Particles and Forces in the Universe
The Crab Nebula evolved from the supernova explosion of a star in the year 1054. During such explosions, unimaginable amounts of particles and radiation are released. A black hole or – like in this case – a pulsar remains.
Humankind has always tried to understand the Universe, its components, and the forces acting between them. Today we know that the structures in the Universe are closely linked with fundamental interactions of elementary particles.

Scientists of the KIT Center Elementary Particle and Astroparticle Physics (KCETA) perform theoretical fundamental research and undertake international large-scale projects to study basic problems, including the origin of mass, the asymmetry between matter and antimatter, the composition of Dark Matter, the nature of Dark Energy, the neutrino mass, or the origin of cosmic rays.

**KIT Center Elementary Particle and Astroparticle Physics (KCETA)**

KCETA comprises several institutes of KIT. Research and education in KCETA are funded by the state of Baden-Württemberg, the Helmholtz Association, the Federal Ministry of Education and Research, the German Research Foundation (DFG), and the European Union.

Research at KCETA concentrates on eleven topics:

- Cosmic rays
- Dark Matter
- Quantum field theory
- Experimental collider physics
- Theoretical collider physics
- Flavor physics
- Neutrino physics
- Computational physics
- Detector Instrumentation and Data Acquisition
- Computing & big data
- Beam physics and technology

The task of KIT is the triangle of knowledge: research – teaching – innovation. Education and training at KIT are highly attractive due to its proximity to top-ranking research. The international exchange of PhD students and young scientists is as important as are research stays abroad and visits of numerous guest scientists.
One of the four fluorescence telescopes at the Pierre Auger Observatory in Malargüe, Argentina. These detectors observe the trail of nitrogen fluorescence light and track the development of air showers by measuring the brightness of the emitted light.
The Earth is exposed to a constant flow of high-energy particles from the Universe. Their generation, acceleration, propagation, and their interaction with the Earth’s atmosphere still prompts scientific questions. When entering the atmosphere, high-energy cosmic rays produce cascades of secondary particles, called extensive air showers that are detected on the ground. KIT concentrates on investigating the highest energy events of this type, initiated by extragalactic particles.

**Pierre Auger Observatory**

The higher the energy of the cosmic particles, the rarer they are. Only one ultra-high energy particle hits the atmosphere per square kilometer per century. To detect these particles, an international collaboration of researchers from 16 countries, with KIT being the largest group, has established the Pierre Auger Observatory in the Argentine Pampa. It covers 3.000 km² and is the largest cosmic ray detector worldwide.

**Particle Astrophysics**

The results obtained by the Pierre Auger Observatory so far are so exciting that under the leadership of KIT, the consortium is enhancing the sensitivity of the observatory by a coordinated upgrade, called AugerPrime. With the upgraded experiment, the elemental composition of the extragalactic particles will be determined to understand the origin of the cosmic rays better.

To investigate cosmic rays and neutrinos at 100 times lower energy, KIT is now participating in the activities of the IceCube Observatory at the South Pole.

**Open Science**

KIT is supporting the public access to scientific data. Here, the KASCADE Cosmic Ray Data Centre KCDC (https://kcdc.ikp.kit.edu) is a pioneering effort, as all the 20-years scientific data from the dismantled KASCADE experiment is publicly available.
In the EDELWEISS experiment, germanium detectors with a mass of 800 g each surrounded by copper casings are cooled down to extremely low temperatures (20 mK). If a WIMP collides with a germanium nucleus, energy will be deposited: the temperature of the crystal is temporarily increased and the vicinity of the collision point is ionized. Both signals are recorded simultaneously.
Dark Matter

The objects we see with telescopes, for example stars and planets, make up only about 5% of the energy and matter density in the Universe. According to our most recent knowledge, the dominant 95% consist of the so-called Dark Energy and Dark Matter, the physical nature of which is unclear. Dark Energy fills the Universe homogeneously and causes it to expand and accelerate. Dark Matter has been established through astrophysical and cosmological observations. KIT is strongly involved in theoretical and experimental research on Dark Matter, for instance with cryogenic detectors such as the EDELWEISS experiment, with AMS-02 at the International Space Station, with the CMS experiment at the Large Hadron Collider (LHC), and with the Belle experiment in Tsukuba, Japan.

Theory

Dark Matter requires the extension of the Standard Model of particle physics in order to incorporate a new particle with the required properties. Research groups at KIT investigate the implications of various extensions of the Standard Model in the context of Dark Matter. We consider theoretical aspects of the modified theory, mechanisms to produce the right amount of Dark Matter in the early Universe, and possible signatures in various experiments searching for Dark Matter.

EDELWEISS

The EDELWEISS (Expérience pour DETecter Les Wimps En SIte Souterrain) experiment is located in the French-Italian Fréjus tunnel. It was designed to search for a certain class of possible Dark Matter particles called WIMPs (Weakly Interacting Massive Particles), which in rare cases may scatter off normal matter and leave a tiny signal in the detector. Amongst other tasks, KIT is responsible for the data acquisition and the muon veto counter.

Alpha Magnetic Spectrometer AMS-02

The AMS-02 experiment has been in operation on the International Space Station (ISS) since 2011. Groups at KIT have been involved in setting up the data acquisition, they analyse the measured data and investigate how cosmic rays from the annihilation of two WIMPs can reach the Earth’s atmosphere.

FUNK

The FUNK (Finding U(1)s of a Novel Kind) experiment uses a spherical mirror of about 15m² located in a dark room at KIT to search for an exotic type of Dark Matter called “dark photon”, which may convert into a real photon at the surface of the mirror.
The mathematical description of interactions of the constituents of matter is based on relativistic quantum field theories, a synthesis of the special theory of relativity and quantum mechanics.
The fundamental constituents of matter, elementary particles, are described by the so-called Standard Model: it allows the prediction of their properties and the forces acting between them.

**Production and Decay Rates of Elementary Particles**

In general, relativistic quantum field theories can only be treated in an approximate manner. Nevertheless, they often allow for predictions of high accuracy. With the help of new mathematical methods, innovative algorithms, and by the development of computer algebra, KIT has reached a world-leading position in this field.

**Quark Masses and Coupling Constants**

By comparing predictions to measurements, coupling constants and quark masses can be determined, a major condition for tests of theory and the development of new theoretical models at the same time.

**Unified Field Theory**

Within the framework of a Grand Unified Theory, the values of the strong, electromagnetic and weak coupling constants may be reduced to a single parameter. Investigations at KIT indirectly provide hints regarding the structure of this fundamental theory.

**Non-perturbation Theory Effects**

Anomalous baryon number violation in the electroweak theory is assumed to play a key role in the origin of cosmic particle-antiparticle asymmetry. This phenomenon is studied at KIT using non-perturbative methods.
At the Large Hadron Collider (LHC) conditions for particle interactions are generated that existed in the Universe at the time of about $10^{12}$ seconds after the Big Bang. The CMS detector is one of the four large detectors installed at the LHC. This photo shows the insertion of the new pixel detector where KIT has been strongly involved.
The Institute for Experimental Particle Physics (IETP, the former Institute of Experimental Nuclear Physics, IEKP) researches at the most powerful particle accelerators worldwide: the Large Hadron Collider (LHC) at CERN (Switzerland) and the electron-positron beauty factory SuperKEKB in Tsukuba (Japan).

**The CMS Experiment at LHC**
The Large Hadron Collider started operation in 2009. The IETP has made major contributions to the CMS experiment, since 1995. Part of the LHC data are processed and saved at GridKa, the large data processing center facility at KIT. In 2012 researchers from KIT participated in the Nobel prize winning discovery of the Higgs boson with CMS. In 2017, a new precision pixel detector has been inserted into the center of CMS, where groups from KIT again have been strongly involved. In the coming years, different production and decay mechanism of the Higgs boson will be investigated. Further topics are studies of the strong interaction at TeV scales, the search for new forces and particles in conjunction with top quarks and the search for supersymmetric particles.

**The LHC at higher energies and luminosities**
In 2015 the center of mass energy at LHC was raised to 13 TeV and data are being taken at luminosities of $10^{34} \text{cm}^{-2} \text{s}^{-1}$. These energy and luminosity increases extend the physics reach well into the TeV range but also pose challenges to the detectors. Groups from KIT participate in extensive upgrade programs to ensure data taking with CMS up to 2035.

**The Belle II Experiment at KEK**
Starting in 2019, the SuperKEKB accelerator in Tsukuba, Japan, will collide electrons and positrons at luminosities of up to $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$ which will be the world record. KIT is involved in the upgrade program of the only detector at KEK, Belle II. This next-generation B-factory experiment will explore physics beyond the Standard Model through precision methods and probe indirectly multi-TeV mass scales. In this aspect, SuperKEKB will be on par with the LHC with its direct methods. To this end, matter-anti-matter asymmetries and rare decays will be studied. Also fundamental parameters will be measured with unprecedented precision.
Simulation of a Higgs decay into two Z bosons which decay further into two muons ($H \rightarrow ZZ \rightarrow 4\mu$).
Information about the forces acting between elementary particles is obtained by experiments in which particles with very high energies are scattered. Highest energies, and hence smallest distances are reached at modern colliders such as the LHC in Geneva. Theoretical collider physics makes predictions for these experiments and helps with the interpretation of the data.

Quantum Corrections
For the precise prediction of measurements, quantum corrections of the production rates of complex processes have to be calculated. These calculations are made for the scattering processes of quarks, gluons and leptons.

New Phenomena
A goal of the experiments at the LHC is the search for new phenomena. At KIT models with additional spatial dimensions or with supersymmetry are studied and predictions are made with respect to the expected signatures of such ‘new physics’.

Monte Carlo Development
Transformation of quarks and leptons in theoretical calculations into particles directly observable at the colliders requires the simulation of stochastic processes with so-called Monte Carlo programs describing these transitions.

Young Scientists at KCETA discuss the calculation of event rates at the LHC.
The B factory experiment Belle at the KEK laboratory in Tsukuba, Japan. Scientists of KCETA have been members of the Belle Collaboration since 2008 and perform analyses concerning CP violation and rare decays of bottom and charm quarks. They make important contributions to the upgrade experiment Belle II in the field of computing and in software and detector development.
Basic components of matter are quarks (that make up protons and neutrons) and leptons (electrons and neutrinos). Six different types, called flavors, of both classes exist. These flavors are grouped into three generations of two quarks and two leptons each. The nature surrounding us consists of particles of the first, lightest generation only. Particles of the other two generations have much higher masses, are unstable and decay into light particles within short periods of time.

Decays
Heavier particles can only be produced by accelerators. Flavor physics studies their decays to measure constants of nature from precision measurements, tests the current Standard Model, and finds indications of new laws of nature. These determine the physics on length scales smaller than 1/10,000 of the diameter of the atomic nucleus. Such measurements led to the prediction of the existence and the masses of the charm and top quark, for instance, long before they were discovered directly.

CP Violation
Spectacular and of particular relevance to fundamental physics is the so-called CP violation: laws of nature for matter and antimatter differ slightly. As a consequence, today’s Universe, in which matter prevails over antimatter has evolved from the Big Bang. However, the sources of CP violation found so far are not sufficient to explain the observed amount of matter in the Universe. Many interesting problems remain to be solved. The upcoming experiment Belle II will also search for decays of heavy quarks into Dark Matter particles, using software algorithms developed at KIT.
In KCETA theoretical calculations are performed in flavor physics and an experimental group is participating in the Japanese experiment Belle II.
The main spectrometer of **KATRIN** is 24 m long and measures 10 m in diameter. It is the largest ultra-high vacuum chamber in the world. The inside of the spectrometer is equipped with a complex electrode system made of 22000 wires.
The 70 m long KATRIN experiment consists of several components: the tritium source (1), a pumping and transport section (2), the pre- and main spectrometers (3+4), and an electron detector (5).

Neutrinos are the most abundant massive particles in the Universe, with each cubic centimeter containing about 336 neutrinos. Their investigation will answer fundamental questions in particle physics and cosmology. Neutrinos play a central role in the investigation of the origin of mass. As cosmic architects, they contributed to the design of large visible structures of the Universe.

**KATRIN**

Since two decades we know that neutrinos possess a rest mass. The far-reaching implications of this finding were recognized through the Nobel Prize in physics in 2015. The absolute value of the neutrino mass, which is tiny compared to other elementary particles, could so far not be measured. This is the aim of the Karlsruhe Tritium Neutrino Experiment (KATRIN), which in the course of the past ~10 years has been set up at the Tritium Laboratory (TLK) of KIT by an international collaboration. The measurement principle is based on the extremely precise spectroscopy of the highest-energy electrons produced by the beta decay of tritium. KATRIN can only be realized at KIT. Only here all necessary technical conditions are at hand: the Tritium Laboratory Karlsruhe, which is unique in Europe, experience in high-vacuum technology and cryotechnology for large scientific devices, know-how in the construction and operation of large facilities, and expertise in neutrino and astroparticle physics.

After successfully passing first electrons through the full 70 m long beamline in the “First Light” campaign in October 2016, KATRIN is undergoing a thoroughly commissioning program before the start of data taking with tritium to reveal finally one of the last secrets of the neutrinos.
Simulation of particle collisions at the LHC.
Research in the field of particle and astroparticle physics is not feasible without the use of high-performance computers. Optimal use of computer resources, however, requires the implementation of effective algorithms in specialized computer programs. On various levels, KIT develops software that is used to solve physical problems in particle and astroparticle physics.

**Parallel Computer Algebra**
When calculating scattering cross sections in a mathematical theory describing the interaction of elementary particles, enormous amounts of data are generated which have to be processed efficiently. At KIT, a worldwide unique project is being pursued, which allows the parallel processing of large data flows with the help of a computer algebra system.

**Simulation of Particle Collisions**
To interpret the experimental results obtained at the LHC, particle collisions are simulated and compared with the experiment. In an international collaboration, KIT researchers are developing a software package to run such simulations with high precision.

**Quantum Corrections**
High experimental precision requires quantum effects to be considered in theoretical predictions. Researchers at KIT are working on a largely automated calculation of quantum corrections based on methods of perturbation theory.
Analog readout electronics for astroparticle physics. Sophisticated analog signal processing is indispensable to realize innovative detector systems and high-performance data acquisition. Challenges are low noise, high frequencies and extreme environmental conditions.
Detected Instrumentation and Data Acquisition

Cutting-edge experiments rely critically on cutting-edge detector technology and instrumentation. KIT has a very strong history in conceptual detector design, layout, construction and operation. With current accelerator facilities or observatories like the LHC at CERN, Geneva, being in operation, KCETA scientists are already working on the development of novel detectors and technologies for the next generation of experiments. We are always considering the complete signal processing chain including sensors, analog and digital electronics, online and offline data analysis and long-term data storage. Novel sensing concepts are being developed, and the shrinking of transistor sizes requires careful consideration of analog effects in custom integrated circuit design. We build on unique assembly infrastructures and testing facilities.

Integrated Systems
Emphasis is put in particular on new technologies for highly integrated, pixelated detector systems, as well as sensors for electromagnetic waves like radio antenna systems. The innovative sensors including semiconductor and other sensing media, low-noise, low-power and cryogenic detectors, ultra-fast data transfer and real-time data reconstruction techniques. Our integrated systems design includes tailored analysis and visualization of the ever-increasing data streams generated by the detector system.

Novel Algorithms
Efficient algorithms are embedded in hardware and software. Frequently so-called trigger algorithms play a crucial part in distinguishing real and background events within microseconds to cope with the flood of data.
Our application fields range from astroparticle physics and high-energy physics to Dark Matter searches and novel beam monitoring devices for THz radiation with picosecond time resolution.

Front-end board KALYPSO, high-end instrumentation for accelerator research.
GridKa, the German Tier-1 high-energy physics data and computing center, provides storage and compute systems as well as specific services to several high energy physics and astroparticle physics experiments, including all four LHC experiments. As a Tier-1 center, GridKa plays a major role in the Worldwide LHC Computing Grid.
Large-scale data management systems, high-throughput computing and high-performance computers are increasingly important for particle and astroparticle physics.

Limited computing and data resources and the expected high data rates of the upcoming particle and astroparticle physics experiments, such as Belle-II, the High Luminosity LHC or the upgraded Pierre Auger Observatory, pose a major challenge.

Significant improvements of the existing data analysis algorithms and in particular also the computing models are required to cope with the huge amounts of data. At KIT, interdisciplinary teams from physics and computer science develop efficient algorithms, scalable methods and powerful tools for the evolving federated computing and data infrastructures that are indispensable to solve the grand challenges in science, such as the European Open Science Cloud (EOSC).

**GridKa**

GridKa, the German Tier-1 centre of the Worldwide LHC Computing Grid (WLCG) is further developed and enhanced to play its role as a data and analysis hub for high energy and astroparticle physics in these federated infrastructures, in particular the Helmholtz Data Federation (HDF), a federated research data infrastructure for Germany and national building block for the EOSC.
A 110 m electron storage ring and synchrotron, is KIT's test-facility for cutting-edge accelerator research and provider of radiation from the terahertz range via the infrared and visible spectrum to soft and hard X-rays for institutes of KIT and their collaboration partners.
KIT operates a 110 m circumference electron storage ring with the dual mission to conduct cutting-edge accelerator research and to supply synchrotron radiation. The electrons are accelerated up to 2.5 GeV and provide radiation over most of the electromagnetic spectrum in the microwave, terahertz, infrared, visible to the soft and hard X-ray region. A novel linear accelerator-based terahertz source named FLUTE for the investigation of picosecond to femtosecond short electron bunches is presently under construction. KCETA accelerator research encompasses advanced beam control, beam dynamics and beam diagnostics as well as technologies for future accelerators.

**Femtosecond Pulses**

New detection and recording methods for ultra-short (femtosecond) pulses are a particular research focus, as is the generation of ultra-short bunches. This requires technologies as diverse as magnets, lasers, communication techniques, in addition to materials research for novel electro-optical materials for electron bunch diagnostics. The terahertz sensors and detections methods developed as beam diagnostics tools are used also in other areas of KCETA's research, for example in the search for Dark Matter.

**Particle Acceleration**

Particle physicists require the highest possible beam energies and intensities. Novel acceleration techniques, allowing scientists to build compact accelerators several thousand times smaller than conventional ones, are part of the beam physics research in KCETA. The study of particle acceleration in plasmas can also be viewed as bringing the Universe into the laboratory.

**Colliders**

KCETA's scientists also study technologies for future international projects, such as high-energy linear and circular colliders. New accelerator components, for example for linear collider damping rings or the 100 km Future Circular Collider (FCC), are tested in the storage ring test facility. KCETA research in superconducting materials and cryogenic technology contributes to upgrades of the LHC, paving the way to new records in terms of beam intensity and luminosity.
The institutes contributing to KCETA are: Institute for Experimental Particle Physics (IETP), Institute for Nuclear Physics (IKP), Institute for Micro- and Nanoelectronic Systems (IMS), Institute for Data Processing and Electronics (IPE), Institute for Information Processing Technologies (ITIV), Institute for Technical Physics (ITEP), Institute for Technical Thermodynamic and Refrigeration (ITTK), Institute for Theoretical Particle Physics (ITP), Steinbuch Centre for Computing (SCC), and Institute for Beam Physics and Technology (IBPT).

Qualification and training of young scientists is a central task of KCETA and is supported by the KIT Departments of Physics, Electrical Engineering and Information Technology, Informatics, and Chemical and Process Engineering.

In KCETA the education of PhD students is of great significance and is funded through research training groups and the graduate school KSETA. This comprises a comprehensive, coordinated training program and the exchange of ideas, concepts, knowledge, and skills. The PhD students play major roles in the KCETA research portfolio.

In the past years, PhD students of KCETA have been highly successful in science and industry.

**Graduate School KSETA**

The ‘Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology’ (KSETA) is the Graduate School of KCETA. It has been funded within the Second Phase of the Excellence Initiative since 2012. KSETA offers a structured and specialized training, builds links between physicists and engineers, and thus provides a solid foundation for their interdisciplinary research.

Further information:
Dr. Irmgard Langbein, www.kceta.kit.edu
Karlsruhe Institute of Technology (KIT)
The Karlsruhe Institute of Technology (KIT) is The Research University in the Helmholtz Association. Its major research areas address long-term societal challenges and seek to develop sustainable solutions to urgent future questions. The objective is to contribute importantly, by top-level research, teaching, and innovation, to the success of major societal projects, such as the “Energiewende”, safe and sustainable mobility or intelligent technologies for the information society. Major topics represented by KIT Centers are energy, humans and technology, materials, elementary particle and astroparticle physics, climate and environment, mobility systems, and information. More than 9,200 members of staff, of whom about 5,800 are engaged in science and higher education, and about 26,000 students make the KIT one of Europe’s largest institutions for research and higher education.

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