The Snowmass UHECR White Paper on Ultra-High-Energy Cosmic Rays

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Abstract. This proceeding summarizes the talk given at the opening of the UHECR 2022 conference in L'Aquila on the whitepaper 'Ultra-High-Energy Cosmic Rays: The Intersection of the Cosmic and Energy Frontiers' [Astroparticle Physics 149 (2023) 102819 - arXiv:2205.05845] that has been prepared for the Snowmass survey in the USA. The whitepaper provides an overview of recent progress and open questions regarding the particle physics and astrophysics related to ultra-high-energy cosmic rays (UHECR) and outlines the connections between the particle and astrophysics aspects of cosmic rays. It also discusses what instrumentation is needed to address the major scientific questions in ultra-high-energy cosmic-ray physics. While the upgraded Pierre Auger Observatory and Telescope Array will remain the workhorses at the highest energies in the current decade, new experiments with significantly higher exposure are needed in the coming decade. Ground arrays featuring simultaneous detection of the position of the shower maximum and the size of the muonic component will enable particle astronomy by measuring the rigidity of individual events. They should be complemented by other detectors maximizing the total exposure. This can be achieved by a few next-generation experiments using the latest developments in detection and analysis techniques: GRAND as a ground-based radio array, and POEMMA as a space-borne stereo fluorescence telescope will feature complementary approaches to provide maximum exposure; IceCube-Gen2 with its surface array, and GCOS aim at increased statistics with high accuracy for particle physics and rigidity-based galactic and extra-galactic astrophysics. While designed to discover the astrophysical cosmic-ray sources at the highest energies, the same experiments also contribute to particle physics, e.g., by studying the muon puzzle in cosmic-ray air showers, and by their discovery potential for exciting new physics, such as certain Dark Matter candidates. With the full whitepaper available as a reference, this proceeding will briefly present the science cases of the experiments, highlighting their individual strengths and outlining how they complement each other.

1 Introduction

Snowmass is a 'particle physics community planning exercise' which is run every decade in the United States to discuss the scientific questions and experiments of the coming decades in order to inform U.S. funding agencies [2]. Cosmic-ray physics is part of the Snowmass 'Cosmic Frontier' [3] topical group 7 'CF7 - Cosmic Probes of Fundamental Physics' [4], whose conveners solicited a whitepaper about the status and future of ultra-high-energy cosmic rays (UHECR). By eliciting the help of the international UHECR community, we have prepared the requested whitepaper, which meanwhile has been published in Astroparticle Physics [1].

The whitepaper presents the recent progress and open questions on both the particle physics and astrophysics side of UHECR physics, and additionally summarizes relations to other fields of science. Earlier, for the Astro2020 survey in the U.S., two shorter whitepapers were published with a more specific focus on Galactic and extragalactic cosmic rays, respectively [5, 6]. While these are still worth reading, the Snowmass whitepaper is more comprehensive and is the result of a more extensive community process, including input from the major UHECR collaborations and individual scientists through several small online workshops. Finally, scientists who did not contribute directly were given the option to comment on and endorse the whitepaper. As the whitepaper reflects a wide community effort, it is highly recommended to read at least its executive summary [1].

Since that executive summary of the whitepaper stands on its own, this proceeding does not provide a redundant full summary, but instead provides an overview on

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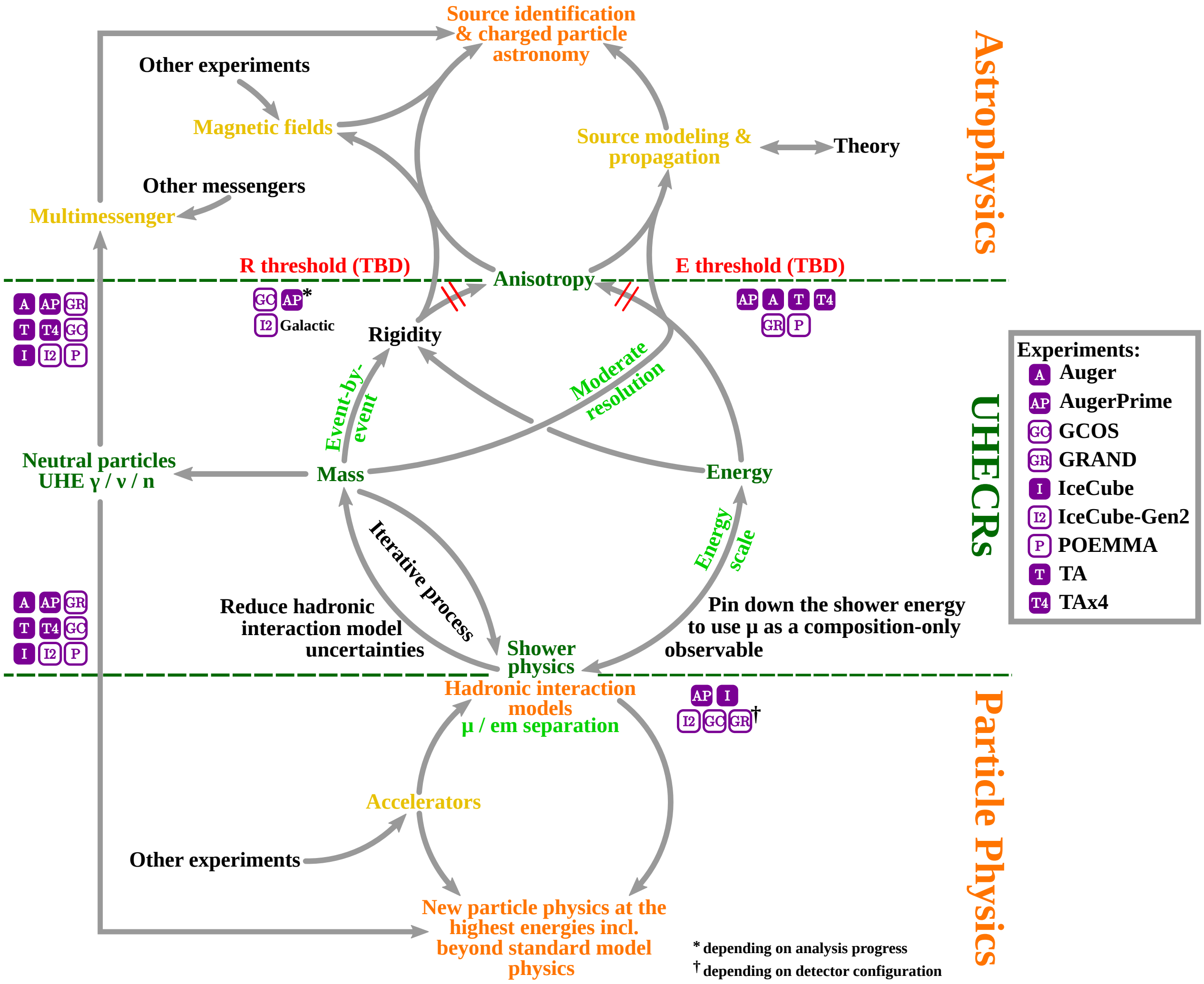

Figure 1. Sketch of how ultra-high-energy cosmic rays (UHECRs) are related to astrophysics and particle physics, and how current and future experiments contribute to each of these areas of physics. The mass and energy of the primary UHECRs are derived from air-shower measurements. These air-shower measurements are also used to study hadronic interactions and complement accelerator experiments, particularly in the forward region. Improvements of hadronic interaction models, in turn, will increase the accuracy of the mass derived from the measured air showers. Depending on the mass resolution, the astrophysics question of the UHECR sources is targeted either by rigidity-enhanced anisotropy measurements, which potentially enables particle astronomy by back-tracking through the magnetic fields in space, or by statistically comparing source models to measured anisotropy and mass composition. Finally, the search for neutral EeV particles, such as photons and neutrinos, enables a multi-messenger access to the UHECR sources and offers discovery potential for new particle physics beyond the standard model. (Figure from Ref. [1])

two particular aspects discussed in the whitepaper. These are connections between the particle and astrophysics aspects of UHECR and the major experiments planned to address open questions regarding UHECR physics. Nonetheless, also for these topics, the whitepaper itself contains a wealth of valuable information that are not presented here in the same detail.

Definition of ultra-high-energy cosmic rays (UHECR): UHECR are typically defined as cosmic rays above an arbitrary energy threshold. Often, 1 EeV is chosen as the threshold because of a prefix step when using the unit eV for energy, although no apparent physics change is happening at this energy. For the whitepaper, we have instead chosen approximately 10^{17} eV, which is close to the heavy/second knee(s) in the energy spectrum [7–10], where presumably the transition to extragalactic cosmic ray starts.

2 UHECR: Particle Physics and Astrophysics at the Highest Energies

Ultra-high-energy cosmic rays are the most energetic particles known in the Universe. In the past decades, we have learned that UHECR are atomic nuclei of a mixed mass composition [11, 12]. Neutral particles, such as photons or neutrinos have yet to be discovered at EeV energies, setting strong limits on their flux [13–15]. Together with the UHECR anisotropy discovered above 8 EeV [16], these experimental results provide evidence that (at least the majority of) UHECR are not the decay products of some un-

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Figure 2. Current and future experiments leading the field of ultra-high-energy cosmic rays. To some extent, all experiments contribute to both astrophysics and particle physics related to UHECR. Nonetheless, they have different strengths and complement each other: the Pierre Auger Observatory currently provides the highest measurement accuracy and largest exposure for UHECR and is in the southern hemisphere; the upgraded Telescope Array will provide a similar exposure at the highest energies in the northern hemisphere; IceCube(-Gen2) with its surface and in-ice arrays is a unique laboratory to measure air showers up to a few EeV, i.e., up to the energy range of the Galactic-to-extragalactic transition; GRAND and POEMMA will offer the highest statistics for UHECR with very complementary approaches and will additionally target UHE neutrinos; GCOS will be optimized for high statistics and high accuracy at the same time to provide an event-by-event rigidity measurement of UHECR. (Figure from Ref. [1])

known superheavy particles, but originate from natural accelerators, and are, at the highest energies, of extragalactic origin.

The composition of UHECR is lightest in the energy range of the ankle of the cosmic-ray energy spectrum at about 5 EeV [12], which implies that the fraction of protons is high at the ankle energy and decreases towards higher energies. Protons are not excluded making up a small fraction of the UHECR flux at the highest energies, but as of yet, no strong evidence exists for protons at energies significantly above 10^{19} eV. Therefore, although several air showers beyond 10^{20} eV have been measured, the highest energy per nucleon might be limited to around 10^{19} eV, and the highest rigidity of UHECR reaching Earth might be around 10 EV.

For astrophysics, this situation makes reaching the goal of particle astronomy with UHECR more challenging, since the magnetic deflection at 10 EV is still significant. Consequently, if really no particles would exist with rigidities significantly about 10 EV, then particle astronomy cannot be achieved by simply collecting higher statistics at the highest energies, but will additionally require tracing individual UHECR deflections back through the Galactic and extragalactic magnetic fields. On the one hand, this means the magnetic fields will need to be known well enough, which will possibly be achieved during the coming decade. On the other hand, particle astronomy will be difficult without an approximate measurement of the rigidity of the individual cosmic rays and, thus, per-event mass sensitivity at least for the energy range from 10^{19} eV to several 10^{19} eV.

Possibly, the composition will be nearly pure at extremely high energies around and above 10^{20} eV, i.e., dominated by nuclei of one mass group. In that scenario, once the mass composition around 10^{20} eV is measured statistically, the rigidity can easily be determined from the energy alone, and per-event mass sensitivity will be unnecessary at the highest energies. At lower energies, higher statistics will even help without knowing the mass on per-event level, as the average mass composition and anisotropy can be tested against theoretical models. Therefore, while it is mandatory to have at least one UHECR observatory featuring event-by-event rigidity resolution below 10^{20} eV, the need for event-by-event rigidity resolution above 10^{20} eV is not yet clear and depends on whether or not UHECR have a mixed or pure mass composition at the highest energies.

Given the unknown mass composition above 10^{20} eV, it is advisable to have at least one UHECR observatory of each type, i.e., at least one observatory that maximizes the exposure at the highest energies, and one observatory that features per-event mass sensitivity enabling rigidity-based particle astronomy. In any case, full sky coverage for UHECR is important, which requires a space-borne observatory or at least two sites for ground arrays.

For particle physics, even 10^{19} eV is far beyond the reach of accelerator experiments. In addition to guaranteed progress in particle physics, such as the measurement of the proton-air cross-section [17, 18], UHECR also provide a probe for new physics, such as the search for Lorentz invariance violation [19], or super-heavy Dark Matter [20, 21]. Moreover, cosmic-ray air showers will continue to be a unique probe of hadronic interactions in the forward region, a phase space which is difficult to cover in accelerator experiments.

Of particular interest in this respect is the study of the muon puzzle. Several UHECR air-shower experiments have measured with high significance that Monte Carlo simulations of air showers using state-of-the-art hadronic interaction models predict fewer muons than measured by these experiments. The discrepancy increases with energy [22], and there are tensions between hadronic interaction models and measurements also regarding other muon-related observables, such as the dependence on zenith angles [23] or the muon production depth [24]. More accurate air-shower measurements are needed to test the predictions of improved hadronic interaction models. Air-shower arrays also offer many synergies with accelerator experiments, including, but not limited to, the investigation of the muon puzzle [25].

Finally, a better understanding of the particle physics in air showers also has a positive impact on UHECR astrophysics. This is because the hadronic interaction models are used to interpret air-shower measurements, and better models will improve the accuracy of the air-shower reconstruction, in particular, regarding the mass of the primary particle. In a virtuous circle, air-shower detectors can iteratively contribute to a better understanding of the particle physics in these showers. Then, this better understanding improves the quality of the cosmic-ray mass reconstructed from air-shower measurements, which in turn can be used to test for finer discrepancies between the hadronic interaction models and the measurements. Consequently, also the astrophysics science related to UHECR benefits from progress on the particle physics side.

3 Experiments for the next Decades

This section provides an overview of current and future UHECR experiments that are needed to address the particle and astrophysics questions. In addition to the running experiments Auger, TA, and IceCube with their ongoing/planned enhancements AugerPrime, TAx4, and IceCube-Gen2, three future experiments have been identified as being crucial for UHECR science in the coming decade. These are the Giant Radio Array for Neutrino Detection (GRAND), the Probe of Extreme Multi-Messenger Astrophysics (POEMMA), and the Global Cosmic Ray Observatory (GCOS), which complement each other in detection techniques and science goals. Fig. 2 contains those experiments that have been identified in the whitepaper as the major efforts needed in the field. This list is not complete. It does not contain experiments for lower cosmic-ray energies, and there can be additional experiments making a unique contribution to a specific aspect of UHECR physics. Except for IceCube-Gen2 and GRAND, all of the major experiments were represented by dedicated contributions at the conference, which is why this section only provides a short overview, instead focusing on the complementary approaches to the particle and astrophysics sides of UHECR science.

With their upgrades close to completion, the **Pierre Auger Observatory** in Malargüe, Argentina [26], and the **Telescope Array (TA)** in Utah, USA [27] will remain the workhorses of UHECR physics until at least the end of the decade. The upgrade of TA, called **TAx4**, primarily increases the size of TA: at the highest energies, TA will feature an aperture in the northern hemisphere similar to the aperture of Auger in the southern hemisphere. The upgrade of Auger, called **AugerPrime**, does not change the size of the surface array, but rather increases the measurement accuracy for individual showers, which enables a number of new analyses, such as mass-sensitive anisotropy studies or more stringent tests of hadronic interaction models. For recent results and the status of the upgrades of Auger and TA, please check the dedicated contributions

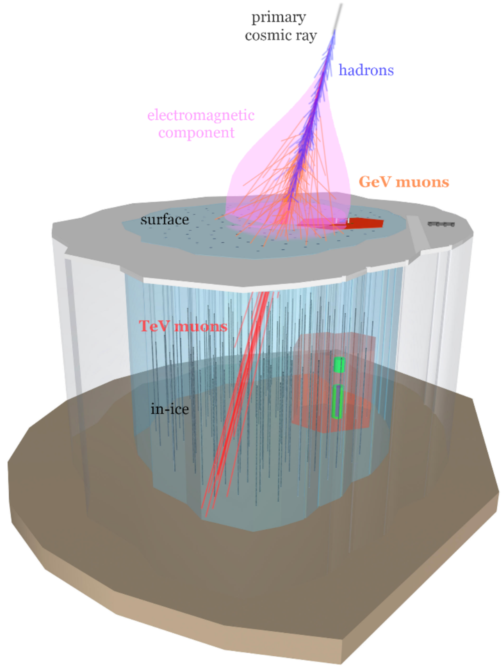

Figure 3. IceCube-Gen2, though optimized for neutrino astronomy, will also be a unique lab to study particle physics in air-showers because a surface measurement of the electromagnetic component and low-energy muons is combined with a high-energy muon measurement in the ice. Compared to the current IceCube detector with its surface array IceTop (in red), the larger IceCube-Gen2 detector (light blue) will measure surface-deep coincidences for a wider range of zenith angles. Together with the larger surface area, this will result in an overall 30x increase of aperture for such surface-deep coincident events. [Figure courtesy of the IceCube-Gen2 collaboration [28]]

presented at this conference. Important in the context of next-generation experiments is that AugerPrime will pioneer the concept of a detector dedicated to an event-by-event mass sensitivity, realized by adding scintillators (for vertical and mildly inclined events) and radio antennas (for very inclined events) to the water-Cherenkov detectors of the surface array.

Built primarily for neutrino astronomy, **IceCube** also is a unique lab for cosmic-ray air showers due to the combination of a surface array and a deep optical detector [29], and makes essential contributions to the physics of the most energetic Galactic cosmic rays in the energy range up to around one EeV. With **IceCube-Gen2** [30], both arrays will be extended, and a new design for the surface array will enhance the accuracy. Mitigating the problem of snow accumulation above the existing ice-Cherenkov tanks of the IceTop surface array, the IceCube-Gen2 surface array will consist of elevated scintillators and elevated radio antennas [31, 32]. The latter provides a measurement of energy of the electromagnetic shower component [33–35] and of $X_{\max}$ [36–39], which enhances the total accuracy for studies of the cosmic-ray mass composition. In combination with the high-energy muons from the in-ice optical detector, IceCube-Gen2 will feature per-event mass sensitivity for the energy range of the Galactic-to-extragalactic transition. Through its higher aperture, it will extend IceCube's anisotropy measurements from currently a few PeV [40] to around 100 PeV.

In addition to the astrophysics of the most energetic Galactic cosmic rays, IceCube-Gen2 provides distinct capabilities to study particle physics in air showers. This is because the deep optical array in the ice can measure the TeV and PeV muons produced in the same shower detected by the surface array (see Fig. 3). Through its larger area and larger range of zenith angles for surface-deep coincidences, IceCube-Gen2 will have a thirty times larger aperture for such cosmic-ray events measured simultaneously in the surface and deep arrays. These can be used to study atmospheric leptons in general, such as the muon puzzle, and specifically also prompt decays, such as muons originating from charm decays. Studying hadronic interactions is a science goal by itself. Nonetheless, improved knowledge on the hadronic interactions and particularly on the flux of prompt leptons will also lower uncertainties on atmospheric backgrounds for neutrino astronomy, and it will help in general to interpret air-shower measurements more accurately.

Other experiments reaching into the energy range above 100 PeV are **LHAASO**, potentially **SWGO**, and the **SKA**. While SWGO [41] and LHAASO [42] have gamma astronomy as their primary target, they will also make important contributions to cosmic-ray physics with their ultra-dense arrays and, in the case of LHAASO, through the simultaneous measurements of air showers by several detection techniques. The low-frequency array of the Square Kilometer Array (SKA-low) will feature several 10,000's of radio antennas and enable unprecedented precision on the radio signal of air showers [43]. While radio detection of air showers has become a standard technique [44, 45], e.g., for energy and $X_{\max}$ measurements, SKA can measure finer details of the shower profile beyond $X_{\max}$ [46]. On the one hand, this increases the accuracy of the proton and Helium fractions among the cosmic rays around the second knee energy; on the other hand, the ultra-high precision enables new ways to test hadronic interaction models, as these differ not only in the number and distribution of muons, but also predict slightly different longitudinal profiles of the electromagnetic component [46]. Therefore, even without the capability to measure high-energy muons, the SKA will make an important complementary contribution to cosmic-ray astrophysics and particle physics below 1 EeV.

For the highest energies, GCOS will provide high measurement accuracy for air showers in combination with a larger full-sky aperture. It will be complemented by two experiments aiming at huge full-sky exposure of UHECR that exceeds the currently leading Pierre Auger Observatory by more than an order of magnitude: POEMMA and GRAND.

POEMMA [47] will consist of two space-borne fluorescence telescopes for stereo observation of air showers. The goals of POEMMA are searching for UHE neutrinos and measuring UHECR with unmatched statistics. The fluorescence technique is mature and provides high accuracy for energy and $X_{\max}$, which translates into high precision for the average mass composition. Building on the experience of the JEM-EUSO program [48, 49], POEMMA will bring key advances to multi-messenger astronomy at the highest energies.

GRAND [50] will be a giant radio array aiming at UHE neutrino as primary science case. Nonetheless, if built to its full size of about 200,000 antennas distributed among several sites totalling 200,000 km^2, GRAND will provide a similar exposure for UHECR as POEMMA. During the next years, further R&D is required to apply radio detection as a stand-alone technique on such a large scale, and the radio emission of nearly horizontal showers needs to be understood in further detail. For this purpose, various prototypes of GRAND are planned, and dedicated simulation studies are performed. Although from the UHECR perspective the science goals are similar to POEMMA, GRAND is very complementary in the approach (huge ground array vs. space-borne stereo telescope, and promising radio vs. established fluorescence technique).

Finally, **GCOS** [51] will be the UHECR ground array that will be designed for the maximum per-event measurement accuracy feasible, enabling rigidity-enhanced particle astronomy. The exact design of GCOS is currently under discussion in the community, with the plan to conduct necessary R&D and tests during this decade. At least two sites of several 10,000 km^2 total are needed, better a few sites for smooth full-sky coverage. Several sites will also facilitate the participation of several countries in the project, and with both GRAND and GCOS featuring several sites, at least one of the sites should be in common for the purpose of cross-calibration and to benefit from shared infrastructure.

The baseline design of a GCOS site is a ground array of particle detectors, possibly segmented or nested water-Cherenkov detectors enhanced by radio antennas, to provide a 24/7 measurement of the electromagnetic (for energy and $X_{\max}$) and muonic shower component over a wide range of zenith angles. Due to the complementary mass sensitivity of muons and $X_{\max}$, a simultaneous measurement of both observables for each individual event is essential to estimate the rigidity of the primary cosmic rays. Also, some of the sites can feature additional detectors, such as next-generation fluorescence telescopes which would further enhance the measurement accuracy of the electromagnetic component during clear nights [52, 53]. Nonetheless, decent $X_{\max}$ measurements may already be possible with the particle detectors alone, e.g., by using neural networks for the analysis of the traces of water-Cherenkov detectors [54]. The high accuracy for both, the muon number and $X_{\max}$, will also help other science cases, such as the selection of protons or the search for neutral particles.

4 Conclusion

Thanks to the increasing quality of UHECR measurements in the past decade, UHECR science has entered an interesting era with the resolution of its most exciting puzzles possibly in reach. The discovery of anisotropy and mixed mass composition in the past decade provided evidence for UHECR originating from astrophysical accelerators, and the first UHECR sources may be discovered by the upgraded observatories during this decade. Nonetheless, it is unknown to what extent this answers the question of the origin of UHECR, and it is likely that a comprehensive picture of the sources can only be obtained by the next generation of UHECR observatories.

Also, in regard to the particle physics of air showers, in particular, for discrepancies between hadronic interaction models and measured muons, progress is expected from the upgraded UHECR observatories, as well as new accelerator experiments. While the muon puzzle may be solved during the next decade, it often happens that a more accurate generation of experiments discovers new puzzles and discrepancies between models and measurements. Furthermore, searching for BSM physics and for neutral EeV particles certainly requires a new generation of air-shower observatories with higher exposure.

In parallel to increasing the exposure, the mixed mass composition mandates an increase in accuracy for the reconstruction of the mass of the primary cosmic-ray particles. It is important to realize that the event-by-event precision for the mass is intrinsically limited by shower-to-shower fluctuations. Perfect resolution of either the muon number or $X_{\max}$ alone is insufficient, and therefore, a simultaneous measurement of both shower parameters is necessary to improve the accuracy of the rigidity of individual events.

Current observatories, such as AugerPrime, provide ideal testbeds for next generation instrumentation. Especially R&D of optimized detectors designs, such as surface detectors for simultaneous $X_{\max}$ and muon measurements, is needed during the next years to prepare for the construction of future ground arrays. Featuring an event-by-event rigidity estimate, GCOS will be the ground array leading the field of rigidity-enhanced particle astronomy. GCOS' UHECR physics will be complemented by the observation of other messengers up to EeV energies, and by the huge UHECR exposure of GRAND and POEMMA.

References

[1] A. Coleman et al., Astropart. Phys. **149**, 102819 (2023), 2205.05845

[2] J.N. Butler et al., *Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021) Summary Chapter*, in *2022 Snowmass Summer Study* (2023), 2301.06581

[3] A.S. Chou et al., *Snowmass Cosmic Frontier Report*, in *2022 Snowmass Summer Study* (2022), 2211.09978

[4] R.X. Adhikari et al. (2022), 2209.11726

[5] F.G. Schröder et al., Bull. Am. Astron. Soc. **51**, 131 (2019), 1903.07713

[6] F. Sarazin et al., Bull. Am. Astron. Soc. **51**, 93 (2019), 1903.04063

[7] W.D. Apel et al. (KASCADE Grande), Phys. Rev. Lett. **107**, 171104 (2011), 1107.5885

[8] R.U. Abbasi et al. (Telescope Array), Astrophys. J. **865**, 74 (2018), 1803.01288

[9] M.G. Aartsen et al. (IceCube), Phys. Rev. D **100**, 082002 (2019), 1906.04317

[10] P. Abreu et al. (Pierre Auger), Eur. Phys. J. C **81**, 966 (2021), 2109.13400

[11] A. Aab et al. (Pierre Auger), Phys. Lett. B **762**, 288 (2016), 1609.08567

[12] H.P. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev, PoS **ICRC2017**, 533 (2018), 1711.11432

[13] P. Abreu et al. (Pierre Auger), Astrophys. J. **933**, 125 (2022), 2205.14864

[14] A. Aab et al. (Pierre Auger), JCAP **10**, 022 (2019), 1906.07422

[15] R.U. Abbasi et al. (Telescope Array), Astropart. Phys. **110**, 8 (2019), 1811.03920

[16] A. Aab et al. (Pierre Auger), Astrophys. J. **891**, 142 (2020), 2002.06172

[17] P. Abreu et al. (Pierre Auger), Phys. Rev. Lett. **109**, 062002 (2012), 1208.1520

[18] R.U. Abbasi et al. (Telescope Array), Phys. Rev. D **92**, 032007 (2015), 1505.01860

[19] P. Abreu et al. (Pierre Auger), JCAP **01**, 023 (2022), 2112.06773

[20] P. Abreu et al. (Pierre Auger) (2022), 2203.08854

[21] P. Abreu et al. (Pierre Auger) (2022), 2208.02353

[22] D. Soldin (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array), PoS **ICRC2021**, 349 (2021), 2108.08341

[23] W.D. Apel et al. (KASCADE-Grande), Astropart. Phys. **95**, 25 (2017), 1801.05513

[24] A. Aab et al. (Pierre Auger), Phys. Rev. D **90**, 012012 (2014), [Addendum: Phys.Rev.D 90, 039904 (2014), Erratum: Phys.Rev.D 92, 019903 (2015)], 1407.5919

[25] J. Albrecht et al., Astrophys. Space Sci. **367**, 27 (2022), 2105.06148

[26] A. Aab et al. (Pierre Auger), Nucl. Instrum. Meth. A **798**, 172 (2015), 1502.01323

[27] T. Abu-Zayyad et al. (Telescope Array), Nucl. Instrum. Meth. A **689**, 87 (2013), 1201.4964

[28] IceCube-Gen2 Collaboration, e.g., IceCube-Gen2 Technical Design Report (in preapration); and proceedings of the 6th ARENA 2022 (submitted)

[29] R. Abbasi et al. (IceCube), Nucl. Instrum. Meth. A **700**, 188 (2013), 1207.6326

[30] M.G. Aartsen et al. (IceCube-Gen2), J. Phys. G **48**, 060501 (2021), 2008.04323

[31] F. G. Schroeder for the IceCube-Gen2 Collaboration (IceCube-Gen2), PoS **ICRC2021**, 407 (2021)

[32] A. Leszczynska for the IceCube-Gen2 Collaboration (IceCube-Gen2), PoS **ICRC2021**, 411 (2021)

[33] A. Aab et al. (Pierre Auger), Phys. Rev. Lett. **116**, 241101 (2016), 1605.02564
[34] P. A. Bezyazeekov et al. - Tunka-Rex Collaboration (Tunka-Rex), JCAP **01**, 052 (2016), 1509.05652
[35] W.D. Apel et al. (LOPES), Eur. Phys. J. C **81**, 176 (2021), 2102.03928
[36] W. D. Apel et al. - LOPES Collaboration (LOPES), Phys. Rev. D **85**, 071101 (2012), 1203.3971
[37] S. Buitink et al. (LOFAR), Phys. Rev. D **90**, 082003 (2014), 1408.7001
[38] W. D. Apel et al. - LOPES Collaboration, JCAP **09**, 025 (2014), 1404.3283
[39] P. A. Bezyazeekov et al. - Tunka-Rex Collaboration, Phys. Rev. D **97**, 122004 (2018), 1803.06862
[40] M.G. Aartsen et al. (IceCube), Astrophys. J. **826**, 220 (2016), 1603.01227
[41] P. Abreu et al. (2019), 1907.07737
[42] C. Zhen et al. (LHAASO), Chin. Astron. Astrophys. **43**, 457 (2019)
[43] T. Huege et al., EPJ Web Conf. **135**, 02003 (2017), 1608.08869
[44] T. Huege, Phys. Rept. **620**, 1 (2016), 1601.07426
[45] F.G. Schröder, Prog. Part. Nucl. Phys. **93**, 1 (2017), 1607.08781
[46] S. Buitink et al., PoS **ICRC2021**, 415 (2021)
[47] A.V. Olinto et al. (POEMMA), JCAP **06**, 007 (2021), 2012.07945
[48] A. Santangelo et al. (JEM-EUSO), Exper. Astron. **40**, 3 (2015)
[49] E. Parizot et al. (JEM-EUSO), *The JEM-EUSO program*, in *These Proceedings* (2023)
[50] J. Álvarez-Muñiz et al. (GRAND), Sci. China Phys. Mech. Astron. **63**, 219501 (2020), 1810.09994
[51] J.R. Hörandel (GCOS), PoS **ICRC2021**, 027 (2021), 2203.01127
[52] T. Fujii et al., Astropart. Phys. **74**, 64 (2016), 1504.00692
[53] M. Malacari et al., Astropart. Phys. **119**, 102430 (2020), 1911.05285
[54] A. Aab et al. (Pierre Auger), JINST **16**, P07019 (2021), 2101.02946