Particles and Forces in the Universe
The Crab Nebula evolved from the supernova explosion of a star. During such explosions, unimaginable amounts of particles and radiation are released. A pulsar (e.g. the Crab Nebula) or a black hole remains.
Man has always tried to understand the development of 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. The KIT Center Elementary Particle and Astroparticle Physics (KCETA) performs theoretical fundamental research and undertakes international large-scale projects to study basic questions, including the origin of mass, asymmetry of matter and antimatter, composition of dark matter and dark energy, mass of neutrinos, or the origin of cosmic rays.

**KIT Center Elementary Particle and Astroparticle Physics**

The KIT Center Elementary Particle and Astroparticle Physics (KCETA) comprises 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.

Work of KCETA concentrates on nine topics:

- Cosmic rays
- Dark matter
- Quantum field theory
- Experimental collider physics
- Theoretical collider physics
- Flavor physics
- Neutrino physics
- Computational physics
- Technology development

KIT emphasizes the triangle of knowledge: research – teaching – innovation. Its proximity to top-ranking research makes education and training at KIT highly attractive. Active international exchange of PhD students and young scientists is as important as research stays abroad and visits of numerous guest scientists.

The Figure shows tracks expected from the production of a Higgs boson candidate from a pair of tau leptons in the CMS detector.
The Pierre Auger Observatory in the Argentine pampa consists of more than 1600 autonomous particle detectors in an area of 3000 square kilometers. In highly pure water, energetic particles produce light flashes in these detectors. In addition, four telescope stations at the edge of the detector field observe the light tracks of cosmic particle showers.
Earth is exposed to a constant flow of high-energy particles from the universe. Their generation, acceleration, propagation, and interaction with the Earth’s atmosphere are still unclear. When entering the atmosphere, high-energy cosmic rays produce cascades of secondary particles, called extensive air showers, that can be detected on the ground. KIT concentrates on investigating the highest energy events of this type, which are initiated by extragalactic particles.

**Pierre Auger Observatory**

The higher the energy of the cosmic particles, the more rare they are. Only one ultra-high energy particle hits the Earth’s atmosphere per square kilometer per century. To detect these particles, an international collaboration of researchers from 18 countries, with the largest group coming from KIT, has established the Pierre Auger Observatory in the Argentine Pampa, the largest cosmic ray detector worldwide.

**Particle Astronomy**

The first results obtained by the Auger Observatory are so exciting that a worldwide consortium is performing studies for an experiment even larger and more sensitive. With this experiment extragalactic particles could be observed over the entire sky and in greater numbers.

**New Technology**

Positively and negatively charged particles in air showers are deflected in the magnetic field of the Earth and, as a result, generate radiosignals. By using this effect researchers at KIT develop a new and efficient detection method for high-energy cosmic rays based on radio antenna stations for different frequency ranges from MHz to GHz. Engineering arrays were set-up at the Pierre Auger Observatory in Argentina and at the KASCADE-Grande experiment located at KIT.

With the help of the Pierre Auger Observatory, a map has been created showing arrival directions of ultra-high energy particles, revealing significant deviations from an isotropic distribution: a part of the particle directions correlate with active galactic nuclei in our cosmic neighborhood.
In the EDELWEISS experiment more than 40 germanium detectors with a mass of 800 g each are cooled down to extremely low temperatures (20 millikelvin). If a WIMP collides with a germanium nucleus, energy will be deposited: the temperature of the crystal is temporarily increased and the surroundings of the collision are ionized. Both signals are measured and the data processed.
What we see with telescopes, for example stars and planets, makes up only about 5% of the energy density and matter in the Universe, according to our most recent knowledge. 95% consist of the so-called Dark Energy and Dark Matter, the physical nature of which is completely unclear. Dark Energy fills the Universe homogeneously and causes it to expand in an accelerated manner. In many astrophysical observations, Dark Matter becomes noticeable by its gravitational effects. KIT is significantly involved in experiments searching for Dark Matter – with cryogenic detectors, such as the EDELWEISS experiment and its follow-up project EURECA, with AMS-02 at the International Space Station, or with the CMS experiment at the Large Hadron Collider (LHC).

WIMPs
Extensions of the Standard Model of particle physics predict the existence of a particle that has been named the “WIMP” by physicists: “Weakly Interacting Massive Particle”. These WIMPs are deemed major candidates for explaining Dark Matter. It is expected that they concentrate in particle clouds around galaxies and, in rare cases, scatter off normal matter or annihilate themselves producing additional cosmic rays.

EDELWEISS
The EDELWEISS (Expérience pour DEtecter Les Wimps En Site Souterrain) experiment was designed to search for WIMPs and built in the French-Italian Fréjus tunnel. It is shielded from cosmic radiation by 1800 m of rock. Amongst others, KIT is responsible for data selection 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 were 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.
Mathematical description of interactions of the components 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, from the smallest to astronomic distances.

Production and Decay Rates of Elementary Particles
Relativistic quantum field theories can in general be solved in an approximate manner only. Nevertheless, they often allow for predictions of arbitrary 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 and 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. Recently, the most precise values worldwide for the strong coupling and mass of the heavy charm and bottom quarks were determined at KIT.

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.
In the Large Hadron Collider (LHC) conditions for reactions are generated that existed 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.
KIT works at the most powerful particle accelerators worldwide: the Tevatron at Fermilab (USA), the Large Hadron Collider (LHC) at CERN (Switzerland) and the Electron-Positron Ring KEKb in Tsukuba (Japan).

**The CDF Experiment at Tevatron**
Until the beginning of the LHC, the Tevatron – location of the CDF detector – was the highest energy collider of the world. Here, the heaviest elementary particle known to date, the top quark, was discovered in proton-antiproton collisions. Other important discoveries included CP violation in beauty hadron decays, as well as the observation of matter-antimatter oscillations. Groups from Karlsruhe were involved in both discoveries and in the physics program of the CDF experiment.

**The CMS Experiment at LHC**
The LHC started operation in August 2008 and will be the most powerful particle accelerator worldwide for a long time. With development work on parts of the construction of the silicon tracking detector and its commissioning, KIT has made a major contribution to the CMS experiment, one of the two large universal detectors at the LHC. Part of the LHC data are processed and saved at GridKa.

With the CMS experiment different production mechanism of the Higgs boson, which was detected in 2012, and its properties can be investigated. Further topics are studies of the strong interaction at 1 TeV, the search for new forces and particles decaying into top quarks or for which top quarks represent an important background, as well as for supersymmetry particles.

**The LHC at higher energies and luminosities**
In 2015 the center of mass energy at LHC will be doubled and after a few years the collision rate shall be quintupled. Groups at KIT are significantly involved in development work for the pixel detector and silicon sensors.

Construction of the CMS silicon strip detector, with KIT providing a major contribution.
Simulation of a Higgs decay into two Z bosons which decay further into two muons ($H \to ZZ \to 4\mu$).
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 at Geneva. Theoretical collider physics makes predictions for these experiments and helps with the interpretation of the data.

**Measured Parameters**
Scattering experiments produce particle flows of rather complex patterns, which have to be related to theoretical models by optimum parameters. KIT theoreticians made major contributions, in particular to the search for the Higgs boson that is directly responsible for the masses of all elementary particles.

**Quantum Corrections**
For a precise prediction of measurements, quantum corrections of the production rates of complex processes have to be calculated. These calculations are made for the scattering 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 supersymmetry are studied and predictions are made with respect to the expected signals 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.

*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 run analysis concerning CP violation, rare decays and charm physics. They provide important contributions to the upgrade experiment Belle II in the field of computing as well as 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 particles each. 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, test the current standard model, and find indications of new laws of nature. These determine the physics on length scales smaller than 1/10000 of the diameter of the atomic nucleus. Such measurements led to the prediction of the existence and mass of the charm and top quarks, for instance, long before they were discovered directly.

**CP Violation**

Spectacular and of particular relevance to fundamental physics is the discovery of 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 investigated.

In KCETA theoretical calculations are performed in flavor physics and an experimental group is doing research at the Japanese experiment Belle.
KATRIN – The Neutrino Scales:
The main spectrometer of KATRIN is a cylinder of 10 m in diameter and 25 m in length. It is the largest ultra-high vacuum chamber in the world. Its walls have been electro-polished. The complete KATRIN experiment is 70 m long and consists of several components: the tritium source, a pumping section, a pre-spectrometer, the main spectrometer, and an electron detector.
Neutrinos are the most abundant massive particles in the universe. Each cubic centimeter is expected to contain 336 neutrinos. Their investigation leads to fundamental questions in particle physics and cosmology. Neutrinos play a central role in the investigation of the origin of mass. As cosmic architects, they are partly responsible for the design of visible structures of the universe.

**KATRIN**

For some years now, it has been known that neutrinos possess a rest mass. The Karlsruhe Tritium Neutrino Experiment (KATRIN) will be able for the first time worldwide to directly measure the mass of neutrinos. KATRIN is being set up within an international cooperation at the Karlsruhe Tritium Laboratory (TLK) of KIT. The experimental measurement principle is the extremely precise spectroscopy of the highest energy electrons produced by the beta decay of tritium. KATRIN can only be realized in Karlsruhe at KIT. Only here are all necessary technical conditions fulfilled: the tritium laboratory that is unique in Europe, experience in high-vacuum technology and cryotechnology for large scientific devices, experts in superconductor development, know-how and infrastructure for the construction and operation of large facilities, and excellence in neutrino and astroparticle physics. KATRIN offers students at KIT excellent conditions for the acquisition of various key qualifications.

After the spectacular transport of the main spectrometer all around Europe to Karlsruhe, the experiment is now being set up. The essential measurements will start in 2015.

The spectacular highlight of the transport of the main spectrometer all around Europe was the passage through the village of Eggenstein-Leopoldshafen.
Simulation of particle collisions at the LHC.
Research in the field of particle and astroparticle physics is no longer feasible without the use of high-performance computers. Optimum 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.

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.

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.

Worldwide LHC Computing Grid with distributed computing centers and the current data transfer between those centers.
GridKa, the Grid Computing Center Karlsruhe, provides experiment-specific services and resources to ensure optimum use of the extensive computing infrastructure at Karlsruhe by both local groups and their cooperation partners.
To successfully study central questions related to the basic building blocks of matter, and the emergence and development of the Universe, elementary particle and astroparticle physicists have to constantly adapt and improve their tools. While the largest particle accelerator in the world, the LHC at CERN, Geneva is started up, scientists of KCETA are already working on the development of novel detectors for the next accelerator generation. It is important to make detectors more resistant to radiation-induced damage and increasing the effective acceptance area by using novel cooling techniques.

Furthermore, construction and connection technologies are developed for finest electrical contacts as well as ultrafast optical data transfer technologies.

Detection of radio signals in air showers opens up new promising options in the investigation of cosmic rays. The method is optimized in prototype experiments.

For the KATRIN experiment, so far unique high-vacuum systems and cryogenic facilities are designed and taken into operation.

In all our research experiments within KCETA, so-called trigger algorithms play a crucial role, which allow for the quick distinction between real and background events, among others. These algorithms and the related electronic systems have to be adapted to the constantly growing data flows of new experiments.

In spite of these algorithms, the increasing data rates can only be handled by a revolution of data analysis, the worldwide grid. It will sustainably influence the quality of research and science, and the competitiveness of many industry branches. The grid should be usable in a transparent and intuitive manner, with all data appearing to be located at one place and being processed on a virtual supercomputer.

KIT is operating one of the largest grid nodes in the world: the central computing center of German particle physicists, GridKa, that also supports astroparticle physics and other scientific areas.

Radioantennas in the KASCADE field for measuring cosmic rays.
The supporting institutes of KCETA are, in the university domain of KIT, the Institute for Experimental Nuclear Physics, the Institute for Theoretical Particle Physics and the Institute for Theoretical Physics as well as, in the Helmholtz domain of KIT, the Institute for Nuclear Physics and the Institute for Data Processing and Electronics.

Associated institutions cooperating with KCETA with key technologies are: the Institute for Technical Physics and the Steinbuch Centre for Computing.

The topics of KCETA are developing dynamically. As an example the portfolio will be complemented strategically by theoretical astroparticle physics.

Qualification and training of young scientists is a central task of KCETA and the faculty of physics, which, due to the attractive studies offered, has been among the largest faculties of physics in Germany for many years now.

The comprehensive teaching program of KCETA is complemented by a large number of seminars and colloquia as well as by an international guest scientist program.

In KCETA the education of PhD students is of great significance and is funded within the frame of research training groups and graduate schools. This comprises a comprehensive, coordinated training program and the exchange of ideas, conceptions, knowledge, and skills. The PhD students assume major roles in the KCETA research program.

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

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

The Karlsruhe Institute of Technology (KIT) is the merger of Forschungszentrum Karlsruhe, member of the Helmholtz Association, and Universität Karlsruhe (TH). KIT has a total of 9000 employees and an annual budget of EUR 730 million. The merger into KIT gave rise to one of the biggest research and teaching institutions worldwide, which has the potential to assume a top position in selected research areas. It is aimed at establishing an institution of internationally excellent research in natural and engineering sciences, outstanding education, promotion of young scientists, and advanced training. KIT closely cooperates with industry as an innovation partner. It is a leading European energy research center and plays a visible role in nanosciences worldwide. KIT focuses on the knowledge triangle of research, teaching, and innovation.