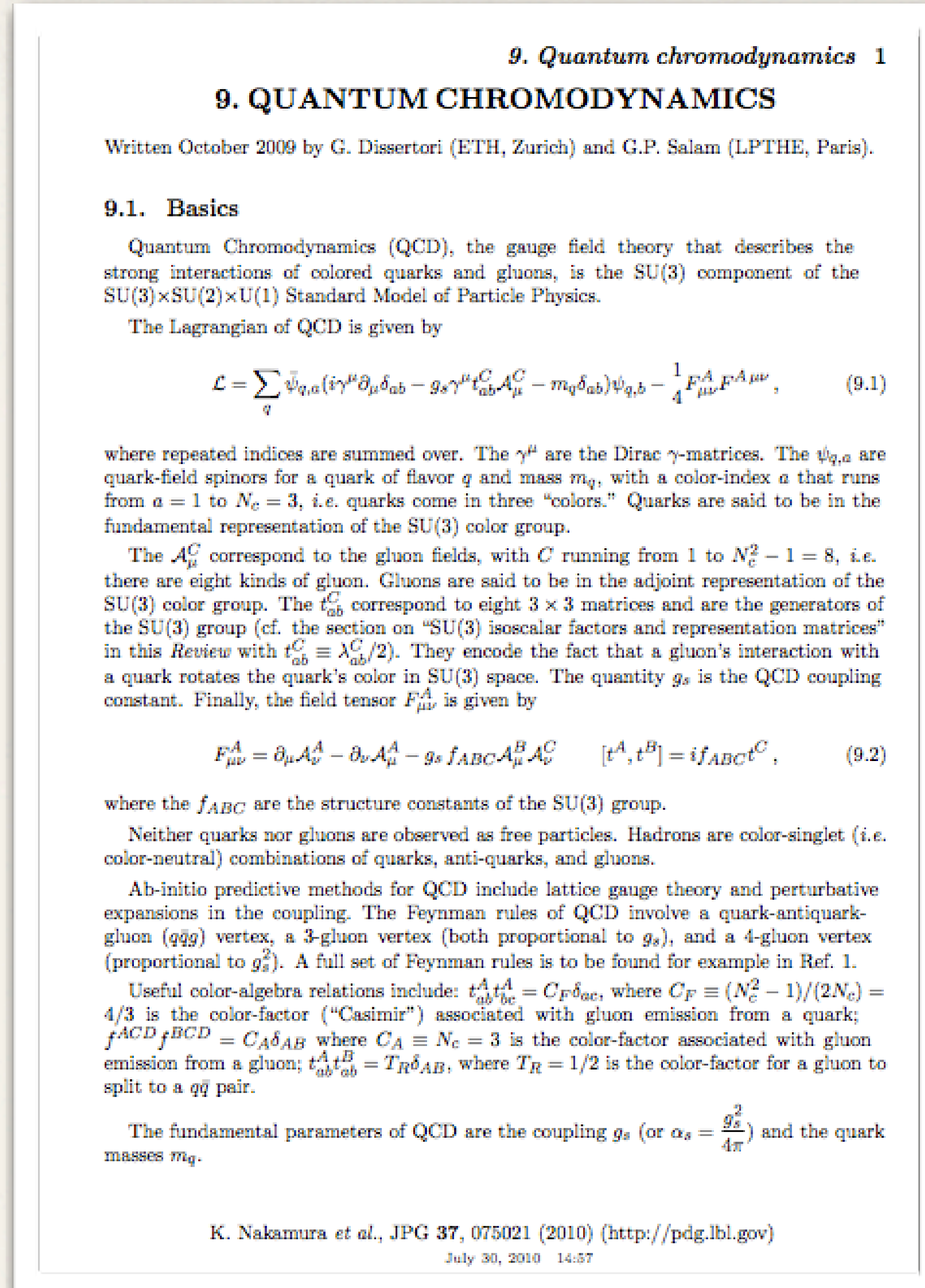

9. Quantum chromodynamics 1

9. QUANTUM CHROMODYNAMICS

Written October 2009 by G. Dissertori (ETH, Zurich) and G.P. Salam (LPTHE, Paris).

9.1. Basics

Quantum Chromodynamics (QCD), the gauge field theory that describes the strong interactions of colored quarks and gluons, is the SU(3) component of the SU(3)×SU(2)×U(1) Standard Model of Particle Physics.

The Lagrangian of QCD is given by

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu} , \qquad (9.1)$$

where repeated indices are summed over. The γ^μ are the Dirac γ-matrices. The $\psi_{q,a}$ are quark-field spinors for a quark of flavor q and mass m_q, with a color-index a that runs from $a = 1$ to $N_c = 3$, *i.e.* quarks come in three "colors." Quarks are said to be in the fundamental representation of the SU(3) color group.

The $\mathcal{A}^C_\mu$ correspond to the gluon fields, with C running from 1 to $N_c^2 - 1 = 8$, *i.e.* there are eight kinds of gluon. Gluons are said to be in the adjoint representation of the SU(3) color group. The t^C_{ab} correspond to eight 3×3 matrices and are the generators of the SU(3) group (cf. the section on "SU(3) isoscalar factors and representation matrices" in this *Review* with $t^C_{ab} \equiv \lambda^C_{ab}/2$). They encode the fact that a gluon's interaction with a quark rotates the quark's color in SU(3) space. The quantity g_s is the QCD coupling constant. Finally, the field tensor $F^A_{\mu\nu}$ is given by

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C , \qquad (9.2)$$

where the f_{ABC} are the structure constants of the SU(3) group.

Neither quarks nor gluons are observed as free particles. Hadrons are color-singlet (*i.e.* color-neutral) combinations of quarks, anti-quarks, and gluons.

Ab-initio predictive methods for QCD include lattice gauge theory and perturbative expansions in the coupling. The Feynman rules of QCD involve a quark-antiquark-gluon ($q\bar{q}g$) vertex, a 3-gluon vertex (both proportional to g_s), and a 4-gluon vertex (proportional to g_s^2). A full set of Feynman rules is to be found for example in Ref. 1.

Useful color-algebra relations include: $t^A_{ab} t^A_{bc} = C_F \delta_{ac}$, where $C_F \equiv (N_c^2 - 1)/(2N_c) = 4/3$ is the color-factor ("Casimir") associated with gluon emission from a quark; $f^{ACD} f^{BCD} = C_A \delta_{AB}$ where $C_A \equiv N_c = 3$ is the color-factor associated with gluon emission from a gluon; $t^A_{ab} t^B_{ab} = T_R \delta_{AB}$, where $T_R = 1/2$ is the color-factor for a gluon to split to a $q\bar{q}$ pair.

The fundamental parameters of QCD are the coupling g_s (or $\alpha_s = \frac{g_s^2}{4\pi}$) and the quark masses m_q.

K. Nakamura *et al.*, JPG **37**, 075021 (2010) (http://pdg.lbl.gov)
July 30, 2010 14:57

QCD Review

G. Dissertori / ETH Zurich G. Salam / CERN, Princeton and Paris

20.11.2010

A complete re-write

- Old review (by Ian Hinchliffe) was mostly a compilation of α_s measurements and a final combination
- Our goal was:
  - complete overhaul, with changed focus
  - tried to address modern aspects of QCD (theoretical and experimental), with focus on perturbative QCD and collider physics. Motivated by
    - our own expertise
    - the LHC start-up

Sections

- Basics (Lagrangian, parameters etc)
- Running coupling
- Quark masses (short, with reference to dedicated review)
- Structure of QCD predictions
  - Inclusive cross sections
    - e^+e^- , scale dependence
    - Processes with initial state hadrons:
      - DIS
      - Hadron-Hadron collisions
      - Photoproduction
      - High-Energy limit
  - Non-inclusive cross sections
    - Soft and collinear Limits
    - Fixed-order predictions (LO, NLO, NNLO)
    - Resummation
    - Fragmentation functions (short, with reference to dedicated review)
    - Parton shower Monte Carlo generators
    - Accuracy of predictions

Sections (cont.ed)

- Experimental QCD
  - Hadronic final state observables
    - Jets (modern jet algorithms)
    - Event shapes
    - Jet substructure, quark vs gluon jet
  - State-of-the-art QCD measurements at colliders
    - e^+e^-
    - DIS and photoproduction
    - Hadron colliders
  - Tests of the non-abelian nature of QCD
  - Measurements of the strong coupling constant
    - summarizing the most recent studies and world-average by S. Bethke

Main referee feedback

- Overall very positive
- some comments on text, references etc.
- main points
  - inclusion and discussion of Lattice results, also in the context of the α_s discussion
  - usage of Bethke's result for the α_s world average

Our comments regarding the α_s world average

- The motivations behind using Siggi's average were
  - space: fitting both an overview of QCD (see section headings before) and a complete discussion of a new world average would not be possible, within the given space limitations (remember the main aim of this new review)
  - time: performing a complete, independent analysis towards a new world average, and in addition writing this new review, would not have been possible within our time constraints
- However, we are convinced that what is given is a sensible average
  - we had very extensive discussions with Siggi, on the various uncertainties

Our suggestions for the future

- Lattice QCD would deserve a dedicated review
  - in a similar spirit as the dedicated reviews on quark masses, PDFs and fragmentation functions
- maybe also a dedicated discussion/separate review on effective theories?
- α_s world average:
  - again, probably deserves a dedicated "review" or section
  - a group of experts could be formed, who work on such a unique world average (try to avoid going back to the widespread use of two world averages, one from PDG, one from Bethke)
  - Indeed, an effort in this direction has been launched recently
    - a first workshop to be held in Feb 2011, at MPI Munich
    - Gavin will give a talk there
    - we will both follow closely those developments and give input with our "PDG" hats

The last slide....