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. 68-72, 173, 283-301
  - Perkins, pp. 291-293, 303, 307
  - Williams, pp. 179-181
  - PDG review of QCD - earlier parts too detailed, suggest starting at Sec

Previous lecture

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

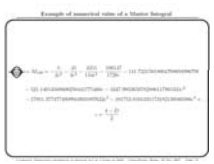
Quantum Field Theories in PP – QED and QCD

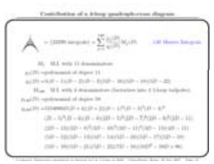
- QED developed ~1948 by Feynman, Tomonaga, Schwinger
- Locally Gauge Invariant Theory
  - Effectively equivalent to having an arbitrary zero of electric potential
  - Conservation of charge leads to "choice of gauge" (in Maxwell Equations)
  - Symmetry of the theory (physics of interactions the same 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).

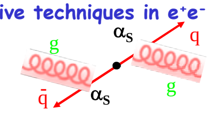
Examples of what is involved in obtaining such precision

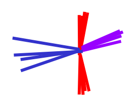




Strong Coupling "constant", α_S

- 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^-

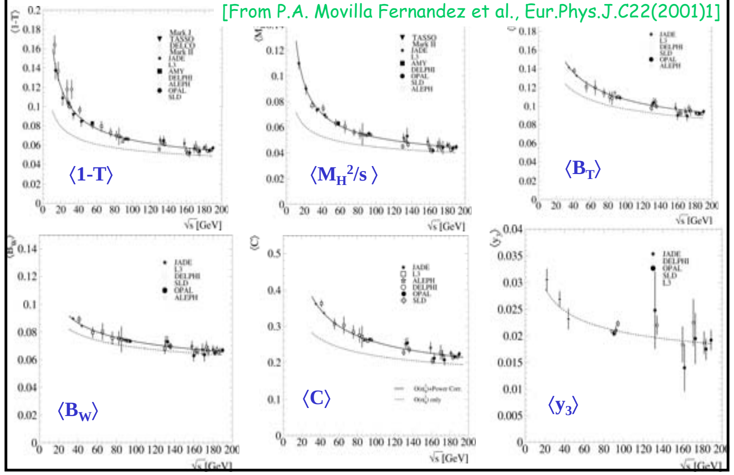




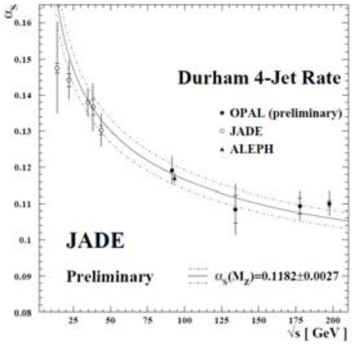
- Precision low, $\mathcal{O}(\%)$ cf. electroweak $\mathcal{O}(10^{-5})$

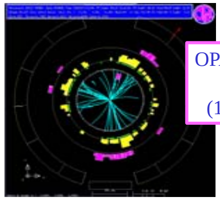
Global α_s measurements, various e^+e^- observables

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

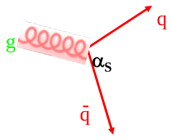


Strong coupling constant





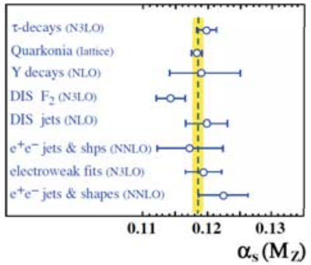
OPAL Detector at LEP (1989-2001)

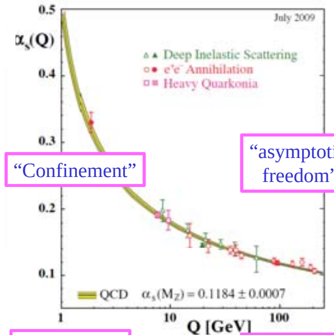


- α_s is strong force coupling constant
- Momentum scale-dependent value
  - Illustrate by measurement at different centre-of-mass energies in e^+e^- collisions

α_s Summary

Consistency of coupling measured in different physics environments





"Confinement"

"asymptotic freedom"

Long range (low energy)

Short range (low energy)

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