The Problem With Quantum Chromodynamics (and a stringy solution)

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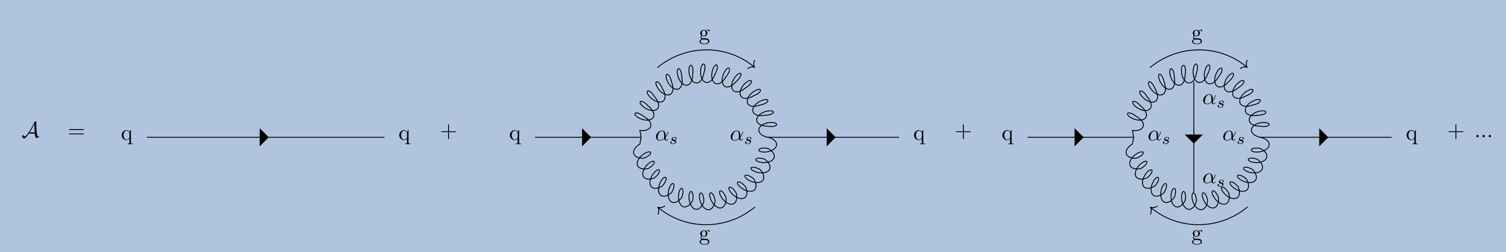
What is a Quantum Field Theory? - A field is something that takes a value at every point in space (and time), for example a temperature field. In a QFT a particle is interpreted as an excitation of its quantum field (QF) and the value the QF takes is the probability of finding that particle at a given location.

What is Quantum Chromodynamics (QCD)? - QCD is a theory that uses the framework of a QFT to describe the strong interaction of quarks and gluons, these can then come together to form hadrons like protons and neutrons that make up the nuclei of atoms.

1. The Problem With QCD

Working out the probability of interactions to occur can be difficult as we have to add together all the different ways the particles can combine:

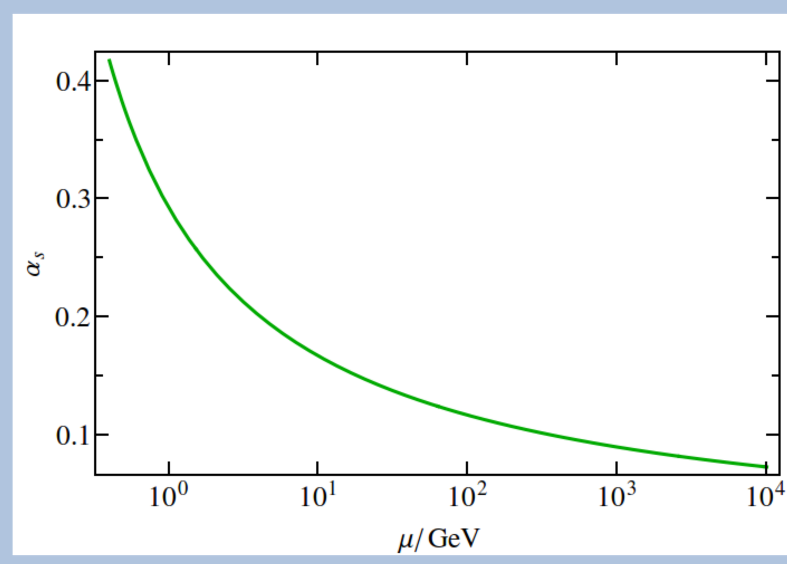


The above is the probability of a quark (q) to move from one location to another. We have to include that the quark can change into gluon--s (g) or other quarks as it propagates. The quarks and gluons carry colour charge each with a factor of α_s, the coupling strength, that tells us about the strength of the force associated with QCD.

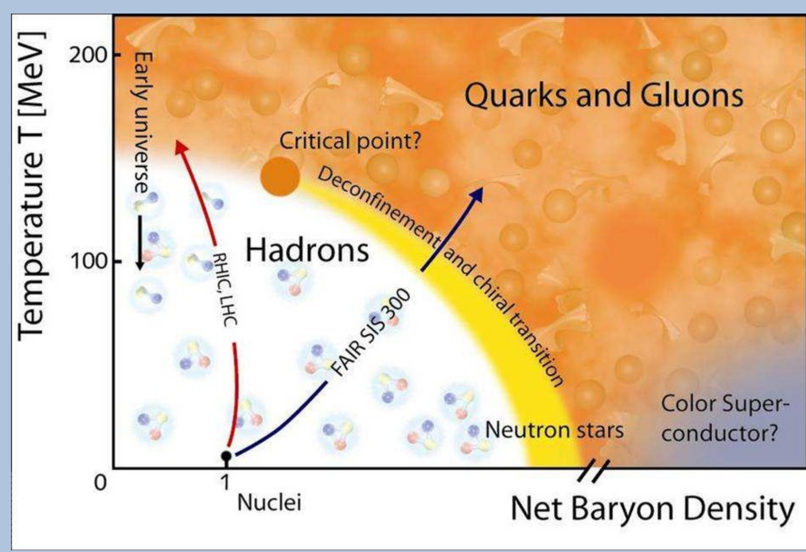
To see how important each diagram is to the total probability we multiply the couplings together:

$$\mathcal{A} = 1 + \alpha_s^2 + \alpha_s^4 + ...$$

If α_s is small we can neglect the higher order terms: the problem with QCD is that α_s is not always small!.



This can make calculations in QCD impossible with our current understanding, for example calculating the QCD phase diagram:



Scientific American Sp 15, 74 - 81 (2006)

2. A Stringy Solution

A possible solution is to use the gauge/gravity duality.

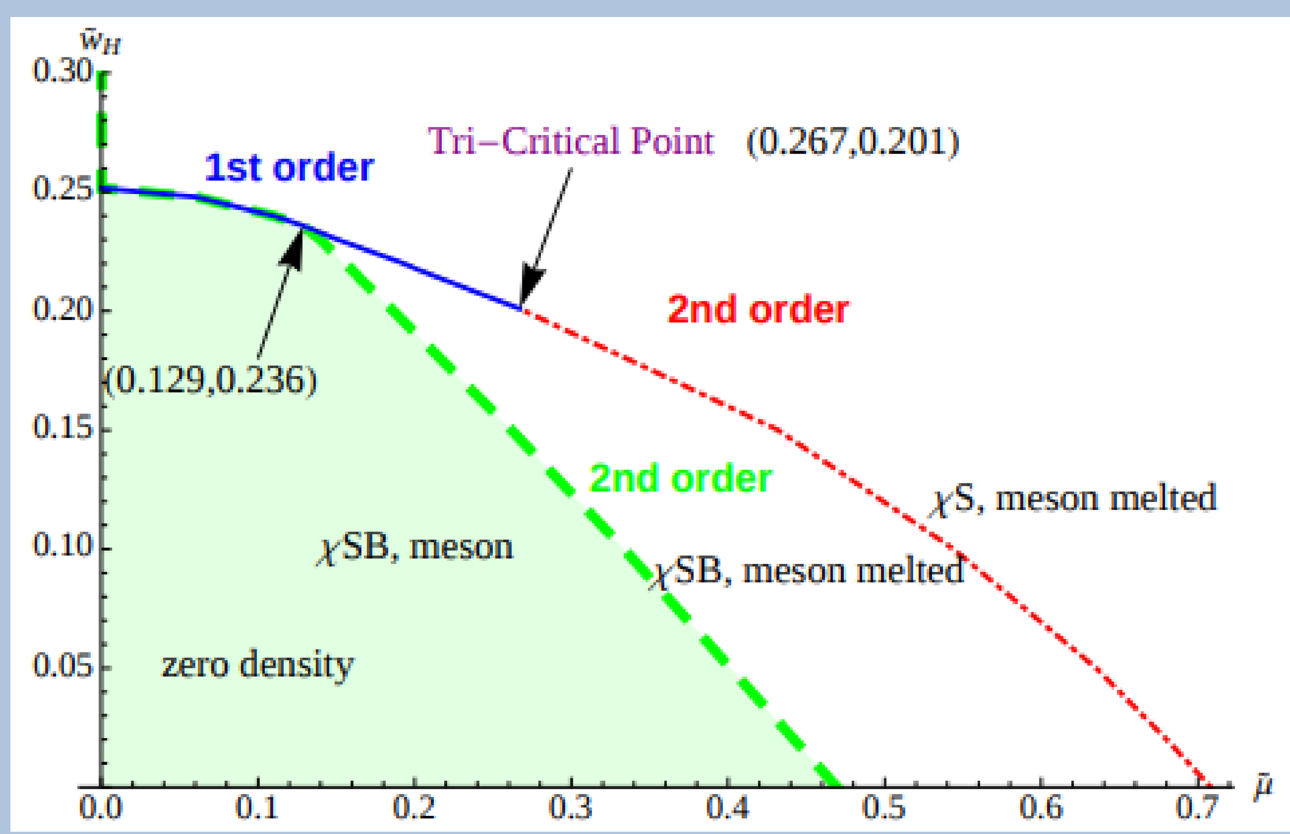
- A duality means that all of the physics in one theory is completely equivalent to all of the physics in another theory.
- The gauge/gravity duality is a dual between a string theory (gravity) and a QFT.
- Dualities can have special properties, for example the QFT is in one less dimension than the string theory. Another useful property:

  → A large coupling in one theory becomes a small coupling in the dual theory.

  This means that instead of doing our difficult (or impossible) large coupling calculation in the QFT, we instead can calculate it in the string theory with a small coupling. And as they are dual, the physics is the same!

3. QCD phase diagram from gauge/gravity

Lets see if we can calulcate something from QCD: the QCD phase diagram (above). We choose a string theory to give a QFT dual that is similar to QCD and plot temperature against density:



N Evans, A Gebauer, K-Y Kim,M. Magou, JHEP (2010) 2010:132

There are some similarities with the phase diagram given above:

- There is a region with mesons/hadrons (particles made from quarks and gluons bound together) and a region where the meson/hardons have 'melted' - the quarks and gluons are no longer bound inside particles.
- There is a phase transition between these two states and a point where first and second order phase transitions meet.

4. What's the catch?

- The QFT dual is not actually QCD (for example it has extra partners of quarks), it only has ingrediants to make it look like QCD.
- For example, in the phase diagram calculated using the duality, the '1st order' and 'second order' transitions are actually the wrong way round.
- It would be useful to one day find a string theory that gives the real QCD as its dual.