Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - Mesons, baryons
- Quark Model
  - Meson and baryon multiplets
  - Isospin, strangeness, c, b, t quarks
- Particle Interactions
  - Colour charge, QCD, gluons
  - Virtual particles and range of forces
  - Strong and weak decays, conservation rules
  - Parity, charge conjugation, CP
  - Weak decays of quarks
  - Charmonium and upsilon systems
- Electroweak Interactions
  - Charged and neutral currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator physics

Today

- Lecture 10 (4 slides/page) - QCD
  - Griffiths, pp. 66-72, 173, 283-301
  - Perkins, pp. 291-293, 303, 307
  - Williams, pp. 179-181
  - PDG review of QCD - earlier parts too detailed, suggest starting at Sect. 9.3

Previous lecture

- Lecture 9 (4 slides/page) - colour charge
  - Griffiths, pp. 181-188
  - Perkins, pp. 283 285

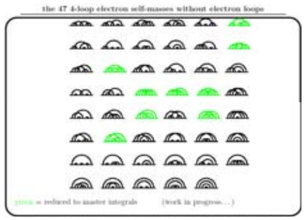
Quantum Field Theories in PP – QED and QCD

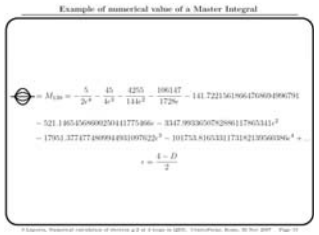
- QED developed ~1948 by Feynman, Tomonaga, Schwinger
- Locally Gauge Invariant Theory
  - Effectively equivalent to having an arbitrary zero of electric potential
  - Conservation of charge leads to "choice of gauge" (in Maxwell Equations)
  - Symmetry of the theory (physics of interactions the same after any global change in potential)
    - ⇒ leads to charge conservation (Noether's Theorem)
- The "local" aspect extends idea to arbitrary choice at any point in space
- QED, gauge symmetry group is called U(1)
- QCD, gauge symmetry group is called SU(3) – three colour charges
  - "non-Abelian" theory (order of operations such as rotations important in 3d)
- Renormalizable Theory
  - Can be used for real calculations in perturbation theory without introducing uncontrolled divergences (infinities)
- Concepts advanced, will not do any more than skim surface (apologies!)
  - Interested in details, will put further references on web

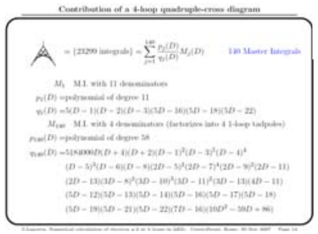
Quantum ElectroDynamics – QED

- Measured/predicted to ~6 parts in 10^{10} precision
- D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. 100, 120801 (2008).

Examples of what is involved in calculations to reach such precision…

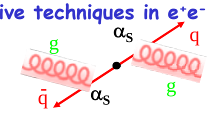


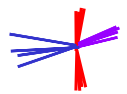




Strong Coupling "constant", α_S

- α_S the fundamental, universal QCD parameter
- Standard Model predicts "momentum scale", Q (~√s) evolution, but not the absolute value of α_S
  - Perturbative effects, varying as ~ 1/lnQ
  - Non-perturbative effects, varying as ~ 1/Q
- Test: measure different processes, energies
- Intuitive techniques in e^+e^-

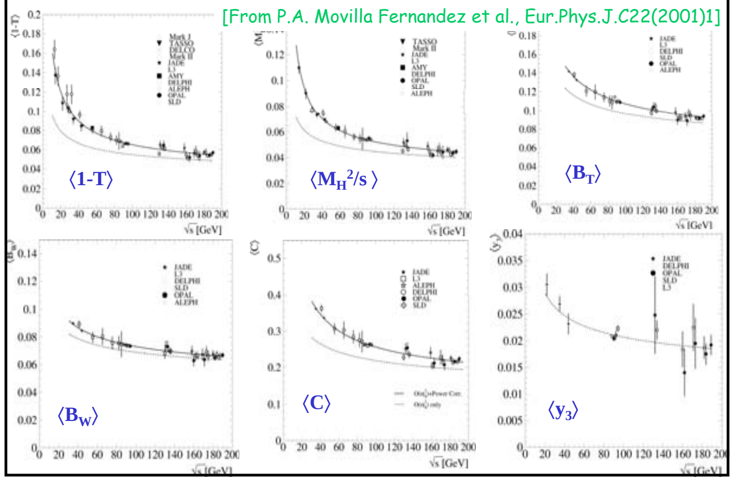




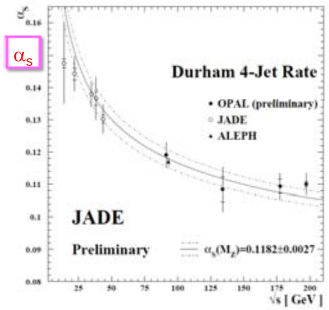
- Precision low, O(%) cf. electroweak $O(10^{-5})$

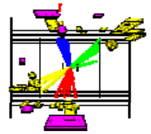
Global α_s measurements, various e^+e^- observables

[From P.A. Movilla Fernandez et al., Eur.Phys.J.C22(2001)1]



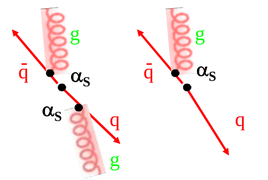
Data: strong coupling constant, α_s





$e^+e^- \rightarrow$ 4 jets (W^-W^+) in OPAL detector at LEP

"parton level" pictures ($e+e \rightarrow Z \rightarrow qqgg$)



- α_s is strong force coupling constant
- Ratio of rate of 3-jet vs. 4-jet events
  - Directly related to α_s
  - Analogous to "R", many factors cancel
- Momentum scale-dependent value
  - Illustrated by measurements at varying energy in e^+e^- collisions

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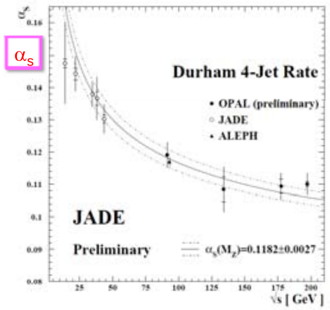
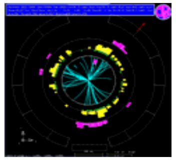
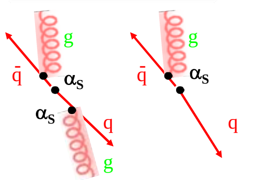




$e^+e^- \rightarrow$ 3 jets in OPAL detector at LEP (1989-2001)

"parton level" pictures



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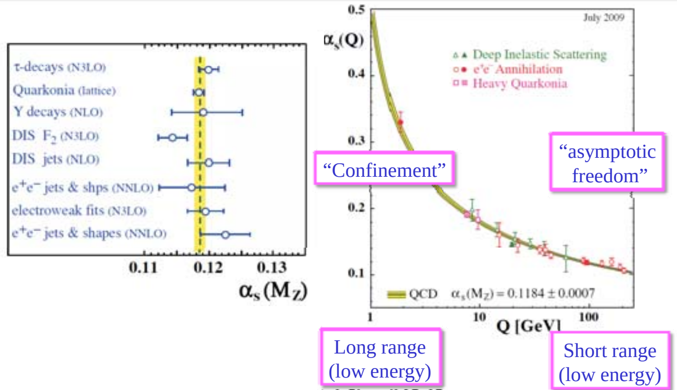
α_s Summary

Consistency of coupling measured in different physics environments



K. Nakamura *et al.* (Particle Data Group), J. Phys. G 37, 075021 (2010)
[http://pdg.lbl.gov/2011/reviews/rpp2011-rev-qcd.pdf]