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Elementary Particle Physics

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In the physics of elementary particles a peculiar and fascinating situation has emerged. On the one hand, a theoretical model for the description of the fundamental building blocks of matter and their interactions exists, which has been confirmed in all those cases where experimental tests can be performed. This theory is called the Standard Model of elementary particle physics. On the other hand, the Standard Model offers many open problems, which are difficult to tackle experimentally or theoretically, but whose solutions are important for the foundation of the Standard Model as well as for its phenomenological predictions. How does this come about?

The Standard Model is formulated in the framework of relativistic quantum field theory. The fundamental constituents of matter are fermions, which obey the Pauli principle. These are the quarks, out of which the strongly interacting hadrons are built, and the leptons, which comprise the electrons and their heavier sisters muon and tau, as well as the neutrinos. Apart from gravity, which is negligible in the subnuclear world, three types of fundamental interactions are known. These are the familiar electromagnetic forces, the weak interactions and the so-called strong interactions. The latter are responsible for the binding of quarks into hadrons, like protons, neutrons or mesons. In the Standard Model the interactions are described in a mathematically very elegant way in terms of force mediating fields, which are associated with an infinite-dimensional symmetry, the local gauge symmetry.

The greatest challenges in the theory of elementary particles are provided by the strong interactions. The corresponding sector of the Standard Model is Quantum Chromodynamics (QCD). A characteristic feature of the strong interactions is their "asymptotic freedom". This property implies that for processes at high energies or small distances the coupling strength is small, so that perturbation theory can be applied to derive theoretical predictions. The Nobel price for physics was awarded in 2004 to Gross, Politzer and Wilczek for the discovery of asymptotic freedom in QCD. The flip side of the coin is that the coupling increases at low energies such that the region of applicability of perturbation theory ends there. Low-energy properties of hadrons, including their mass spectrum, are of a genuine non-perturbative nature. In particular, the confinement of quarks, namely the fact that they only exist bound inside hadrons, cannot be understood perturbatively.

The numerical simulation of QCD on high-performance computers is one of the most powerful methods to investigate the non-perturbative regime. For this purpose the theory is discretized on a space-time lattice with lattice spacing a and finite extent L. Monte Carlo simulations of QCD and other physically interesting field theories have become a field of very active international research. They also constitute a driving force for the development of algorithms and machines.

The first aim of Monte Carlo simulations of QCD is to test its claim to correctly describe the physics of strongly interacting particles. This means that non-perturbative quantities are computed, which can be compared to experimentally known values. Notably the spectrum of masses belongs to this class. Secondly, a large amount of present activities is devoted to the calculation of fundamental parameters of the Standard Model, like quark masses, coupling constants and mixing angles. These parameters are not directly accessible and difficult or even impossible to determine experimentally. Thirdly, one of the most interesting aims is of course to arrive at predictions for new quantities or phenomena.

Systematic errors in Monte Carlo calculations of QCD are due to the finite lattice spacing a and the finite lattice size L. Much effort is devoted to reach the regime of sufficiently small lattice spacings, where properties of physics in the continuum can be extracted reliably.

In recent years QCD simulations have reached a stage, where dynamical quarks can be incorporated in physically relevant situations. Due to the Fermi statistics of quarks it is not possible to incorporate them directly in terms of number valued variables. Their contribution to the dynamics has to be included through the so-called fermion determinant. Its calculation requires a huge amount of computing resources, so that in the past it often has been neglected in the quenched approximation, where it is replaced by a constant. Present supercomputer resources allow to implement situations where the fermion determinant is taken into account on sufficiently fine and sufficiently large lattices.

In simulations with dynamical quarks another source of systematic errors occurs. The masses of the lightest quarks in nature are rather small. The necessary computer time increases drastically with decreasing quark masses. This has so far prevented calculations with realistic values for the lightest quark masses. The article by Jansen describes attempts to solve this problem by using new types of actions for lattice QCD.

Another aspect of the physics of quarks in lattice QCD is their chiral symmetry. This symmetry of massless QCD in the continuum is broken by straightforward lattice discretizations. In order to minimize the effects of this artificial symmetry breaking one can employ lattice actions which represent chiral symmetry as good as possible. Overlap fermions are an example. They are used in the calculations described in the article of Schierholz. In this work the spectrum of hadron masses is calculated, as well as nucleon matrix elements, which give valuable information about the internal structure of nucleons.

Overlap fermions are also being used by Wittig and collaborators in their research about the decays of kaons. They address non-perturbative problems in connection with these mesons, which are important for the understanding of the symmetries of the Standard Model and their violations.

New types of particles are the subject of the article of Schäfer et al. Pentaquarks, hadrons made out of five quarks, have been searched experimentally in recent years, but not been identified convincingly. In the calculations described here the question whether pentaquarks exist is addressed in the framework of lattice QCD.