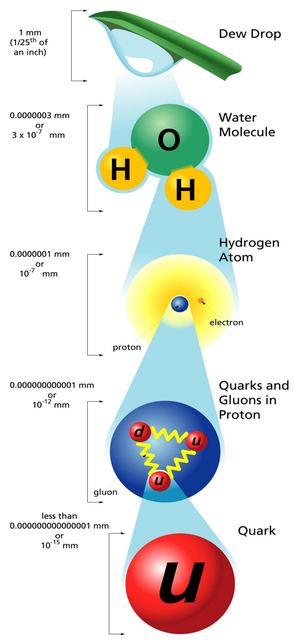
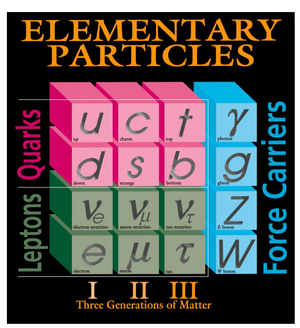
# Lattice QCD and Particle Physics

## Quantum Chromodyamics




Ordinary matter consists of protons and neutrons (nucleons), each of which contains three point-like particles called quarks. The quarks in a nucleon are of only two types, or flavors, called *up* and *down*.

The strong force, one of the four fundamental forces of nature, binds quarks to each other. It is transmitted between quarks by particles called *gluons*. The theory describing the interactions of quarks and gluons is called Quantum Chromodynamics or **QCD**.

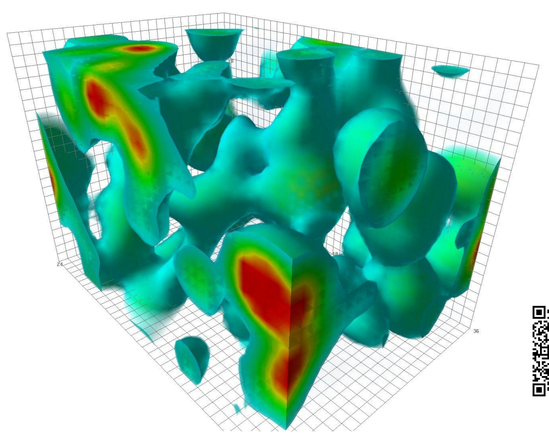
Six flavors of quarks are known: the *up* and *down* quarks of ordinary matter and the heavier *strange*, *charm*, *bottom* and *top* quarks seen by experiments at particle accelerators. The *bottom* and *top* quarks were discovered by experiments at Fermilab.

Quarks and leptons are grouped into three generations of particles in the Standard Model. Quarks are distinguished by their masses and how readily they decay into one another via the weak force (carried by the W and Z bosons). Scientists work to measure precisely quark masses and decay probabilities as a way of looking for new physics beyond the Standard Model. Of particular interest are CP-symmetry-violating decays in which particles do not show perfect mirror symmetry with their anti-particles.

## Lattice QCD

Theorists must resort to large-scale numerical simulations to solve QCD for many of the most important Standard Model problems. The technique is called Lattice QCD (LQCD).

See the accompanying poster *Clusters and GPUs for Lattice QCD* for details.



## Exascale Lattice QCD

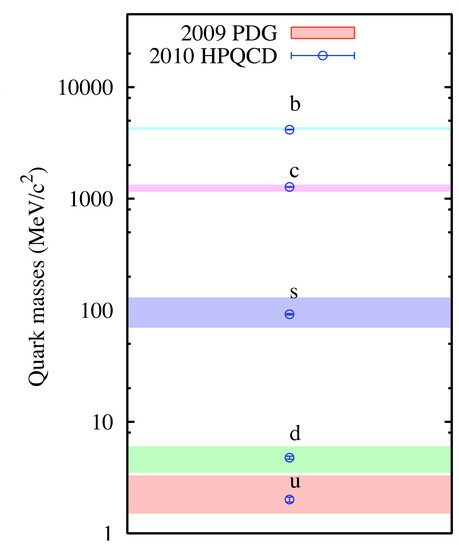
Lattice QCD simulations are critical to understanding the validity of the Standard Model and the results from High Energy and Nuclear Physics experiments. In the coming decades Energy Frontier experiments at CERN, and Intensity and Cosmological Frontier experiments at Fermilab and other sites, likely will uncover physics beyond the Standard Model. Simulation techniques developed for Lattice QCD will be key to understanding these experimental results and developing theories Beyond the Standard Model (BSM).

The computational demands of Lattice QCD and BSM simulations will require the exploitation of exascale computing hardware and the evolution of (or revolutions in) techniques, algorithms, and software.

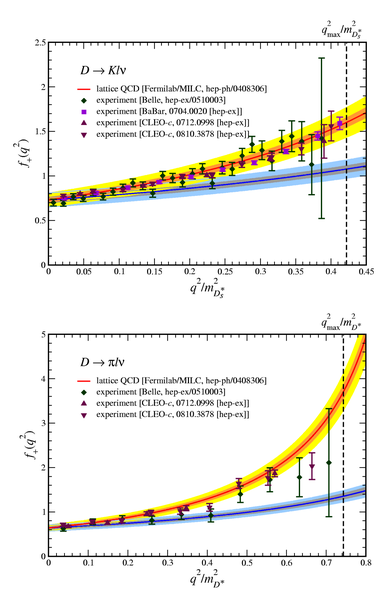
## Computing quark masses

Quark masses, which are parameters of the Standard Model, can be computed from Lattice QCD simulations. The figure compares the masses resulting from LQCD simulations with the best or "world average" values of the masses determined from experiment. The vertical widths of the plotted bands indicates the probable range of the mass according to the world average. The points are the results from lattice QCD. The lattice QCD error bars are significantly smaller than the experimental errors.

The much heavier *top* mass (172,900 MeV/$c^2$) is not shown. Unlike the other quarks, the mass of the *top* quark can be measured with high precision, directly from experiment.




## Decays of the charm quark




Each figure shows the form factor describing a decay of a D meson (containing a *charm* quark) into a lighter meson. If the *charm* quark decays into a *strange* quark, then a kaon is produced (top figure). If the *charm* quark decays into a *down* quark then a pion is produced (lower figure).

The points (with error bars) in each figure show the experimental measurements. The colored bands indicate the results from a first principles calculation in Lattice QCD. Lattice and experiment are in good agreement.