Statement of the Pierre Auger Collaboration as input for the 2026 European Particle Physics Strategy

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Abstract

This document describes, on behalf of the Pierre Auger Collaboration, the close relation between the research interests of the particle and astroparticle physics communities. We underline the main areas in which synergies between the CERN and the astroparticle physics fields of reasearch can be developed, providing input to the 2026 European Particle Physics Strategy Update. We conclude with recommendations on cooperation in topics of mutual interest, and on suggested astroparticle-related activities at CERN.

Scientific context

Many important and challenging questions about the fundamental constituents of nature, their interactions, and the evolution of the Universe and its extreme environments remain unanswered. Astroparticle physics, situated at the interface of particle physics, astrophysics and cosmology, aims to provide crucial insights to address these fundamental questions. A concerted and vigorous programme of experimental astroparticle and particle physics is needed to exploit the full potential of the observed high-energy universe. It is essential to emphasise the importance of a balanced programme of theoretical, experimental and observational activities. These activities must be synergistic and complementary to the collider program at CERN in order to address the remaining challenging questions.

At the highest-energy frontier, the Pierre Auger Observatory is the worldwide largest and most highly developed experiment for the investigation of ultra-high energy cosmic rays (UHECRs) [1]. Operated by an international collaboration among 17 countries, with about 400 scientists, it started its data collection in 2004 and has since provided data of unprecedented quality and statistics.
The rich harvest of the Pierre Auger Collaboration covers different and complementary areas of research. Our main goal is to discover the sources and the nature of UHECRs, which are key open problems in high-energy astroparticle physics. At the same time, a central goal of the research is to study particle physics interactions in an extreme energy regime (above about 10^{17} eV) and in a phase-space regime that cannot be reached by human-made accelerators, which is essential for the interpretation of our results. The Pierre Auger Observatory is a major contributor to multi-messenger observations, searching for photons and neutrinos of both cosmological and astrophysical nature, correlating its data with those of many other collaborations, such as IceCube, ANTARES, Telescope Array, LIGO and Virgo, and contributing to large networks searching for transients and their counterparts, such as the recently launched Astrophysics Center for Multimessenger studies in Europe, ACME [2].

The Observatory has recently been upgraded [3], adding to its detectors (1660 water Cherenkov stations and 27 fluorescence telescopes) new scintillators and radio antennas and the data acquisition has been extended to ten years more, until 2035.
The purpose of the upgrade is to obtain more information on the mass composition of UHECRs at the highest energies. This will provide a means to discriminate between different classes of models and to learn more about, or even identify, UHECR sources or source regions that have not yet been revealed. At the same time, the relationship between the interpretation of the data in terms of UHECRs nuclear composition and the physics of hadronic interactions will be crucial, since the showers measured with the Auger Observatory typically contain 20 to 30% more muons than predicted by current interaction models. The results obtained at Auger already contributed to trigger enor-

mous efforts to modify hadronic interaction model generators used both at accelerators and for UHECRs. They also opened up the possibility that unexpected behaviour might be due to new physics of hadronic interactions at extreme energy scales or in regions of phase space beyond the reach of the LHC and other particle physics experiments, making the Pierre Auger Observatory a natural laboratory to validate theoretical predictions about interactions at ultra-high energies.

Already since its foundation, the Pierre Auger Collaboration maintains very close ties with then international particle physics community in general, and CERN in particular. The very first meeting of the starting collaboration was held at CERN back in 1995. The Pierre Auger Observatory is a CERN recognized experiment.
The first plans for a closer interlink of the two communities were drawn up already in 2002, in the context of the NEEDS workshop. Regular Auger-related conferences and schools have since then been organized at or with the support of CERN (e.g. ISVHECRI 2002 and 2014, UHECR 2012, ISAPP School 2018, ICRC 2025); the role of UHECRs has been underlined in a dedicated chapter of the "LHC forward physics" report in 2016.
Most recently, CERN hosted the 2024 edition of the XSCRC workshop, where different communities (CR theorists, CR experimentalists, nuclear and particle physicists) met to review theoretical motivations for CR studies, new CR data, and how the modeling of CRs crucially depends on nuclear reactions.

The particle physics questions discussed in the European Strategy for Particle Physics are of direct relevance to the Pierre Auger Observatory. On the one hand, the interpretation of air shower data relies heavily on our knowledge of particle interaction, production, and decay over a very wide range of energies and phase-space regions. The theory of particle physics and the measurements made at accelerators provide indispensable input to the understanding of extensive air showers. On the other hand, studying air showers can provide information not attainable at collider experiments and tests on the predictions of the models in the ultra-high energy region have been performed in the Pierre Auger Observatory in different analyses.
The p-Air cross-section was measured for the first time at $\sqrt{s} = 57$ TeV [4]; based on this result, the stability of the mass composition fits was checked with respect to allowed changes in the p-p cross-section. A deficit in the number of muons predicted at various levels by all models was demonstrated by several independent studies of the muon content in air showers above 0.1 EeV [5, 6], indicating that a 30% to 80% increase in the relative muon number would be needed to match the measurement. At the same time, a study of the relative fluctuations in the muon number [7] showed that the post-LHC models describe well the fluctuations of the energy partition in the first interaction up to ultra-high energies. This result ruled out strong deviations in the first interaction, suggesting that instead a small effect accumulating over many generations could be invoked to increase the muon number. A test of the predictions of the models has recently been performed [8], allowing rescaling of both the electromagnetic and hadronic components in the simulations. A deeper evolution of the shower in the atmosphere, by about 20 to

50 g cm^{-2}, and an increased hadronic signal, by about 15% to 25%, allowed to reduce the differences between the hadronic interaction models used in the shower simulations. Furthermore, the combination of data from the Auger Observatory with astrophysical information extends the reach of physics to fundamental phenomena, e.g. providing important constraints on quantum gravity theories involving Lorentz invariance violation, or on the properties of possible super-heavy dark matter.

Objectives

In many aspects, accelerator and non-accelerator physics work on the same or similar topics in a methodologically complementary way. In the following, we showcase three specific areas in which concrete synergies can be exploited and which enable direct cross-fertilisation while addressing the above-mentioned challenges. Starting from this, we subsequently formulate overarching recommendations for fostering productive collaboration.

Hadronic Interaction Generators

In high-energy and astroparticle physics, event generators play an essential role, even in the simplest data analyses. As analysis techniques become more sophisticated, e.g. based on deep neural networks, their correct description of the observed event characteristics becomes even more important. Physical processes occurring in hadronic collisions are simulated within a Monte Carlo framework. A major challenge is the modeling of hadron dynamics at low momentum transfer, which includes the initial and final phases of every hadronic collision [9]. QCD-inspired phenomenological models used for these phases cannot guarantee completeness or correctness over the full phase space. These models usually include parameters which must be tuned to suitable experimental data. Until now, event generators have been developed and tuned mainly on the basis of data from high-energy physics experiments at accelerators. The wealth of data available from the latest generation of astroparticle experiments has not yet been fully exploited and, in many cases, is not satisfactorily described [10]. Both kinds of data sets are complementary as astroparticle experiments provide sensitivity especially to hadrons produced near parallel to the collision axis and cover center-of-mass energies up to several hundred TeV, well beyond those reached at colliders so far.

To be used in air shower simulations, these models require a unique parameter set for all energies and collision systems, giving them a better predicting power than event generators such as PYTHIA [11] used in the analysis of high-energy physics experiments. This was nicely illustrated at the start of the LHC, when the first results were better predicted by cosmic-ray event generators [12] such as EPOS [13], QGSJET [14] or Sibyll [15]. A collaboration with the ATLAS experiment had been established to make a special version of the EPOS model (EPOS LHC [16]) to be used both to analyze the LHC data and the cosmic ray data. More than 10 years later, this model is still widely used in both minimum bias data analysis and detector simulations of ATLAS, CMS or ALICE experiments. Recent work is also dedicated to adapting PYTHIA/ANGANTYR to be used for air shower simulations [17] and benefit from a global tune and the constraints provided by the Pierre Auger Observatory, and in particular, the correlation between different observables like the maximum shower development and the signal at ground [8].

New versions of hadronic interaction models, EPOS LHC-R [18] and QGSJET-III [19], are currently available taking into account the wealth of measurements done with the CERN facilities. They will improve the consistency of the description of data from the Pierre Auger Observatory, allowing a reduction of the systematic uncertainties associated to these models, and improving the astrophysics understanding of UHECRs [20]. At the same time, the new technical and theoretical development included in these models to describe air showers will be beneficial to the CERN community by a more detailed understanding of the measured data and of the detector response. Indeed, the particle cascade created by a TeV particle in a calorimeter is of the same nature as that of an air shower. The predictive power of these models can also be used to better understand the need for future FCC experiments [21].

Accelerator Data for Hadronic Interactions in Air Showers

The interpretation of cosmic-ray data from the Pierre Auger Observatory relies heavily on understanding particle cascades (“air showers”) in the atmosphere, particularly on accurately modeling hadron-air and nucleus-air interactions that occur during shower development. Therefore, these reactions must be modeled across a wide range of energies, from a few tens of GeV to beyond LHC energies.

Dedicated measurements of hadron production in air shower physics have been conducted at the LHC (e.g., LHCf-ATLAS [23] and CASTOR-CMS [22]) and in fixed-target experiments (e.g., NA61/SHINE at the SPS [24]). In addition, many other data sets help to constrain the hadronic interaction generators used in air shower analyses. In particular, the advent of high-energy data from all LHC experiments has significantly reduced uncertainties in the interpretation of cosmic-ray observations [12]. However, many observations at ultra-high energies remain unexplained by current air shower simulations. These include, but are not limited to, discrepancies between data and simulations in the number of muons in air showers (e.g. [10]) and the depth of muon production [25].

To determine whether these discrepancies arise from new physical phenomena at ultra-high energies or from small modeling inaccuracies that amplify during shower development, both low- and high-energy interactions must be known with percent-level precision. Furthermore, the astrophysical interpretation of Auger data requires a thorough understanding of hadronic interactions to establish the mass and charge of primary particles.

The Pierre Auger Collaboration looks forward to new results from the oxygen runs planned for 2025 at the LHC. These will help eliminate the considerable theoretical uncertainty in the current extrapolation of hadron production parameters from $p-p$ interactions to $p-O$ and $O-O$, both of which serve as relevant reference points for reactions in air showers [26]. Further future constraints on high-energy interactions relevant for air shower physics could be obtained from new experiments at the Forward Physics Facility (FPF) [27].

Search for effects Beyond Standard Model

Despite its impressive successes, the Standard Model of particle physics is known to be incomplete. There are numerous reasons to expect Beyond-Standard-Model (BSM) physics to take place at high scale. Ultimately, UHECRs are the only laboratory for probing such high-scale physics. Among the most emblematic topics, there are searches for Lorentz invariance violation, super-heavy dark matter or signatures of phase transitions in the early universe.

Exact symmetries governing the Standard-Model Lagrangian guarantee invariance under Lorentz and CPT transformations. Yet, theories that aim to describe Planck-scale physics might break these fundamental symmetries [28]. Although the scales at which interactions take place in air showers are many orders of magnitude away from the Planck scale, small effects at low energy might still be observable. To assess and predict possible violations of Lorentz invariance, effective field theories have been designed [29]. These models preserve gauge invariance but introduce Lorentz invariance violation through spontaneous symmetry breaking caused by scalar fields and/or through CPT violation, leading to preferential reference frame effects. This could lead, for example, to changes in the dispersion relations, resulting in different maximum attainable velocities for different particles or in vacuum birefringence and parity violation. Such radical changes compared to the Standard-Model expectations can leave important signatures in the development of air showers that can be observed from, e.g. abnormal fluctuations in the number of muons or abnormal shifts in the slant depth of the maxima of shower developments. Current constraints are already severe [30, 31, 32]; the tests of Lorentz invariance will even be more stringent with improved measurement techniques of muon numbers and depth of shower maxima.

The production of gamma rays and/or neutrinos at energies above $\sim 10^{10}$ GeV is only expected from cascade processes triggered by, for instance, the decay of particles with superheavy masses. Indeed, due to fragmentation effects for particles with mass much larger than the electroweak scale and *a fortiori* the QCD transition scale, high and ultra-high energy particles, including nucleons, electrons, neutrinos and photons, are expected to emerge from the cascade subsequent to the decay. One intriguing scale for BSM physics, as an intermediate step below the Grand Unification one, lies between 10^{10} GeV and 10^{13} GeV. This range encompasses the mass of the inflaton, the mass of the right-handed neutrinos within the vanilla seesaw mechanism, and the instability scale of the Standard Model. The mass spectrum of a hidden sector responsible for dark matter could also reflect this high-energy scale, and various mechanisms in the framework of inflationary cosmology are capable of producing super-heavy dark matter particles [33]. Current limits on ultra-high-energy gamma ray and neutrino fluxes are especially well suited to constrain BSM constructions with super-heavy candidates for dark matter [34, 35]. The enhanced sensitivities to these neutral particles will improve the current constraints and could lead to a serendipitous discovery of super-heavy dark matter.

Phase transitions may have occurred in the early universe. Many theoretical setups predict the existence of $U(1)$ symmetries at high scale for which phase transitions would have led to the formation of cosmic strings, which are regions of space-time that remain in a symmetry unbroken phase due to boundary conditions that topologically restrict their decay. Under certain circumstances, yet, the energy stored in the unbroken vacuum phase can be liberated in the form of high-scale quanta of the fields. This is the case in particular when the dynamics of the strings leads to "cusps", which are short segments with velocity momentarily very close to c. Emission from cusps results in particles with ultra-high energies due to the large Lorentz factors at play. Specific signatures are especially expected in ultra-high energy neutrino fluxes, which are governed in some models by the string tensions. Currently, our limits on neutrino fluxes translate into limits on cosmic string tensions as low as $\sim 10^{-20}$ [36], 4-to-5 orders of magnitude stronger than those obtained with LIGO/VIRGO. Again, enhanced sensitivities to neutrinos will improve the current constraints and could lead to a serendipitous discovery of phase transitions in the early universe.

Recommendations

In addition to the concrete examples of common scientific goals, we provide below general recommendations for action, that we consider essential for the efficient, forward-looking and sustainable development of astro-particle and particle physics in a common and coherent framework.

1. We advocate the continuation and deepening of interaction and collaboration between the astroparticle and particle physics communities. CERN should act as a centre for this dialogue and should continue to support a variety of events related to this goal, including the organization of conferences, workshops and schools, as well as fostering long-term collaboration.

2. The mutual engagement of the particle physics and astroparticle physics communities should continue to include dedicated initiatives in which the particle physics and astroparticle physics communities team up to measure specific quantities needed for astroparticle physics in accelerator-based experiments. The unique role of fixed-target and collider experiments in providing data needed in other fields of science, in particular astroparticle physics, should be recognised and appropriate measurements should be included in plans for accelerator-based experiments and data collection. In particular, we encourage CERN to pursue with high priority the LHC run with light ions, such as p-O, which would fill a very important gap in the data needed for air shower physics. Similarly, measurements at fixed targets and colliders with excellent forward coverage will be extremely valuable for hadron production.

3. Joint theoretical studies of questions in the overlap region between particle and astroparticle physics will be of fundamental importance for making scientific progress. We encourage the interaction of the two communities and the engagement in inter-disciplinary research into theoretical and phenomenological questions. One example is the development and tuning of hadronic event generators as needed in high-energy physics and cosmic ray simulations. Both theoretical and experimental work will be needed to address the well-established muon discrepancy in air showers. While this muon excess relative to predictions is most likely related to shortcomings in simulating hadronic particle production it could also indicate new particle physics at energies beyond the reach of LHC. Moreover, air showers provide a very good testbed for searching for physics beyond the Standard Model for various classes of models, production of including micro-black holes and other heavy states.

4. We strongly support the close collaboration of the particle and astroparticle physics communities in the development of particle physics detection technologies and instrumentation. The applied detection methods and the instrumentation used are very similar and often complementary for these experiments. Joint development efforts will therefore provide large synergies in developing future detectors.

5. It is vital to have very high performance, large-scale computing and data storage facilities for modern particle and astroparticle physics experiments and advanced theoretical simulations. We also encourage the particle physics community to collaborate with the astroparticle physics community in developing the necessary

next-generation computing and storage facilities. These facilities should be open to all relevant scientific communities for contribution and scientific use.

6. We strongly believe that the particle and astroparticle physics communities should work closely together to attract, train and support young scientists throughout their scientific careers. All our activities are underpinned by the principles of diversity, equity and inclusion. Joint efforts should include science communication and outreach activities covering both particle and astroparticle physics.

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