1. QUANTUM CHROMODYNAMICS

Revised September 2011 by S. Bethke (MPPMU, Munich), G. Dissertori (ETH, Zurich) and G.P. Salam (CERN, Princeton University and LPTHE, Paris).

1.1. 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

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a} \left(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab} \right) \psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu} \,, \qquad (1.1)$$

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

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad \left[t^A, t^B \right] = i f_{ABC} t^C \,, \qquad (1.2)$$

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. 3.

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.

QCD Review

S. Bethke (MPPMU), G. Dissertori/ETH Zurich, G. Salam/CERN, Princeton and Paris

6.10.2012

First revision of the complete rewrite in 2010

- Some minor updates and one major change w.r.t. to last version
- Minor changes/updates:
  - Some updates in the theory section
  - Some updates in the exp. results section,
    mostly for including first LHC results
- The major changes:
  - A new, third author: Siggi Bethke
  - Rewrite of the alpha_s part: now the world-average is defined by our PDG evaluation, and not quoted from external source any more.

Main referee feedback and consequences

- The new alpha_s world average, as part of our review, addresses the main comments/concerns on the 2010 edition

- Attempted to communicate/synchronize with authors of other sections, such as EWK (Erler, Langacker), in particular for the alpha_s part

- Referee feedback (5 reviewers) on the new edition:

  - Overall positive

  - A number of detailed suggestions received and implemented

  - No major change to our draft required due to reviewer’s comments

Comments on the new alpha_s section

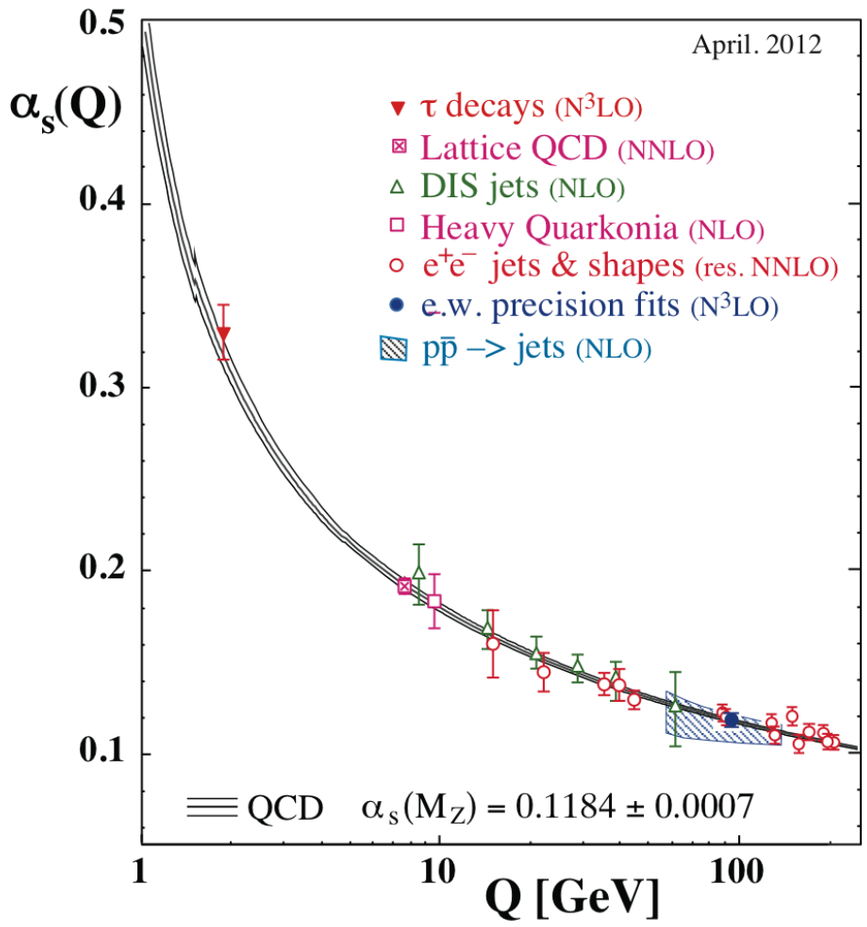
- Only peer-reviewed results based on (at least) NNLO QCD included

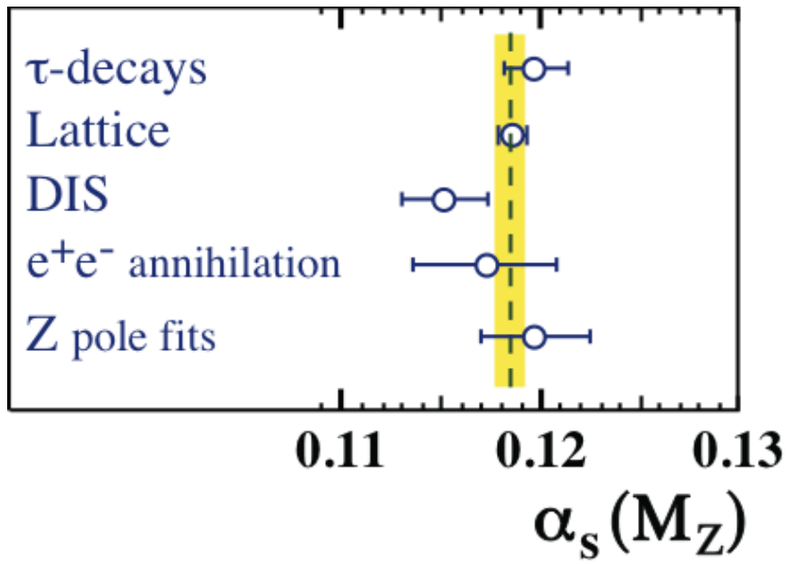
- New procedure of averaging applied:

  – *pre-averages* determined for *sub-classes* (τ-decays, lattice, DIS, e^+e^-, e.w. fits)

  – final world average from *pre-averages*:
  $\alpha_s(M_z) = 0.1184 \pm 0.0007$
  (unchanged from previous report)

- Many systematic checks done (and described in text)





The last slide....