# Strategy documents

Physics research communities
Round table Physics
2020

# Particle and Astroparticle Physics

NWO

# 1. Scope or definition of the working group

The field of Particle and Astroparticle Physics (PAPP) comprises theoretical and experimental research on fundamental building blocks of matter and the structure of space and time itself. It aims to advance our understanding of the fundamental laws of Nature for all elementary constituents of matter, their structure and their mutual interactions. PAPP has experimental and theoretical components in particle and astroparticle physics. The experimental activities are predominantly at Nikhef, a partnership between the NWO Nikhef-institute and six Dutch universities , which allows to execute a National Strategy. The particle physics activities include collider physics, notably performed at CERN's Large Hadron Collider, where the Netherlands are involved in the ATLAS, LHCb and ALICE experiments, and the search for the Electric Dipole Moment (EDM) of the electron as an alternative technique to study particle physics. The Dutch Astroparticle Physics (APP) community is represented by the Committee for Astroparticle physics in the Netherlands (CAN) . The Dutch APP activities focus on multi-messenger observation of the Universe, through the study of gravitational waves (Virgo), the observation and understanding of high-energy cosmic neutrinos (KM3NeT), ultra-high-energy cosmic neutrinos, photons and cosmic rays (Pierre Auger Observatory); direct searches for dark matter (XENON) and searches for signatures of dark matter particles in X-ray and gamma-ray data (CTA). Some of these activities are performed in collaboration with astronomy and observational cosmology.

The Dutch PAPP theoretical research community is constituted by several university groups and Nikhef. Theoretical High-Energy Physics is a distinct discipline, which often makes major progress in unveiling surprising connections and physics principles underlying the fundamental laws of Nature. At the same time, the link with experimental research is of vital importance, challenging theorists to develop new concepts and make new theoretical predictions. The aim of the present theoretical activities is to uncover the fundamental laws governing physics at all distance and energy scales, beyond currently established theories. It revolves around a number of big, unsolved questions that are driving the PAPP field: What physics lies beyond the Standard Model of particle physics? How can we unify quantum theory and general relativity to obtain a quantum theory of gravity? What is the nature of dark matter and dark energy? How did the Universe start? Can we understand black holes? Given the unprecedented wealth of new data from colliders, astroparticle physics and cosmology, there is now added urgency to address these challenging issues. They not only overlap with the experimental research lines within PAPP, but also benefit from a multidisciplinary approach, with input from physics, astronomy, mathematics and computer science.

# 2. Vision for the next ten years

These are exciting times for the field covered by PAPP, with unexpected interactions between research lines and communities that were previously disjoint. With the discovery of the Higgs, the LHC has largely confirmed the Standard Model of particle physics. And yet we are certain there is new physics waiting to be discovered due to observations that cannot be explained within the Standard Model (SM), such as dark matter, neutrino oscillations and the matter-antimatter asymmetry. Other experimental anomalies may be confirmed soon. We know, for the first time since the formulation of the SM, that some new – Beyond the Standard Model (BSM) - physics must exist. Thus, there are a vast range of New Physics scenarios which will be tested with future experiments.

Major upgrades at the LHC are envisaged in the coming years to increase the event rate by an order of magnitude, further boosting the LHC discovery potential. These upgrades will permit to assess the details of the Higgs mechanism and to maximize the reach for the discovery of new particles (ATLAS); to reach the ultimate precision in specific b-quark systems (LHCb), and to expose the collective dynamics of quarks and gluons in extreme conditions (ALICE). It will allow to search for long lived particles at ATLAS and LHCb and directly probe the origin of neutrino masses and baryogenesis. The SHiP experiment at CERN aims to search for low-mass long lived particles in a new generation intensity-frontier experiment. The sensitivity-frontier is further probed through low-energy ultra-high precision measurements of the electric dipole moment of the electron. The mission of the KM3NeT experiment is to discover PeV neutrino sources in the Universe and to study the properties of neutrinos, including BSM physics. The upgraded Pierre Auger Observatory is set to find the sources of the highest energy particles and study their acceleration mechanism, whereas the GRAND experiment will detect neutrinos at the highest energy attainable in the Universe. The particle nature of dark matter, and neutrino physics, will be studied with the XENONnT and DARWIN detectors. Complementary indirect dark matter astrophysical searches will occur with KM3NeT in neutrinos, with XRISM in X-rays, LOFAR and SKA in radio, and FERMI-LAT and CTA in gamma rays.

The detection of gravitational waves from coalescing black holes and neutron stars (Virgo) and the first imaging of a black hole horizon (Event Horizon Telescope) have confirmed the existence of black holes and the validity of Einstein's gravity in a strong gravity regime not previously explored. Gravitational waves are a new window on the universe that enables us to see even further back in time. Their detections are now routinely correlated with other detectors, in what is called multi-messenger astroparticle physics. A future third-generation gravitational waves instrument, the Einstein Telescope, possibly hosted in the Netherlands, has a high scientific potential.

Much higher precision theoretical calculations are required for the LHC upgrades, and beyond, for an exploration of the intensity frontier and for the imminent upgrades in dark matter detection, both direct and indirect, from the ground and from space. In a parallel development, we now also have a "standard model of cosmology". By treating the infant quantum universe as a one-time particle accelerator, we are beginning to probe the first moments in the life of the universe, including questions about the origin of matter, spacetime and the nature of gravity. A quantum theory of gravity remains the holy grail, with tantalizing recent hints that we may finally be able to explain long-standing questions about black holes and the nature of spacetime. A key conceptual and technical challenge for quantum gravity is to bridge the enormous scale gap between Planckian spacetime dynamics and the realms of particle physics and cosmology.

Traditionally, the PAPP field both relies on - as well as moves forward - "enabling technologies" such as physics data processing, where new high-performance algorithms and programming, and flexible computing infrastructures play a major role. Detector R&D in advanced gravitational wave instrumentation and new and "smart" pixel detectors is essential for the coming experimental challenges.

# 3. Scientific challenges/themes

The recent discovery of the Higgs particle and the observation of gravitational waves are ground-breaking scientific achievements, recognized with a Nobel Prize in Physics in 2013 and 2017, respectively. The Netherlands played a major and visible role in both, with top-ranked scientists and NL-built instrumentation.  These discoveries also demonstrate a key characteristic of the experimental efforts in PAPP: the experiments are major international collaborative efforts that take many years to prepare and execute. The Dutch PAPP community has invested heavily in these efforts in the past decades and the coming years will be the time to benefit scientifically. Most experimental efforts have a strong theoretical counterpart and theory often guides the experimental direction. Indeed, the interaction between the experimental and theoretical programs is essential.

The following are, in no particular order, scientific themes and scientific challenges studied in PAPP:

## Theoretical Particle Phenomenology

Signs of physics beyond the Standard Model could explain the dominance of matter over antimatter and the nature of dark matter. Theorists aim to explore, in three mutually coherent approaches, new physics up to the zeptometer scale (1015eV), well beyond the LHC reach. By computing collider physics observables with unprecedented precision, confrontation with data will offer exquisite sensitivity to new-physics effects. Possible imprints from top-down models and bottom-up effective field theory methods are leveraged for maximum benefit. In this direction, there is much interaction with LHC, astroparticle, and low-energy precision experiments as well as with cosmology and the physics of the early Universe. Modern computational and statistical tools (high-performance computing, machine learning, symbolic algebra) are a key ingredient of this endeavor.

1 Nikhef's detailed strategic plan for 2017-2022 and beyond is at https://www.nikhef.nl/wp-content/uploads/2016/03/STRATEGISCH-PLAN_STRATEGY_lowres.pdf
2 CAN's strategic plan for 2014-2024 is at http://www.astroparticlephysics.nl/papers/astro-roadmap-2014-2024.pdf

## The Higgs Particle

All properties of the Higgs particle are fixed by the SM, but at the same time the Higgs particle may be a portal to physics beyond the SM. Unique among all elementary particles known to date, the Higgs boson is believed to be a manifestation of a complex mechanism that regulates several fundamental aspects of Nature, such as the unification at high energy of the electromagnetic and weak nuclear force, the origin of mass of all elementary particles and the CP-violation underlying the particle-antiparticle asymmetry. The ATLAS experiment at CERN aims to stress-test the SM by measuring the life-time, the (self-) couplings and CP properties of the Higgs particle, study Higgs production in exotic regimes and develop a unified theoretical interpretation of Higgs measurements.

## Gravitational waves

With the first detection of gravitational waves, we have unlocked a new research field with implications for particle physics, cosmology and astroparticle physics. The LIGO/Virgo detectors aim to continue the study of gravitational waves with increasing precision and test the physics of black holes. The multi-messenger correlation of electromagnetic, neutrino and charged particle observations with the gravitational wave detection of a neutron star merger provided insight into the production of heavy elements and impacted many other areas of science. ESA's LISA mission will open the long wavelength domain of gravitational waves where supermassive black holes and potential signals from the Early Universe can be studied. Moreover, we are investigating the possibility of hosting the Einstein Telescope in the Netherlands, this would be a Game Changer in the field.

## Quantum and Classical Gravity

A consistent microscopic formulation of quantum theory of spacetime and gravity is a major challenge. We study whether the collective behavior of these quantum degrees of freedom lead both to new physical and observable consequences and demonstrate the emergence of the usual, classical spacetime at macroscopic scales. Several techniques and approaches will be developed further to attack this deep problem, in both non-perturbative quantum gravity and string theory with its connection to the holographic principle and quantum information theory. On the classical side, the emphasis will be on strongly gravitating systems and gravitational waves, and the new insights they can give us into the nature of gravitational theory.

## Discovery of new particles and symmetries

A discovery of new particles can directly indicate what kind of extensions to the SM we should be testing further, and what underlying symmetries these extensions should have, with immense implications on our understanding of the fundamental building blocks of the Universe. The ATLAS experiment searches for signatures of new BSM particles or interactions in LHC data. The abundant production of top quarks and vector bosons at ATLAS offers opportunities to perform high-precision measurements of the top quark mass and search for other very rare phenomena. The LHCb experiment searches for deviations from the SM in precision measurements of exceedingly rare decays, such as Bd μ+μ- and Bs μ+μ- or in studies of CP violation in B-decays to test the CKM paradigm. Separately, a measurement of a non-zero electric dipole moment of the electron would be direct proof of BSM physics. The eEDM program aims to detect the electric dipole moment of the electron using a highly sensitive experiment. All these programs aiming to uncover BSM, require tight interaction between theoretical and experimental work.

## Dark Matter

Numerous astrophysical observations lead to the conclusion that a large fraction of matter is invisible. The identity of this 'dark matter' remains a mystery. Viable particle physics models for dark matter include candidate particles that differ by many orders of magnitude in, e.g. masses and interaction strengths. The dark matter search combines experiments that test particular classes of dark matter models directly or indirectly with strong synergy with cosmology and astrophysics. The XENONnT and DARWIN experiments aim to discover the dark matter particle by searching for 'direct' collisions of dark matter with ordinary matter. ATLAS studies the production of dark matter particles through searches of, e.g. "invisible" particles in pp-collisions. KM3NeT and CTA will look for telltale signs of dark matter annihilation in astrophysical bodies. Finally, LHCb and the proposed SHiP experiment search for long lived or 'hidden' particles that may lead to dark matter candidates. Theorists build dark matter models and combine experimental results with astrophysical and cosmological data, deriving constraints on particle physics models. New Machine Learning tools and statistical methods may find subtle effects due to dark matter in experimental, astrophysical and cosmological data.

### Neutrinos

We now know that neutrinos have non-zero masses, in contrast to what the SM assumes. Other fundamental neutrino properties are still unknown and may hold other surprises. KM3NeT will study atmospheric neutrinos for neutrino oscillation patterns with the goal to establish the neutrino mass ordering. The XENONnT and DARWIN experiments will search for signs that neutrinos are their own anti-particles, i.e. Majorana particles. The Auger and GRAND Observatories will study neutrinos at ultra-high energies. The future DUNE experiment will use an intense beam of neutrinos to study leptonic CP violation and test the neutrino oscillation paradigm.

### Cosmic messengers

Cosmic messengers may expose the origin and acceleration mechanism for ultra-high- energy cosmic rays, arriving at Earth as charged particles, neutrinos and photons. KM3NeT and GRAND aim to discover the neutrino sources in the Universe, while the Auger Observatory investigates the origin and composition of cosmic rays, their consequences for the understanding of astrophysical objects, and the interaction of these particles with the Earth's atmosphere. High-energy photons will be measured with CTA providing detailed localizations of astrophysical sources. Theorists use these observations to make models of some of the most violent phenomena in the Universe and describe cosmic messenger propagation through space. In addition, high-energy neutrinos and cosmic rays provide unique opportunities to test the Standard Model and its extensions in an energy domain well above that available from the LHC.

### Nuclear Matter and Nuclear Astrophysics

Our knowledge of the collective behavior of matter rests on studies of particle ensembles with relatively weak (Abelian) interactions. The ALICE experiment studies the collective effects in QCD, a strong and non-Abelian interaction, using heavy ion collisions, recreating the high temperature state of the Universe just a few microseconds after the Big Bang. The collective behavior in this quark-gluon plasma is tightly connected to the equation of state (EoS) of hot dense QCD matter. These systems are the prime examples of the application of gauge/gravity duality (AdS/CFT correspondence), which is one of the most successful realizations of the holographic principle. The possibility of collective behavior in very small systems has sparked a deeper theoretical investigation of the foundation of fluid dynamics. Another open question is that of the existence of saturated gluon matter in the initial state of such reactions, which can be interpreted as the only classical field limit of a subatomic interaction. Separately, X-ray astronomy (e.g. with NICER) and gravitational waves provide a path towards the dense matter EoS. Studies of the EM counterpart of gravitational waves provide insights into the r-process responsible for the heavy element formation in the Universe. Complementary studies of neutron-rich nuclei in the laboratory, such as planned in the NEXT experiment, provide key data to predict the path of the r-process.

### Theoretical Cosmology

The challenge is to unravel the nature of dark matter, the cause for the accelerated expansion (dark energy) and the quantum origin of the primordial perturbations. In the Netherlands, there is a particular focus on string theory/quantum gravity effects, cosmic inflation, cosmological phase transitions, and ultra-weakly-interacting particles beyond the Standard Model. There is a strong involvement in major international efforts addressing these long-standing puzzles both at CERN (e.g. SHiP) and from space (the EUCLID mission, X-ray probes XMM-Newton and Athena, and the space gravitational wave antenna LISA). The latter activities are primarily coordinated by our colleagues in astronomy.

## 4. Application perspective (incl. societal challenges)

The overall research theme of PAPP is to answer the question “What are the fundamental building blocks of our Universe?”. The activities of the field are therefore represented in the National Science Agenda, in the route “Building blocks of Matter and Fundamental of Space and Time”. In pushing the research frontier, the field makes key contributions to innovative technologies, such as computing and detector technology that can be used in other fields as far apart as medical imaging and seismic monitoring.

The 'Big Questions' on the origin and foundations of the universe provide a strong motivation for students to take up physics, and have a continuing appeal to society at large. Students trained in theoretical and experimental (astro)particle physics have analytical and computational skills that are in high demand in many areas of modern society. Innovative numerical methods and software tools developed in PAPP research programs find their way into other applications in astronomy, cosmology, artificial intelligence and beyond. For example, our machine learning, computer algebra and error propagation tools are relevant for many data-intensive fields outside of academia and are deployed at companies and in government.

# 5. Strengths and infrastructure in NL & international perspective

The experimental research of PAPP is 'Big Science', characterized by large-scale infrastructures with large collaborations. Therefore, the adoption of a national strategic agenda has proven to be very successful over the last decades. The Nikhef partnership coordinates most of the experimental activities in Particle and Astroparticle physics as agreed between NWO and the Executive Boards of the partner universities. Almost all experiments are located abroad and typically last for years or even decades; long-term commitment is essential for successful participation and requires commensurate funding instruments: small project funding will not sustain these efforts. CERN is and remains a foremost research partner for the particle physics program and increasingly also for astroparticle physics (e.g. through the recently established European Center for Astroparticle Theory). Other experimental programs are performed in international collaborations hosted in Argentina, China, France, Italy and the United States.

The Dutch theoretical community has a strong tradition and continues to have a disproportionately large impact on the field internationally. Its strength derives both from the quality of its researchers and the strong national links. In addition to the research groups and institutes at individual universities, many theoretical activities within PAPP take place at the national level: the Dutch Research School for Theoretical Physics (DRSTP) organizes annual PhD schools and the biannual Trends in Theory symposium, the Delta Institute for Theoretical Physics (D-ITP) organizes the national holography and theoretical cosmology meetings, and the theory division of Nikhef organizes monthly theoretical particle phenomenology meetings.

# 6. Specific challenges for the community (optional)

- The experimental PAPP research is built on 'Big Science' projects and commitments. With the new NWO funding instruments, how can we ensure long-term strategic funding?
- Specific to the new NWO structure and Astroparticle Physics: how to further facilitate interactions be tween APP themes in PAPP and the separate NWO domain Science advisory committee Astronomy?
- How can we facilitate hosting the Einstein Telescope as a global international facility in the Netherlands?
- PAPP research is fundamental in nature and can be rather technical or downright esoteric, it is therefore hard to summarize in one-liners. This may lead to challenges in communicating the relevance of the field.

# 7. Research portfolio

| Organization | # PAPP members |
|---|---|
| CERN | 2 |
| NIKHEF | 24 |
| Overig | 1 |
| Radboud Universiteit Nijmegen | 12 |
| Rijksuniversiteit Groningen | 14 |
| SRON | 2 |
| Universiteit Leiden | 4 |
| Universiteit Utrecht | 9 |
| Universiteit van Amsterdam | 19 |
| Vrije Universiteit Amsterdam | 4 |
| **Total** | **91** |

# Composition advisory committee Particle and Astroparticle Physics

| | |
|---|---|
| Patrick Decowski | UvA |
| Ana Achúcarro | LEI |
| Stan Bentvelsen | Nikhef |
| Eric Bergshoeff | RUG |
| Sarah Caudill | Nikhef |
| Steven Hoekstra | RUG |
| Eric Laenen | UvA |
| Thomas Peitzmann | UU |
| Gerhard Raven | VU |
| Hella Snoek | UvA |