Precision Physics from Simulations of Lattice Quantum Chromodynamics

In the last decade, simulations of Lattice Quantum Chromodynamics (QCD) have reached a new level of precision. By now we are able to compute per mill effects of the particle mass spectrum of QCD, by combining Lattice QCD with Lattice Quantum Electrodynamics (QED). This dramatic increase of precision was made possible by the combination of new and more powerful machines and new lattice actions and simulation algorithms.

With these new methods at hand, we have computed the neutron-proton and other mass splittings from first principles [1,2], studied the range of applicability of chiral perturbation theory [3] and extracted the corresponding low energy constants [4]. Furthermore, we have computed the Equation of State of QCD [5], the freeze-out parameters of the cooling quark-gluon-plasma produced in heavy ion experiments [6,7], including the flavor dependency of the freeze-out temperature [8].

In the following, we will briefly discuss these different results.

Precision Spectrum of the Standard Model

Moving beyond the per cent level precision of our 2008 calculation of the light hadron spectrum [9] (see also Fig. 1), requires the addition of two formally per cent level effects in the calculation: Quantum Electrodynamics (QED), due to the magnitude of the fine structure constant $\alpha \approx 1/137$, and the up/down

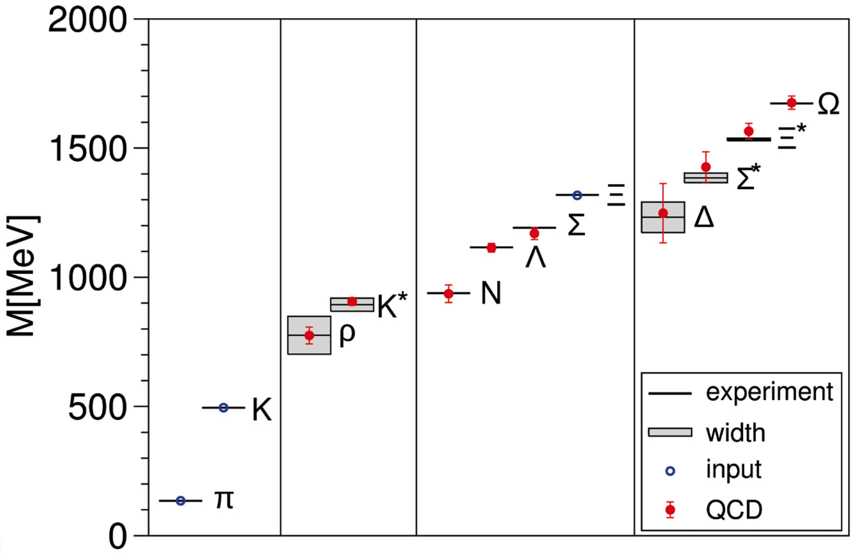

Figure 1: Ab initio calculation of the light hadron spectrum of QCD [9]. Blue circles indicate experimental input required to fix the quark masses and overall scale of the calculation. Red points indicate predictions of QCD. Experimental widths are grey, with the central value indicated by a black line.

quark mass splitting $(m_d-m_u)/\Lambda_{QCD} \approx< 0.01$ (which are of almost the same magnitude). In particular including QED poses a range of conceptual issues [10].

Incorporating these effects allows us to calculate the neutron-proton and other mass splittings. This implies calculating a per mill level difference between particle masses that were previously available at per cent precision. However, by making use of statistical correlations between (e.g., neutron and proton) propagators, it is possible to calculate the spitting directly.

A first step in this direction was our result [2] using quenched QED, i.e. neglecting the effect of QED in quark loops. Such a calculation cannot be fully satisfactory. For our recent result

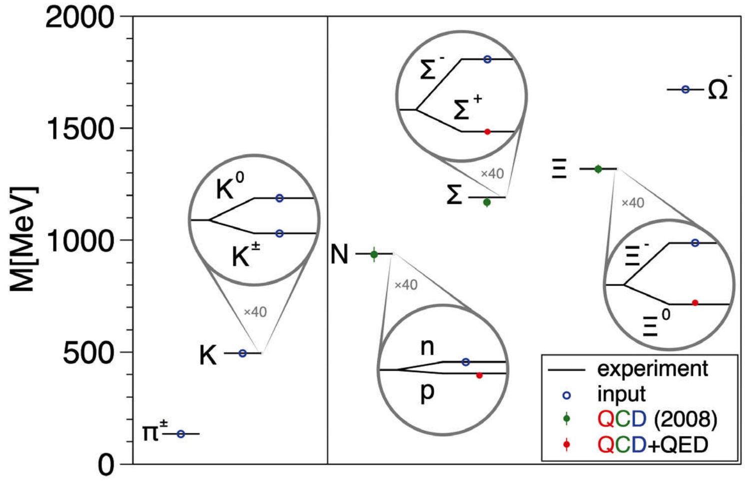

Figure 2: Mass splittings. Shown are individual masses from Figure 1, with the results [1] on the mass splittings shown in 40x magnification.

on the mass splittings [1], we took the next step and included these unquenching effects, which required us to develop new simulation techniques and to calculate finite volume effects analytically [10]. The precision of our results is illustrated in Fig. 2.

Confronting Chiral Perturbation Theory

Chiral perturbation (XPT) theory is an effective theory that is used to compute low-energy properties of QCD. It does not describe the dynamics of quarks and gluons, but rather the dynamics of hadrons. Since it is an expansion around zero quark masses (and momenta), it is in principle unclear if it does in deed apply to the physical world, where the quark masses are non-zero. XPT has also been used in the past to extrapolate from heavier than physical quark masses (due to the costs of simulating with physical parameters) down to the physical mass point.

In 2010, we were the first to compute the quark masses [11] using ensembles with physical quark mass parameters. With these new ensembles that now include the physical point, we could check the applicability of XPT for different observables. Furthermore, we could calculate several (low energy) constants (LECs) of XPT that are not fixed by the theory. This is illustrated in Fig. 3 for one particular LEC, where also the limited applicability of XPT for heavy pion masses is clearly visible.

Lattice QCD for heavy Ion Experiments

Heavy ion experiments (such as RHIC at BNL, LHC at CERN or the upcoming FAIR at GSI) require the Equation of State of QCD (EoS) as a central ingredient for the understanding of the evolution of the quark-gluon plasma generated in collisions of heavy nuclei. The only tool available that allows for a calculation of the EoS from first principles is Lattice QCD.

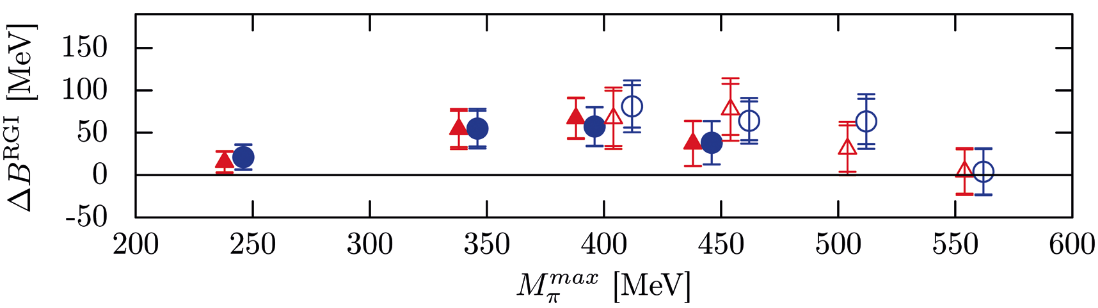

Figure 3: Deviation of the low energy constant B in the RGI scheme from the value at physical mass parameters. Clearly, for simulated pion masses much larger than 300 MeV, the applicability of XPT (SU(2) in this case) to (N_f=2+1) QCD is limited.

In 2013 [5] we presented the first full calculation of this central quantity, by carefully balancing and controlling the different uncertainties and taking the continuum limit (vanishing lattice spacing). Recently, our findings were corroborated by the independent hotQCD collaboration, as shown in Fig. 4. This settled a long standing discrepancy between the collaborations, dating back beyond our first continuum estimate of 2010 and became possible with the most recent results from hotQCD.

By studying so-called generalized susceptibilities (derivatives of the partition function with respect to the chemical potentials), it is also possible to directly match Lattice QCD results at finite temperature and chemical potentials to experimental data.

In heavy-ion experiments, the nuclei rarely hit head on, and the "cross-section volume" is not constant on an event-by-event basis. This implies that otherwise conserved quantities like the total electric charge or the baryon number, as measured from the collision products, fluctuate as well. If additional cuts on the experimental data are applied, this experimental setting can be described using a grand-canonical ensemble and thus be simulated using Lattice QCD. The moments of the distributions of the conserved charges found in experiment can then be matched to Lattice QCD results, when appropriate ratios of moments are taken, such that the interaction volume cancels out. In this way it is possible to extract the experimental freeze-out parameters, i.e. the temperature and chemical potential at "chemical freeze-out" (last inelastic scattering of hadrons before detection).

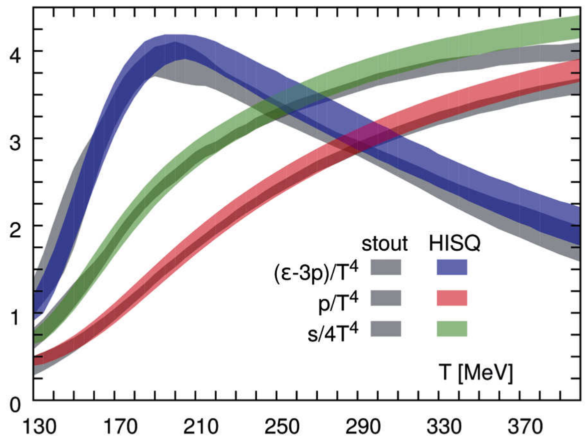

Figure 4: Comparison of independent results for the EoS of QCD (taken from Phys. Rev. D90 (2014) 094503 by hotQCD). Shown are our results ("stout") and the results of the hotQCD collaboration ("HISQ").

We calculated these parameters [6] using preliminary data from the STAR collaboration. Using their latest experimental results, our findings for the freeze-out parameters are consistent [7], independent whether electrical charge or baryon number fluctuations were used for the matching. Furthermore, we see indications that hadrons with different quark flavors may have different freeze-out parameters [8], a finding that could be verified experimentally at LHC.

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• Zoltan Fodor[1, 2, 3]
• Stefan Krieg[1, 2]

[1] JSC & JARA-HPC Forschungszentrum Jülich, Germany

[2] University of Wuppertal, Germany

[3] Eötvös Lorand University, Hungary

contact: Zoltan Fodor, fodor@physik.uni-wuppertal.de
Stefan Krieg, s.krieg@fz-juelich.de