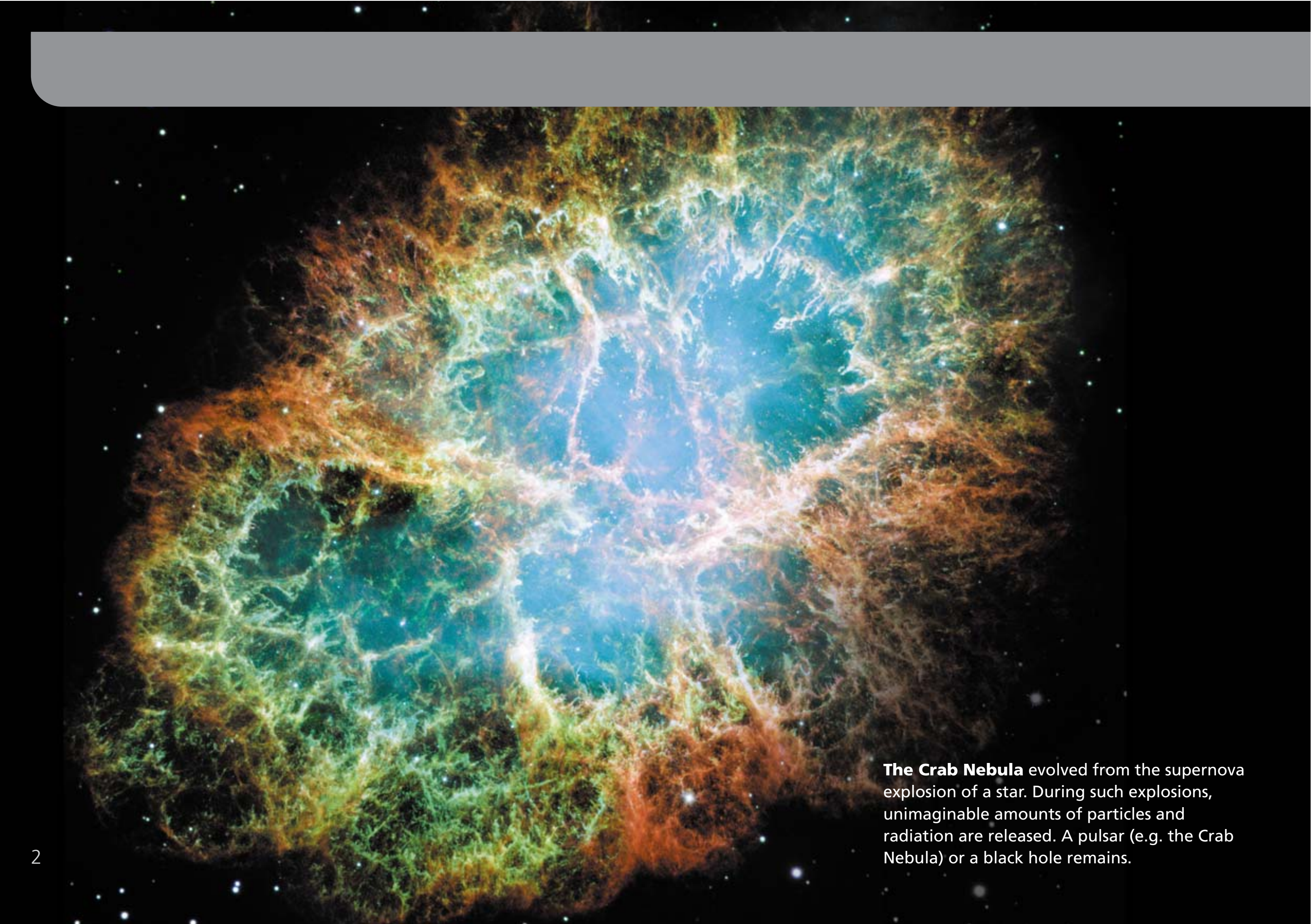
Karlsruhe Institute of Technology

Particles and Forces in the Universe

KIT ELEMENTARY PARTICLE AND ASTROPARTICLE PHYSICS CENTER

KIT – University of the State of Baden-Wuerttemberg and
National Research Center of the Helmholtz Association

www.kit.edu



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 Elementary Particle and Astroparticle Physics Center (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 energy and dark matter, mass of neutrinos, or the origin of cosmic radiation.

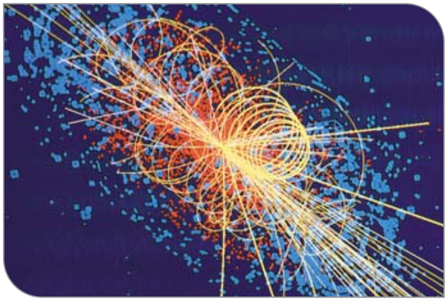
KIT Elementary Particle and Astroparticle Physics Center

The KIT Elementary Particle and Astroparticle Physics Center KCETA comprises institutes of both Forschungszentrum Karlsruhe and the Universität Karlsruhe. 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 the tracks expected from the production and subsequent decay of a Higgs boson in the CMS detector. In the Standard Model the Higgs boson is responsible for the mass of elementary particles.

The Pierre Auger Observatory in the Argentine pampa consists of more than 1600 autonomous particle detectors on an area of 3000 square kilometers: In highly pure water, energetic particles produce light flashes. In addition, four telescope stations at the edge of the detector field observe the light tracks of cosmic particle showers.

Cosmic Rays

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

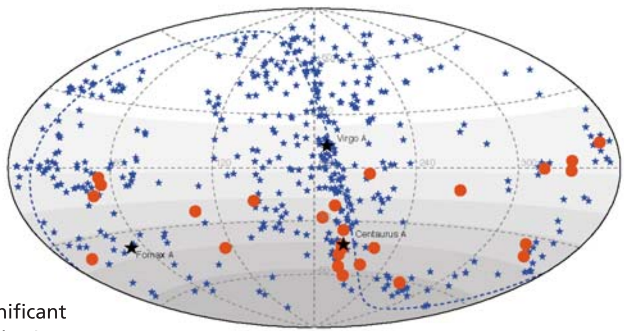
The higher the energy of the cosmic particles is, the more rare they are. Only one ultra-high energy particle hits the Earth's atmosphere per square kilometer and century. To detect these particles, an international collaboration of researchers from 17 countries, with the largest group coming from KIT, has established the Pierre Auger Observatory, the largest cosmic ray detector worldwide, in the Argentine pampa.

Particle Astronomy

First results obtained by the Auger Observatory are so exciting that a second instrument is planned to be built in the northern hemisphere in Colorado/USA. The resulting instrumented area of 20,000 square kilometers will then allow the observation of a sufficient number of extragalactic particles over the entire sky.

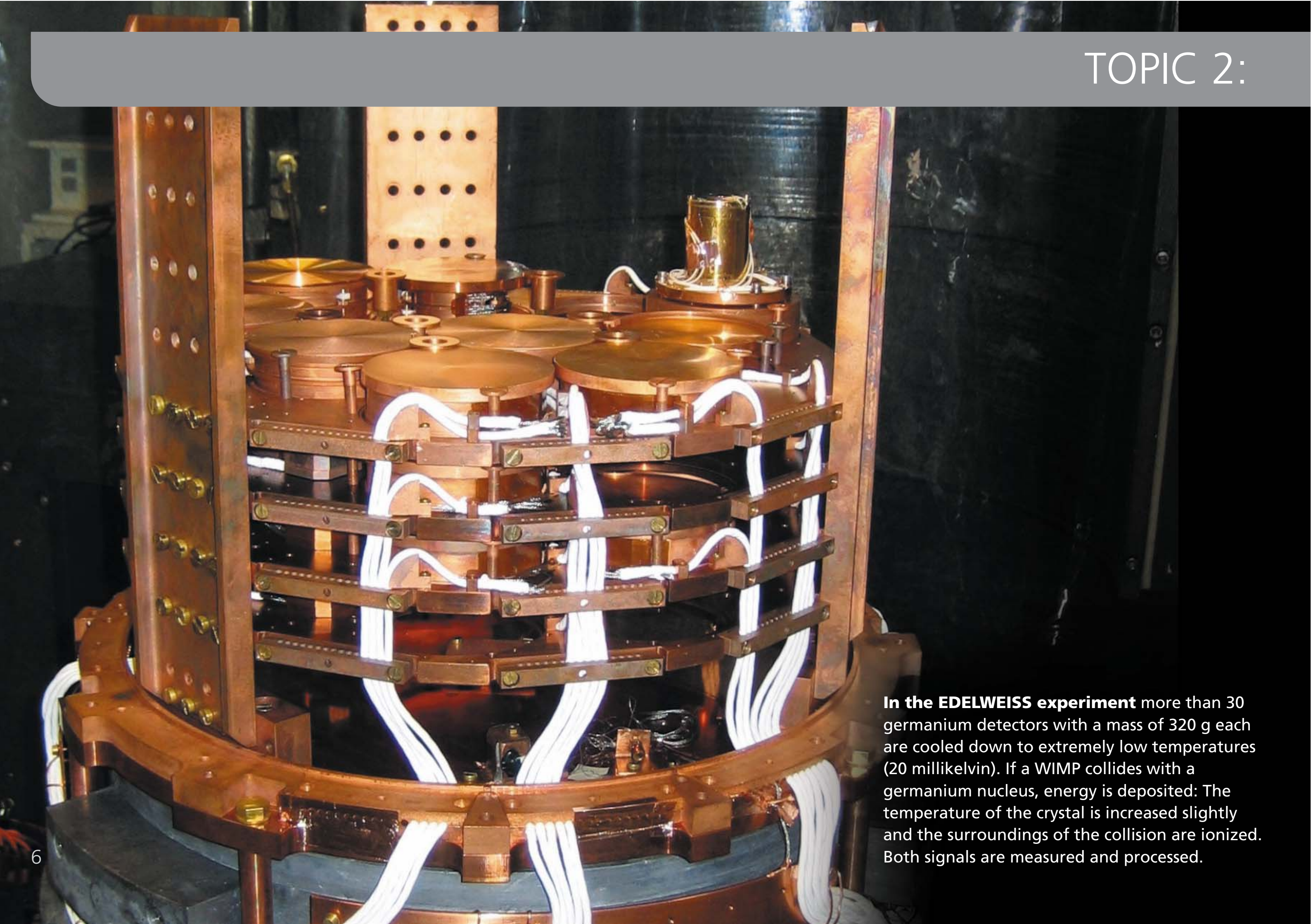
New Technology

Positively and negatively charged particles in air showers are deflected in the magnetic field of the Earth and, as a result, generate radiosignals. Based on this effect, KIT researchers develop a novel method to detect cosmic radiation by means of radio antennas and the 0.5 km^2 large KASCADE-Grande detector.



In 2007, the arrival directions of ultra-high energy particles were mapped for the first time with the help of the Pierre Auger Observatory. This map reveals significant deviations from an isotropic distribution: Particle directions correlate with Active Galactic Nuclei in our cosmic neighborhood.

TOPIC 2:



In the EDELWEISS experiment more than 30 germanium detectors with a mass of 320 g each are cooled down to extremely low temperatures (20 millikelvin). If a WIMP collides with a germanium nucleus, energy is deposited: The temperature of the crystal is increased slightly and the surroundings of the collision are ionized. Both signals are measured and processed.

Dark Matter

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 latest 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 is identified by its gravitational effect. KIT is significantly involved in experiments searching for Dark Matter – with cryogenic detectors, such as the EDELWEISS experiment, or with the CMS experiment at the Large Hadron Collider.

WIMPS

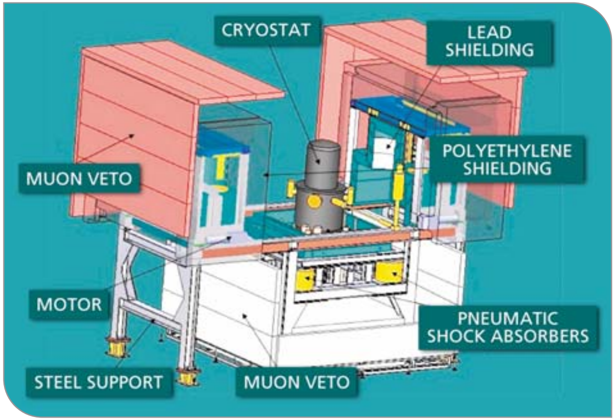
Extensions of the Standard Model of particle physics predict the existence of a particle that has been named “WIMP” by physicists: “Weakly Interacting Massive Particle”. These WIMPs are deemed major candidates for explaining Dark Matter. It is expected that they concentrate in particle clouds around galaxies.

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.

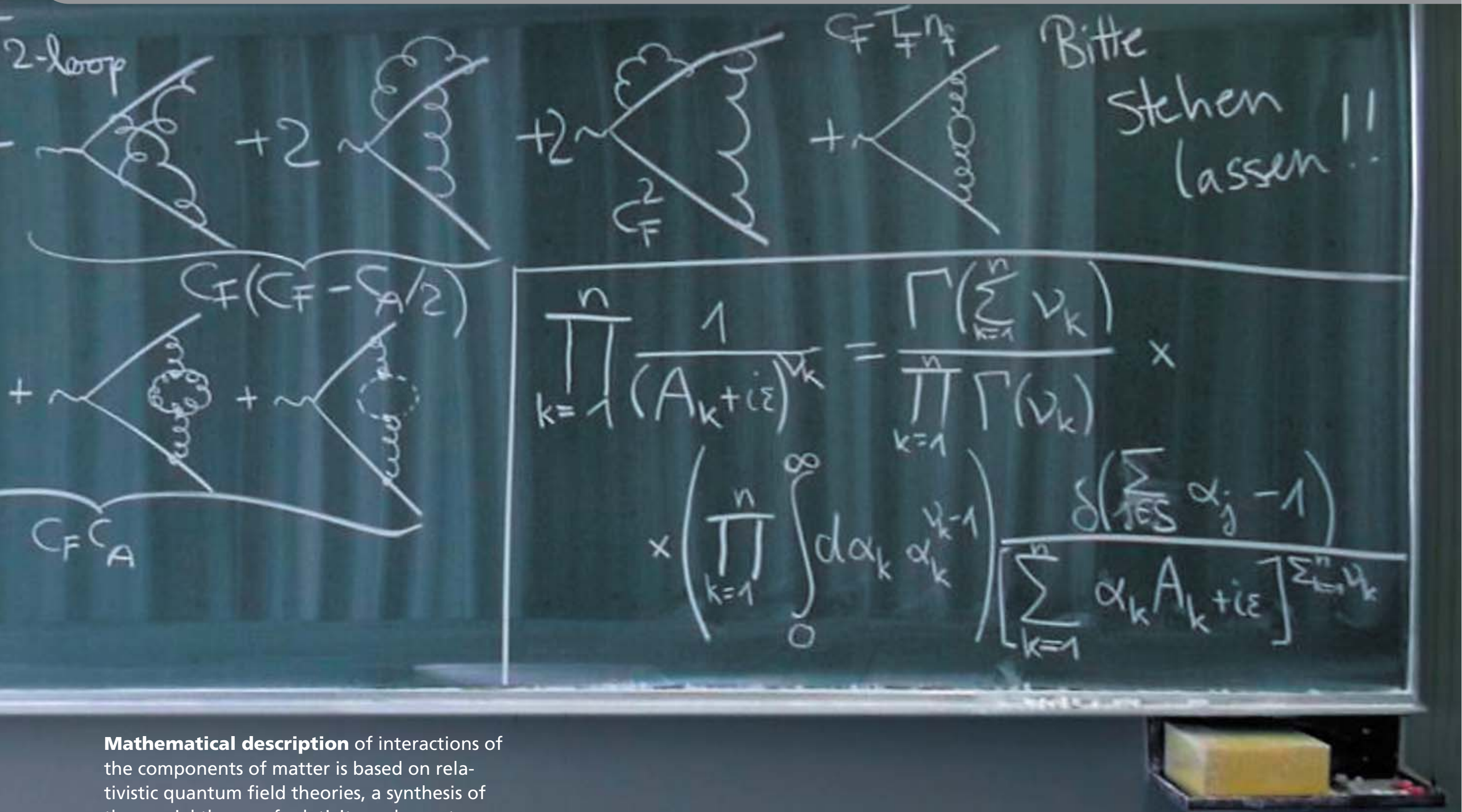
Cosmic Radiation from Dark Matter

In rare cases and in regions of high WIMP density, for example in the Milky Way, two WIMPs interact directly and annihilate. The resulting energy in the form of additional cosmic radiation can be detected by satellites.



The EDELWEISS experiment: One of the responsibilities of KIT is the operation of the muon veto counter with its 100 m^2 of modular surface.

TOPIC 3:



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.

Quantum Field Theory

The properties of the fundamental constituents of matter, elementary particles, are described by the so-called Standard Model: It allows to predict their properties and the forces acting between them from 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 arbitary high accuracy. With the help of new mathematical methods, innovative algorithms, and by the development of computer algebra, KIT has reached a leading position worldwide in this field.

Quark Masses and Coupling Constants

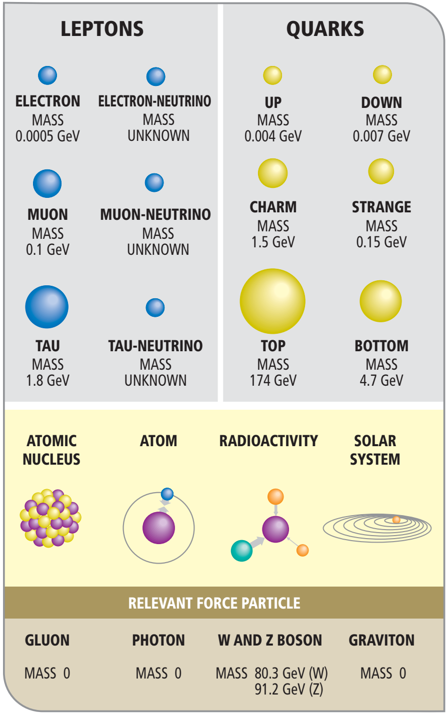
By comparing predictions and measurements, coupling constants and quark masses can be determined, a major prerequisite for tests of theory and the development of new theoretical models at the same time. Recently, the most precise values worldwide for the strong coupling and mass of the heavy charm and bottom quarks were determined at KIT.

Unified Field Theory

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

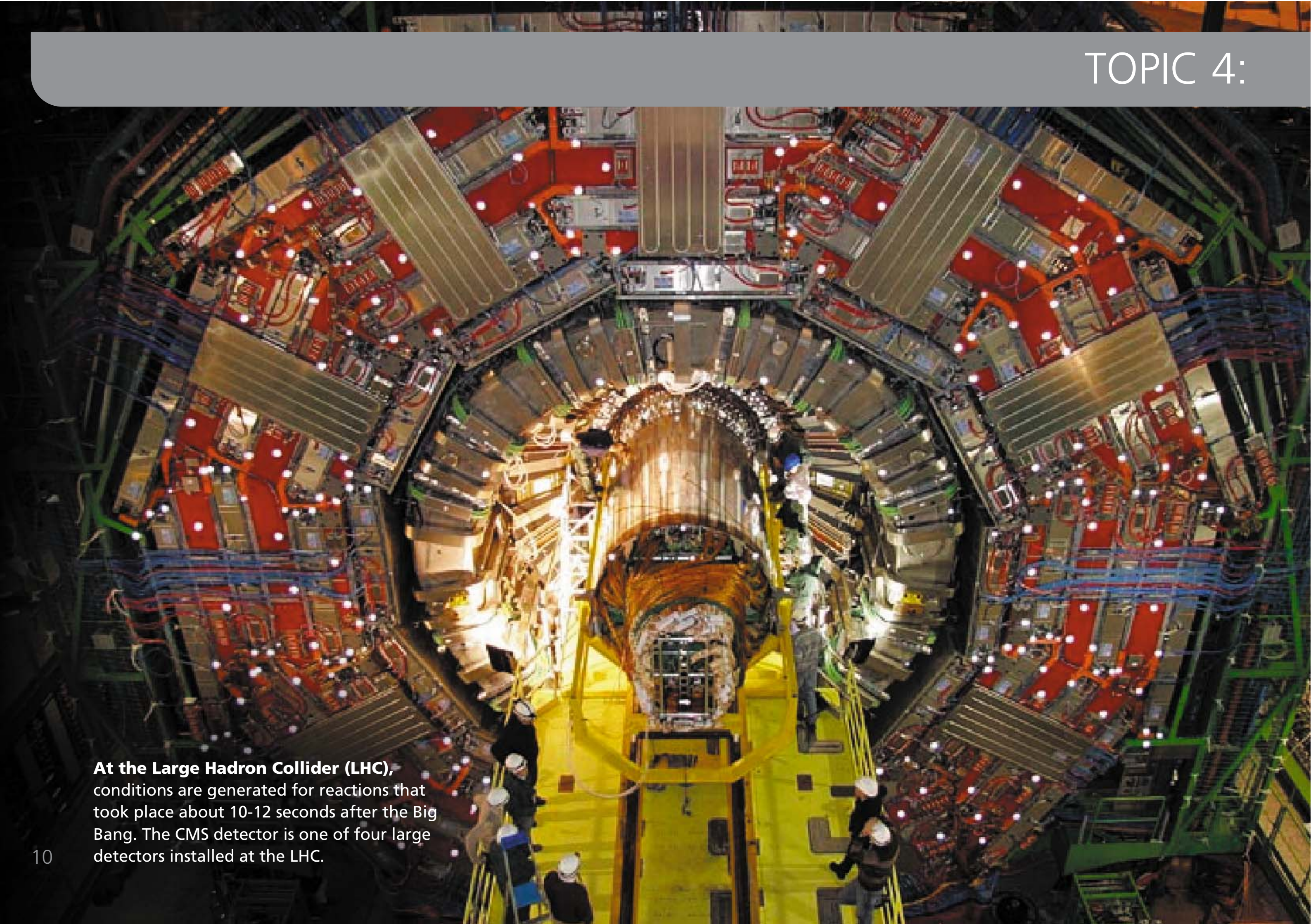
Non-perturbation Theory Effects

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 by KIT using non-perturbative methods.



Fundamental constituents of matter are quarks and leptons.

TOPIC 4:



At the Large Hadron Collider (LHC), conditions are generated for reactions that took place about 10-12 seconds after the Big Bang. The CMS detector is one of four large detectors installed at the LHC.

Experimental Collider Physics

KIT works at the most powerful particle accelerators worldwide, the Tevatron at Fermilab (USA) and the Large Hadron Collider (LHC) at Geneva.

The CDF Experiment at Tevatron

At Fermilab's Tevatron near Chicago, antiprotons collide with protons. Here, the heaviest elementary particle known to date, the top quark, was discovered. 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 these three discoveries.

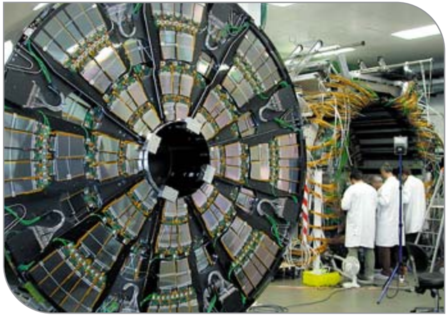
The CMS Experiment at the Large Hadron Collider (LHC)

The Large Hadron Collider at CERN, Geneva, started its operation in August 2008 and will be the most powerful particle accelerator worldwide for a long time. Here, protons collide with protons. KIT contributes a major share to the so-called CMS experiment, one of the two large universal detectors at the LHC. This share comprises development work and the construction of about 20 % of the silicon track detector. KIT searches for the Higgs boson and particles of dark matter. Another focus is the search for forces and new particles decaying into top quarks or for which top quarks represent an important background.

Super-LHC

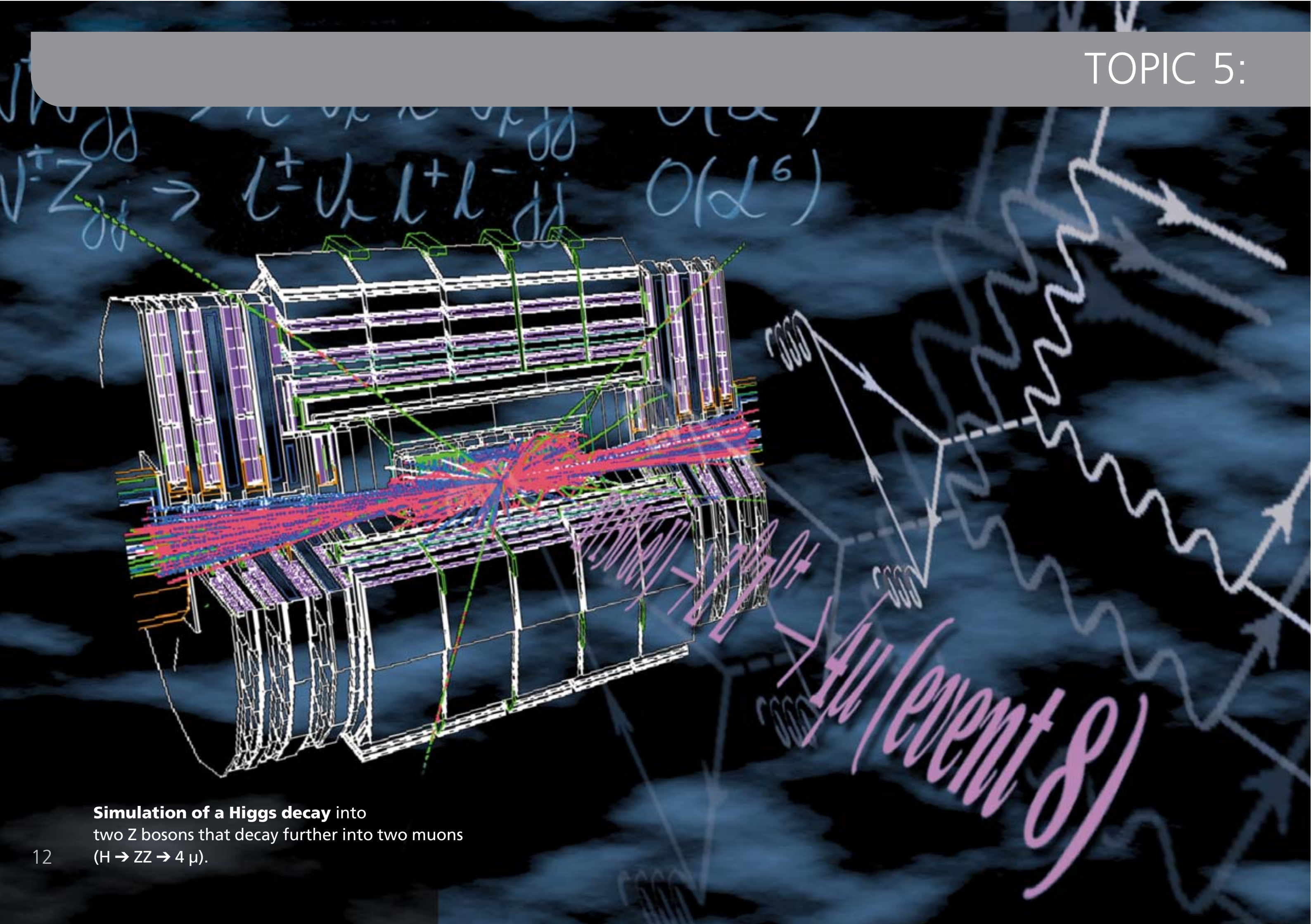
Within a few years, the collision rate at the LHC is planned to be increased by a factor of five. The resulting high radiation level will require new materials and methods for particle detection, which are presently being studied at KIT.

Precision measurement of silicon strip detectors at KIT.



Construction of the CMS silicon strip detector, with KIT providing a major share.

TOPIC 5:



Simulation of a Higgs decay into
two Z bosons that decay further into two muons
(H ➔ ZZ ➔ 4 μ).

Theoretical Collider Physics

Information about the forces acting between elementary particles is obtained by experiments, in which particles are scattered with very high energies. 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 in the interpretation of the data.

Parameters Measured

Scattering experiments produce particle flows of rather complex patterns, which are 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

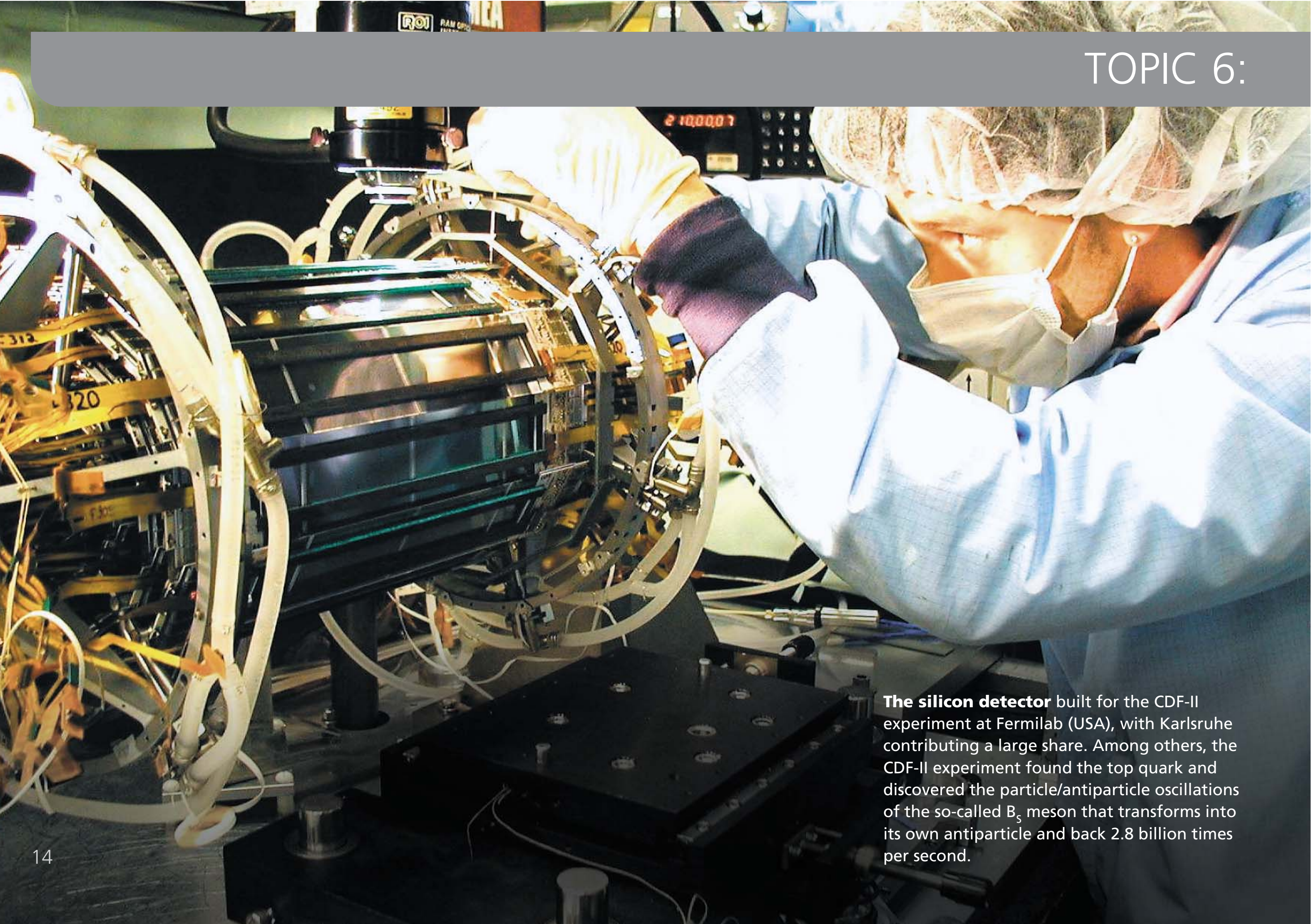
Experiments at the LHC are aimed at searching for new phenomena. At KIT, models with additional spatial dimensions or supersymmetry are studied and predictions are made with respect to the expected signals of such “new physics”.

Monte Carlo Development

Translation of quarks and leptons in theoretical calculations into particles directly observed 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.

TOPIC 6:



The silicon detector built for the CDF-II experiment at Fermilab (USA), with Karlsruhe contributing a large share. Among others, the CDF-II experiment found the top quark and discovered the particle/antiparticle oscillations of the so-called B_s meson that transforms into its own antiparticle and back 2.8 billion times per second.

Flavor Physics

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 four particles each. Nature surrounding us consists of particles of the first, lightest generation only. Particles of the other two generations have much higher masses. They are unstable and decay into light particles within shortest periods of time.

Decays

Heavier particles can be produced by accelerators. Flavor physics studies their decays to determine constants of nature from precision measurements, test the current standard model, and find indications of new laws of nature that 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

Discovery of the so-called CP violation is spectacular and of particular relevance to fundamental physics: 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.

KCETA scientists in the control room of the CDF-II experiment at Fermilab (USA).

TOPIC 7:

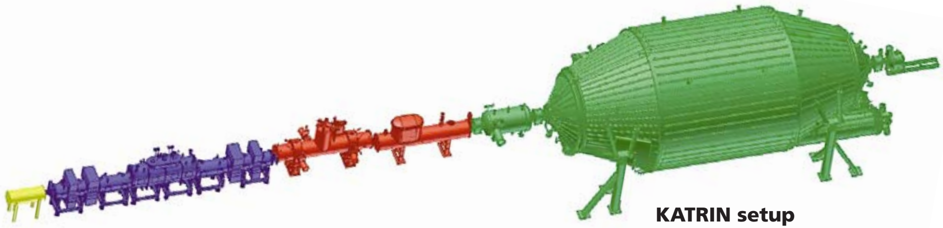
KATRIN – The Neutrino Scales:
The main spectrometer of KATRIN is a cylinder of 10 m in diameter and 25 m in length. It is the largest ultra-high vacuum chamber in the world. Its walls have been electro-polished. The complete KATRIN experiment is 70 m long and consists of several components: The tritium source, a pumping section, a preliminary spectrometer, the main spectrometer, and an electron detector.

Neutrino Physics

Neutrinos are the most abundant massive particles in the universe. Each cubic centimeter is expected to contain 336 neutrinos. Their investigation leads to fundamental problems of particle physics and cosmology. Neutrinos are "microscopic keys" playing a central role in the investigation of the origin of mass. As cosmic architects, they are involved in 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 the first worldwide to directly measure the mass of neutrinos. KATRIN is being set up in 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.

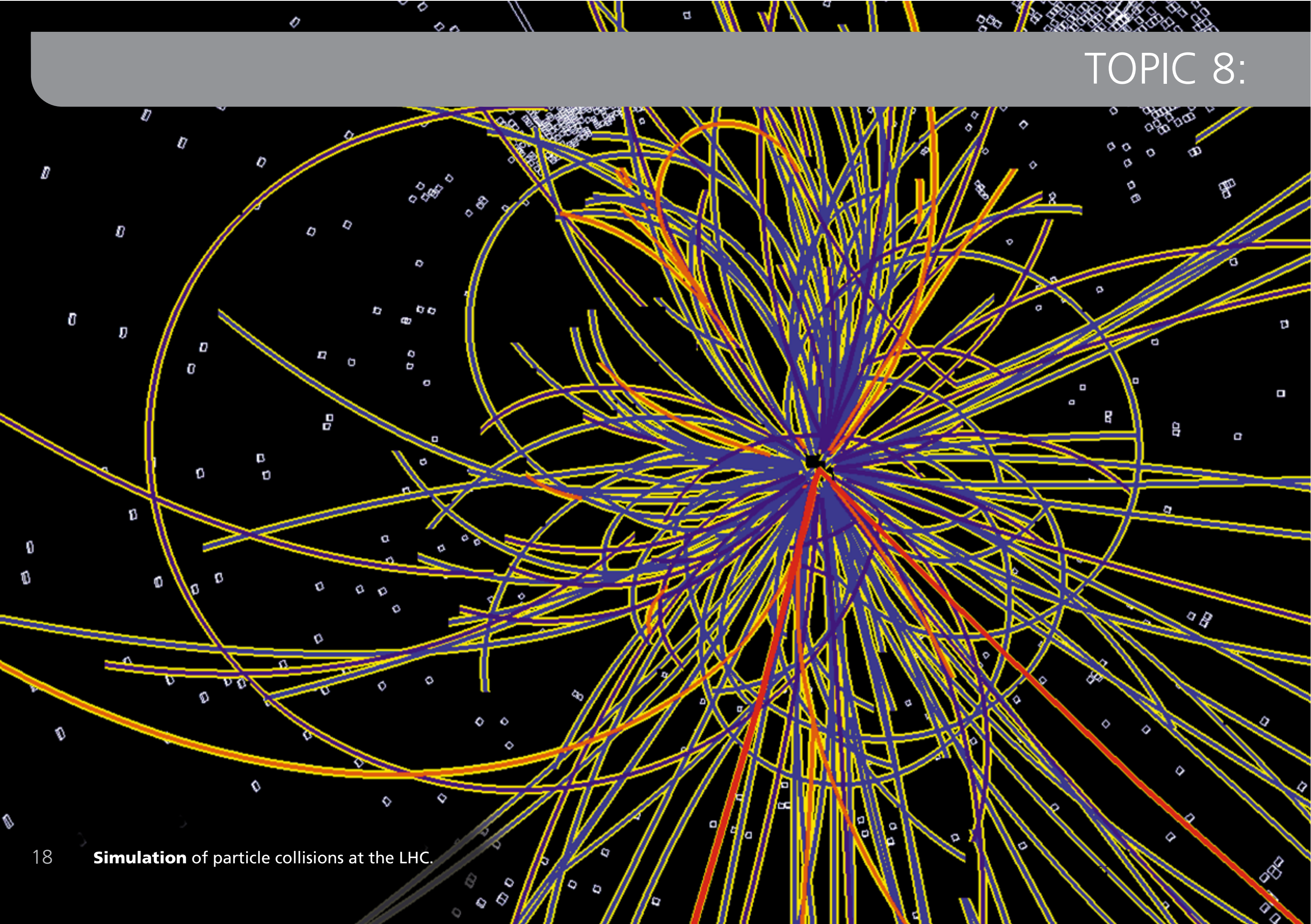


KATRIN setup

Karlsruhe is perfectly suited for accommodating the KATRIN experiment. Only here are all necessary prerequisites 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. At KATRIN, KIT students are offered excellent conditions for the acquisition of various key qualifications.

Following the spectacular transport of the main spectrometer all around Europe to Karlsruhe, the experiment is now being set up. Measurements will start in 2011.

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.

Computational Physics

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. KIT researchers are working on largely automated calculations 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 to develop a parallel computer algebra system aimed at processing large data flows.

Simulation of Particle Collisions

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

Computers are crucial tools in modern physics.

TOPIC 9:

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.

Technology Development

To successfully study central questions relating to 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 ist started up, scientists of KCETA are already working on the development of novel detectors for the next accelerator generation. It is aimed e.g. at making detectors more resistant against radiation-induced damage and increasing the effective acceptance area by using novel cooling techniques.

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

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

In all our research experiments so-called trigger algorithms play a crucial role, which allow for the quick distinction between real and background events among others. These algorithms 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 will be used in a transparent and intuitive manner, with all data appearing to be located at one place and being processed on a virtual supercomputer.

Radioantennas in the KASCADE field for measuring cosmic rays.

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.

The KIT Elementary Particle and Astroparticle Physics Center KCETA

KCETA comprises the Institute of Experimental Nuclear Physics, the Institute of Theoretical Particle Physics, the Institute of Theoretical Physics as well as the Institute of Nuclear Physics of Karlsruhe Institute of Technology.

Other institutes contribute key technologies to KCETA: The Institute for Technical Physics, the Institute for Data Processing and Electronics, and the Steinbuch Centre for Computing.

Technical coordination and planning tasks are executed by a scientific steering body. An international advisory committee accompanies the further strategic development of KCETA.

Qualification and training of young scientists is a central task of KCETA and the Department 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.

Education of PhD students takes place mainly within the framework of the DFG Graduate School for High-energy Physics and Astroparticle Physics with about 70 participants. The graduate school represents the center of a comprehensive, coordinated training program and exchange of ideas, conceptions, knowledge, and skills. The PhD students assume major roles in the KCETA research program. Close cooperation gives rise to synergy effects.

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

The 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 8500 employees and an annual budget of EUR 650 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.

Imprint

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