Precision flavor physics from lattice QCD.

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Introduction to particle physics

Particle physics is the study of basic laws of the Universe. I don't know the answers to the following questions about the Universe.

- Cosmological and astrophysics experiments suggest that roughly 30% of the energy of the Universe is something called dark matter. But what is dark matter?
- Can we calculate the masses of the fundamental particles of existence, such as quarks?
- Why is that the Universe is dominated by matter, rather than an equal balance of matter and anti-matter?
- Can we find a Beyond the Standard Model (BSM) theory which answers all (or even some) of the above questions?

The natural units of particle physics are electron volts: the energy gained by an electron after moving through a potential difference of 1V. Also we work with units where the speed of light is 1 ($c = 1$ in $E = Mc^2$), so we measure the masses of particles in units of MeV (10^6 eV) or GeV (10^9 eV), as well. The language of particle physics is Quantum Field Theory, hence many quantities depend on the energy scale μ they are measured at (eg. $\alpha_s(\mu)$), because of a technique called renormalization.

Introducing QCD

- QCD (Quantum Chromo Dynamics) is the basic theory of nuclear physics.
- The fundamental particles in QCD are quarks and gluons.
- There are six distinct types of quarks, known as flavours. Flavour physics studies the decay of one flavour of quark into another flavour of quark, as well as the distinctive properties of each flavour of quark, such as their masses.

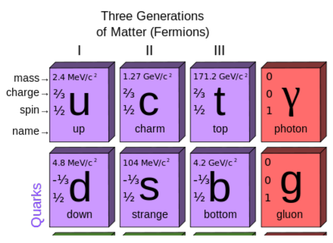


Fig. 1: Fundamental particles in QCD

- No free quarks or gluons have ever been observed experimentally, because of a "property" of QCD called **confinement**.
- Quarks and gluons bind together to form hadrons.

To study the properties of quarks, QCD must be solved, but this can not be done analytically in general.

- For many static quantities, the equations of QCD can be put on the computer, after a lattice is introduced. This technique is known as **lattice QCD**.
- Typically the equations are solved using massively parallel supercomputers with many thousands of compute nodes.
- The main numerical algorithms used to solve the equations are the Monte Carlo method, and sparse matrix inversions.

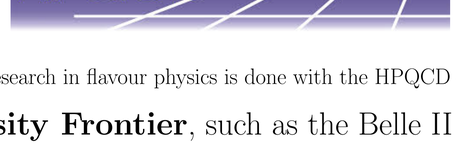


Fig. 2: My research in flavour physics is done with the HPQCD collaboration.

Experiments at the **Intensity Frontier**, such as the Belle II experiment at the SuperKEKB collider in Japan, and the LHCb experiment at CERN, carefully study hadron decays involving quarks, to search for virtual BSM contributions.

Determining the masses of the quarks

- The masses of the quarks are input to the lattice QCD calculations and then they are adjusted to reproduce a hadron's mass, whose value is known from experiment.
- One hadron mass is used to determine the lattice spacing in physical units.
- The plot below shows a summary of different calculations of the mass of the strange quark. My result is the HPQCD one. The black symbols are review talks, and the green and red numbers are the results from other lattice QCD groups.

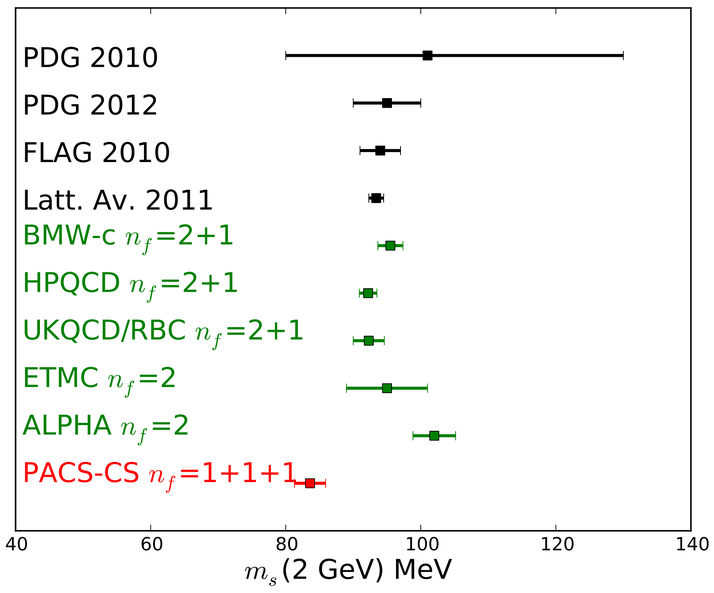


Fig. 3: Summary of the mass of the strange quark

Determining the strong coupling of QCD

- The QCD coupling ($\alpha_s(\mu)$) is a key number that determines the strength of the interaction in QCD.
- The value of the QCD coupling is important for testing the unification of QCD with the electroweak theory (possibly including BSM theories such as SUSY or technicolour).
- In the graph below, my results are labeled by HPQCD. The black results are from non-lattice methods, and the green and blue numbers are from different lattice QCD calculations. The red numbers are from reviews.

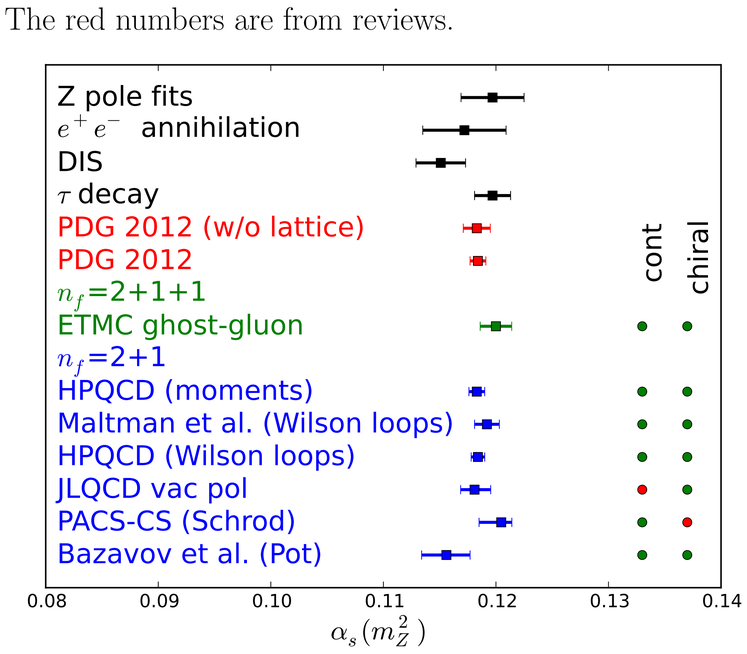
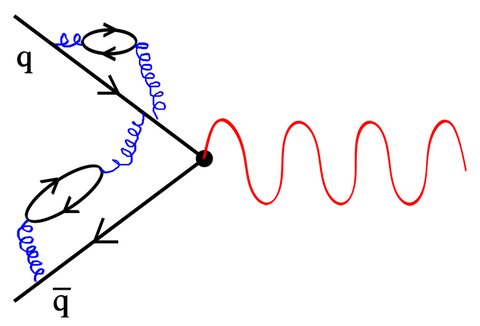


Fig. 4: Summary of estimates of the QCD strong coupling (from [1])

The decay constants of mesons

- The decay constant of a meson is related to the amplitude for the quark and anti-quark in the meson to be together.



- In the decay on the left, virtual particles from a BSM theory could contribute.
- BSM contributions could modify the prediction from the standard model of particle physics, and thus be detected.
- Some decay constants may not be sensitive to BSM contributions, so they are good for validation.

Fig. 5: Decay constants of mesons in QCD

Large scale computer calculations provide accurate numbers when the systematic errors are under full control. To convince non-experts in lattice QCD, who can't follow the details of the calculation, that the results are correct requires some experimental checks to be made. The graph below shows various decay constants computed in lattice QCD calculations, compared to experimental values.

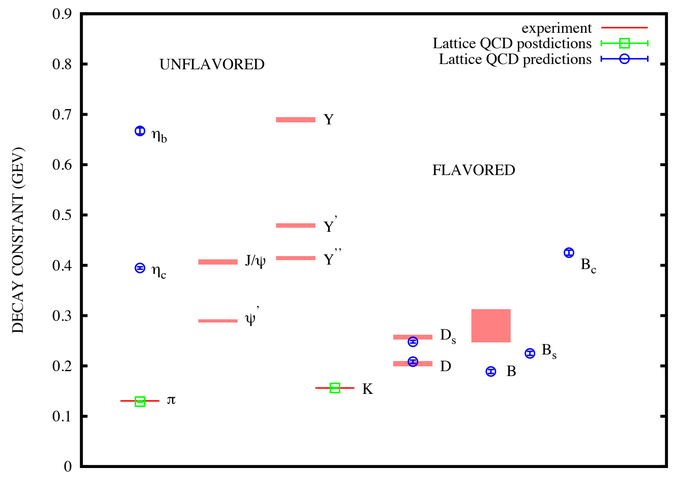


Fig. 6: Summary of decay constants from lattice QCD from the HPQCD collaboration [4]

Conclusions

You can find more up to date information on my research at: `http://math-sciences.org/research-groups/research-physics`

References

[1] C. McNeile, "Strong coupling and quark masses from lattice QCD," Mod. Phys. Lett. A **28** (2013) 1360012 [arXiv:1306.3326 [hep-lat]].

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[3] R. J. Dowdall, C. T. H. Davies, G. P. Lepage and C. McNeile, "Vus from pi and K decay constants in full lattice QCD with physical u, d, s and c quarks," Phys. Rev. D **88** (2013) 074504 [arXiv:1303.1670 [hep-lat]].

[4] C. McNeile, C. T. H. Davies, E. Follana, K. Hornbostel and G. P. Lepage, "Heavy meson masses and decay constants from relativistic heavy quarks in full lattice QCD," Phys. Rev. D **86** (2012) 074503 [arXiv:1207.0994 [hep-lat]].

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