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Elementary Particle Physics

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The goal of the physics of elementary particles is to identify the fundamental constituents of matter and to understand the forces between them. For the presently known elementary particles and their interactions, apart from gravity, a theoretical description has been developed, which is known as the Standard Model. It gives a mathematical formulation of the electromagnetic, the weak and the strong nuclear interactions. Part of the Standard Model is the theory of the strong interactions, called Quantum Chromodynamics, QCD.

Quantum Chromodynamics describes the strongly interacting elementary particles as composed of fundamental constituents, the quarks. They interact with each other through the exchange of force carriers called gluons. Quarks have not been found isolated in nature and it is generally believed that they only occur inside bound states consisting of two or more quarks. This is related to a remarkable property of the strong forces. At increasingly small distances these forces become weaker and weaker. In this regime theoretical methods like perturbation theory, which rely on the smallness of forces, can be applied. With their help results from high energy collider experiments, which probe small distances, can be analyzed. On the other hand, at large distances (on nuclear scales) the strong forces really become strong and perturbation theory cannot be applied any longer. The large strength of the forces between quarks is made responsible for their confinement inside bound states.

The breakdown of perturbation theory at large distances necessitates the use of other, non-perturbative methods for the theoretical investigation of the properties of strongly interacting elementary particles. One of the most powerful tools is the numerical simulation of QCD on a lattice by means of Monte Carlo algorithms. Numerical simulations are different from traditional theoretical approaches. They can be considered as numerical experiments with unknown outcome. Their results are afflicted with systematical and statistical errors.

The objectives of Monte Carlo simulations of QCD are threefold. First of all one would like to check whether QCD yields a correct description of the physics of strongly interacting particles. To this end quantities are computed whose experimental values are well known. This includes the masses of particles. The present results have uncertainties of the order of a few percent and agree quite well with the experimental values. Secondly, one wants to obtain numerical values for fundamental parameters of QCD, like quark masses or the strong coupling constant. These parameters are not directly accessible and difficult or even impossible to determine experimentally. And thirdly, Monte Carlo calculations are used to obtain predictions for new kinds of phenomena or for the behaviour of matter under extreme conditions.

The limitations on storage and computer time restrict the numerical simulations to cover only a tiny part of space and time, just large enough to hold a few elementary particles. This can, however, also be turned into a virtue. Namely, the dependence of certain physical quantities on the size of the artifical subatomic world is related to fundamental parameters of the theory. In this way, exploring the finite size dependence, valuable information can be extracted. This is a central issue in the articles of Lippert et al. and of Jansen et al.

Another limitation is given by the size of quarks masses, which for technical reasons cannot be made too small on the computer. Present calculations have not yet reached the regime where the quark masses take their physical values. In the article by Montvay et al. calculations with dynamical quarks are described, which approach the realistic regime with suitable algorithms and allow to determine important parameters of low energy effective actions.

The internal structure of the pion, the lightest bound state of two quarks, is investigated by Laermann et al. The structure of the pion is described by the so-called form factor, which is of great phenomenological importance. The authors succeed to obtain non-perturbative information about the form factor.

The work by Necco and Sommer aims at predictions from QCD. The theory predicts the existence of unusual particles, called glueballs. They are made out of the strong force field alone, without quarks being involved. Glueballs have hitherto not clearly been identified experimentally. Necco and Sommer obtain predictions for the masses of glueballs, which are relevant for the experimental search.