Glueballs and novel bound states in QCD

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Introducing QCD

QCD (Quantum Chromo Dynamics) is the basic theory of nuclear physics. The fundamental particles in QCD are quarks and gluons.

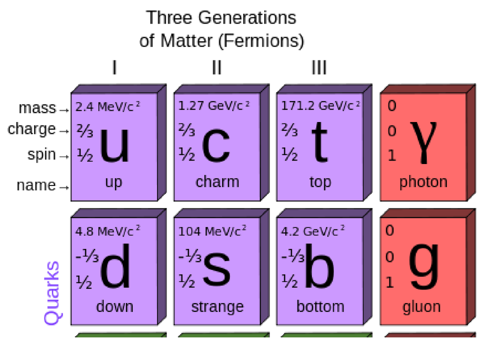

Fig. 1: Fundamental particles in QCD

Bound states in QCD

- No individual quarks or gluons have ever been experimentally observed. Only bound states of quarks and gluons have been detected in an experiment. These bound states are generically called hadrons.
- The surprising fact that the basic particles of QCD are not seen experimentally is "explained" by a property of QCD called **confinement**. Quarks and gluons carry a colour quantum number. Only bound states, with the colours adding up to the neutral white can exist.

Currently the only confirmed bound states in QCD are

Meson - a bound state of quark with antiquark

Baryon - a bound state of three quarks.

In principle QCD allows more complicated bound states than the baryon and meson states currently observed from experiments. For example:

- Glueballs are particles made from glue (see [1] for a review)
- Hybrid mesons are meson like states with excited glue.
- Tetraquark, pentaquark, and/or molecules.

A simple picture of a hybrid meson is

Fig. 2: Cartoon of a hybrid meson with charm quarks.

- Accurate theoretical predictions from lattice QCD are required in the many experimental searches for these new states.
- There are suggestions that a QCD-like theory could be a candidate for a deeper fundamental physics theory, than we currently have. The glueballs are important to the dynamics.

Experimental searches for glueballs and hybrid mesons

There is a vigorous experimental program searching for the above new states. As well as experiments at the LHC, there are dedicated facilities looking for novel QCD bound states.

- The 12 GeV upgrade and GlueX experiment at the Jefferson Lab in Newport USA
- The PANDA experiment at GSI in Germany.

Fig. 3: One of the goals of the Jefferson lab is to find light hybrid mesons

Lattice QCD

- The equations of QCD can not be solved analytically.
- For many static quantities, the equations of QCD can be put on the computer. A lattice is introduced.
- Typically the equations are solved using massively parallel supercomputers with many thousands of nodes to solve the equations.
- The main numerical algorithm used to solve the equations is the Monte Carlo method.
- Calculations which include glueballs typically require a large number of samples [4].

In particle physics we classify bound states using the quantum numbers of symmetry operations. For example:

Parity (P) Reflection in the origin

Charge conjugation (C) Replace a particle with with its anti-particle.

Glueballs in pure Yang Mills theory

Over 10 years ago the glueball spectrum was determined in pure Yang Mills theory (where there are no quarks), by Morningstar and Peardon [2].

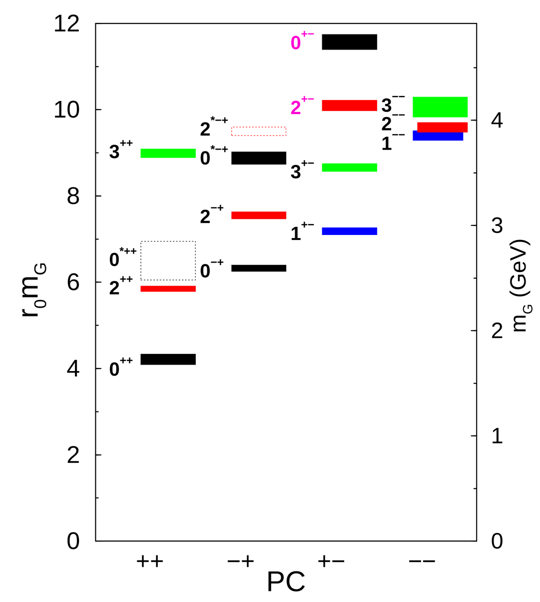

Fig. 4: Glueball masses from pure Yang-Mills theory

- This graph is the masses of glueballs with different charge conjugation (C), parity (P) quantum numbers, and angular momentum (J) quantum numbers.
- The dynamics of quarks is not included in the calculation.
- Recall that the mass of a proton is approximately 1 GeV.
- The challenge is to update this graph to include the dynamics of quarks.

Towards unquenching the masses of glueballs

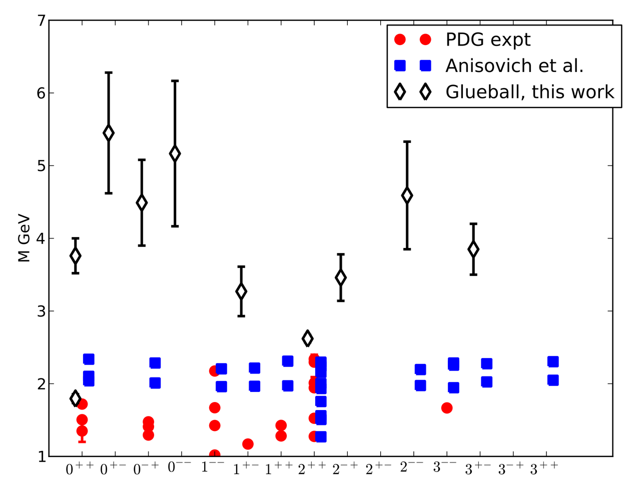

Fig. 5: Unquenching the masses of the glueballs

- The graph is a summary of the masses of the glueballs determined by our group [3], which include the dynamics of sea quarks, at a single lattice spacing.
- We did not take the continuum limit in the calculation, because it was too computationally expensive.
- On the plot the masses of hadrons from experiment are also included.
- We also need to include quark-antiquark operators and include the dynamics of the decay to two mesons.

Insight into glueballs

> The purpose of computing is insight, not numbers.
> Richard Hamming

Large scale computer calculations provide accurate numbers when all the systematic errors are fully under control. Insight into the results can also be gained by studying the parameter dependence of the theory.

- For example, QCD depends on the number of colours N.
- The graph below (from [5]) shows the masses of some glueball states (in simulation units) as the number of colours (N) is varied.
- The dependence of the glueball masses on $\frac{1}{N^2}$ is weak.

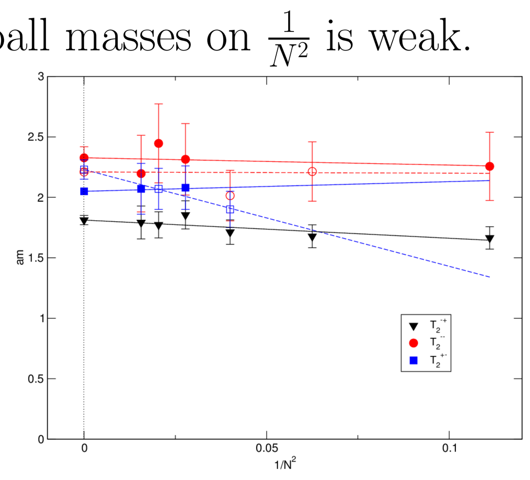

Fig. 6: Colour dependence of glueball masses

Conclusions

You can find more up to date information on our research into glueballs and hybrid mesons at `http://math-sciences.org/research-groups/research-physics`

References

[1] V. Mathieu, N. Kochelev and V. Vento, 'The Physics of Glueballs," Int. J. Mod. Phys. E **18** (2009) 1 [arXiv:0810.4453 [hep-ph]].

[2] C. J. Morningstar and M. J. Peardon, "The Glueball spectrum from an anisotropic lattice study," Phys. Rev. D **60** (1999) 034509 [hep-lat/9901004].

[3] E. Gregory, A. Irving, B. Lucini, C. McNeile, A. Rago, C. Richards and E. Rinaldi, "Towards the glueball spectrum from unquenched lattice QCD," JHEP **1210** (2012) 170 doi:10.1007/JHEP10(2012)170 [arXiv:1208.1858].

[4] B. Lucini, C. McNeile and A. Rago, "Investigating some technical improvements to glueball calculations," arXiv:1511.09303.

[5] B. Lucini, A. Rago and E. Rinaldi, "Glueball masses in the large N limit," JHEP **1008** (2010) 119 [arXiv:1007.3879].