P. Mitra, K. Mulrey and A. Nelles, *et al. Results on mass composition of cosmic rays as measured with LOFAR* PoS **ICRC2021**, 322 (2021) doi:10.22323/1.395.0322

[64] P. Abreu *et al.* [Pierre Auger], *The depth of the shower maximum of air showers measured with AERA* PoS **ICRC2021**, 387 (2021) doi:10.22323/1.395.0387

[65] D. Bergman *et al.* [Telescope Array], *Telescope Array 10-Year Monocular Spectrum Measurement* PoS **ICRC2021**, 339 (2021) doi:10.22323/1.395.0339

[66] P. Abreu *et al.* [Pierre Auger], *Energy spectrum of cosmic rays measured using the Pierre Auger Observatory*, PoS **ICRC2021**, 324 (2021) doi:10.22323/1.395.0324

[67] R. Abbasi *et al.* [Telescope Array and Pierre Auger], *Joint analysis of the energy spectrum of ultra-high-energy cosmic rays as measured at the Pierre Auger Observatory and the Telescope Array*, PoS **ICRC2021**, 337 (2021) doi:10.22323/1.395.0337

[68] D. Ivanov *et al.* [Telescope Array], *Recent measurement of the Telescope Array energy spectrum and observation of the shoulder feature in the Northern Hemisphere*, PoS **ICRC2021**, 341 (2021) doi:10.22323/1.395.0341

[69] P. Abreu *et al.* [Pierre Auger], *Indication of a mass-dependent anisotropy above* $10^{18.7}$ *eV in the hybrid data of the Pierre Auger Observatory*, PoS **ICRC2021**, 321 (2021) doi:10.22323/1.395.0321

[70] Y. Zhezher [Telescope Array], *Mass composition anisotropy with the Telescope Array Surface Detector data*, PoS **ICRC2021**, 299 (2021) doi:10.22323/1.395.0299

[71] Y. Zhezher [Telescope Array], *Cosmic-ray mass composition with the TA SD 12-year data*, PoS **ICRC2021**, 300 (2021) doi:10.22323/1.395.0300

[72] R. Abbasi, M. Ackermann, J. Adams, T. Aguado, J. Aguilar, M. Ahlers, M. Ahrens, C. M. Alispach, A. A. Alves, Junior and N. M. B. Amin, *et al. Observation of Cosmic Ray Anisotropy with Nine Years of IceCube Data*, PoS **ICRC2021**, 320 (2021) doi:10.22323/1.395.0320 [arXiv:2107.11454 [astro-ph.HE]].

[73] W. Gao *et al.* [LHAASO], *Observation of large-scale anisotropy in the arrival directions of cosmic rays with LHAASO*, PoS **ICRC2021**, 351 (2021) doi:10.22323/1.395.0351

[74] M. Chakraborty *et al.* [GRAPES-3], *Large-scale cosmic ray anisotropy measured by the GRAPES-3 experiment*, PoS **ICRC2021**, 393 (2021) doi:10.22323/1.395.0393

[75] R. de Almeida *et al.* [Pierre Auger], *Large-scale and multipolar anisotropies of cosmic rays detected at the Pierre Auger Observatory with energies above 4 EeV*, PoS **ICRC2021**, 335 (2021) doi:10.22323/1.395.0335

[76] P. Abreu *et al.* [Pierre Auger], *The ultra-high-energy cosmic-ray sky above 32 EeV viewed from the Pierre Auger Observatory*, PoS **ICRC2021**, 307 (2021) doi:10.22323/1.395.0307

[77] M. Abe *et al.* [Telescope Array], *Anisotropy search in the Ultra High Energy Cosmic Ray Spectrum in the Northern Hemisphere using latest data obtained with Telescope Array surface detector*, PoS **ICRC2021**, 344 (2021) doi:10.22323/1.395.0344 [arXiv:1707.04967 [astro-ph.HE]].

[78] T. Fujii [Telescope Array], *Update on the large-scale cosmic-ray anisotropy search at the highest energies by the Telescope Array Experiment*, PoS **ICRC2021**, 291 (2021) doi:10.22323/1.395.0291

[79] J. Kim *et al.* [Telescope Array], *Hotspot Update, and a new Excess of Events on the Sky Seen by the Telescope Array Experiment*, PoS **ICRC2021**, 328 (2021) doi:10.22323/1.395.0328

[80] P. Tinyakov *et al.* [Telescope Array and Pierre Auger], *The UHECR dipole and quadrupole in the latest data from the original Auger and TA surface detectors*, PoS **ICRC2021**, 375 (2021) doi:10.22323/1.395.0375

[81] A. di Matteo *et al.* [Telescope Array and Pierre Auger], *UHECR arrival directions in the latest data from the original Auger and TA surface detectors and nearby galaxies*, PoS **ICRC2021**, 308 (2021) doi:10.22323/1.395.0308

[82] A. Vásquez Ramírez *et al.* [Pierre Auger], *Study on multi-ELVES in the Pierre Auger Observatory*, PoS **ICRC2021** (2021), 327 doi:10.22323/1.395.0327

[83] L. Marcelli *et al.* [JEM-EUSO], *Observation of ELVES with Mini-EUSO telescope on board the International Space Station*, PoS **ICRC2021** (2021), 367 doi:10.22323/1.395.0367

[84] J. Remington, *Insight Into Lightning Initiation via Downward Terrestrial Gamma-ray Flash Observations at Telescope Array*, PoS **ICRC2021** (2021), 345 doi:10.22323/1.395.0345

[85] P. Abreu *et al.* [Pierre Auger], *Downward Terrestrial Gamma-ray Flashes at the Pierre Auger Observatory?*, PoS **ICRC2021** (2021), 395 doi:10.22323/1.395.0395

[86] B. Hariharan, S. Ahmad, M. Chakraborty, A. Chandra, S. R. Dugad, U. D. Goswami, S. K. Gupta, Y. Hayashi, P. Jagadeesan and A. Jain, *et al. The azimuthal distribution of thunderstorm events recorded by the GRAPES-3 experiment*, PoS **ICRC2021** (2021), 378 doi:10.22323/1.395.0378

[87] R. Abbasi *et al.* [Telescope], *Observation of Variations in Cosmic Ray Shower Rates During Thunderstorms and Implications for Large-Scale Electric Field Changes*, PoS **ICRC2021** (2021), 297 doi:10.22323/1.395.0297

[88] A. Golzio *et al.* [JEM–EUSO], *A study on UV emission from clouds with Mini-EUSO*, PoS **ICRC2021** (2021), 208 doi:10.22323/1.395.0208

[89] P. Abreu *et al.* [Pierre Auger], *Satellite Data for Atmospheric Monitoring at the Pierre Auger Observatory*, PoS **ICRC2021** (2021), 235 doi:10.22323/1.395.0235

[90] A. Chilingarian, *The progress of High-Energy Physics in Atmosphere achieved with the implementation of particle physics and nuclear spectroscopy methods*, PoS **ICRC2021** (2021), 366 doi:10.22323/1.395.0366