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, fragmentation, running couplings
  - Strong and weak decays, conservation rules
  - Virtual particles and range of forces
  - 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 phy

Today

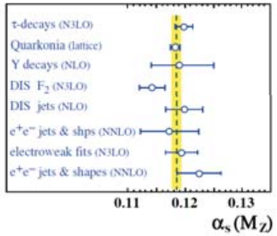
Lecture 12 (4 slides/page) - Particle decays, strong and weak decays, conservation rules
- Griffiths, pp. 66-71,79-82, 84-85.

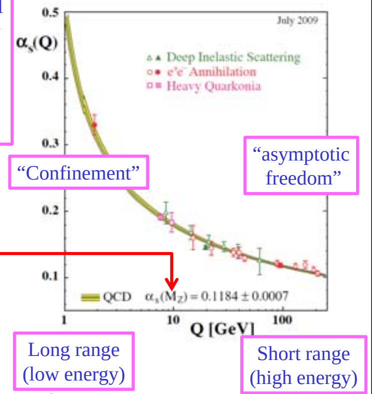
Previous lecture

Lecture 11 (4 slides/page) - Fragmentation, running couplings
- Halzen and Martin,pp. 16-26
- Griffiths, pp. 298-301
- Williams, pp. 221-227
- Perkins (3rd edition), pp. 44-46
- Griffiths, pp. 283-288
- Martin, pp. 160-164.

α_s Summary

Consistent value of α_s measured in many different reactions. Note that values are all transformed ("evolved") to a single energy scale to allow comparison, using "Renormalisation Group Equations". QCD predicts how α_s varies with energy, not its actual value





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

[For info.] Running Couplings

EM case

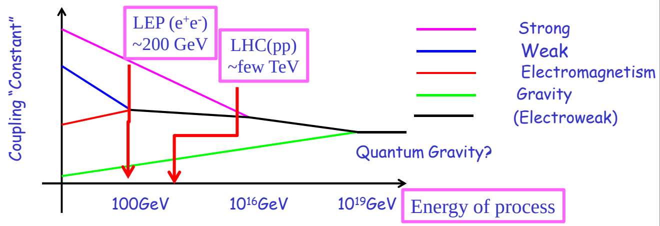
$$\alpha_{EM}\left(\left|q^2\right|\right) = \frac{\alpha(0)}{1-\left(\frac{\alpha(0)}{3\pi}\right)\ln\left(\left|q^2\right|/m^2\right)} \qquad \left|q^2\right| >> m^2$$

QCD case

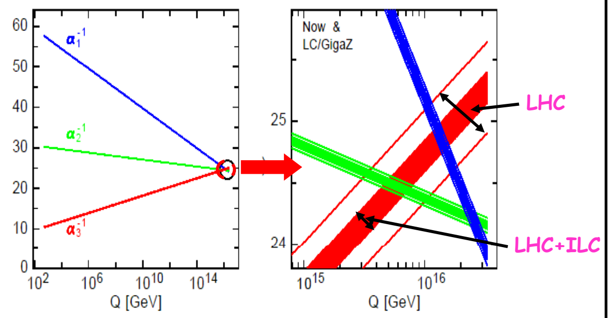
$$\alpha_S\left(\left|q^2\right|\right) = \frac{\alpha_S(\mu^2)}{1+\left(\frac{\alpha_S(\mu^2)}{12\pi}\right)\left[11N_{colours}-2N_{flavours}\right]\ln\left(\left|q^2\right|/m^2\right)} \qquad \left|q^2\right| >> \left|\mu^2\right|$$

Unification of Forces

- Coupling "constants" are said to "run" (change their strength) with energy
- For electromagnetism, the coupling "constant", α_{EM}, increased with energy
- For weak force the coupling constant decreases with energy
  - E.M. and weak merge at ~100 GeV: "electroweak unification"
- For strong force coupling, α_s, decreases with energy



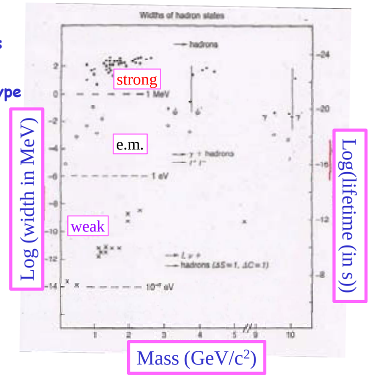
Requires gauge coupling unification
Low energy SUSY
Nucleon decay



[Allanach, Blair, Kraml, Martyn, Polesello, Porod,Zerwas, LHC-LC Report, p339]

Strong, e.m., weak interactions (W.I.)

- So far, have discussed strong interaction in terms of binding quarks into hadrons
- Particle decays also determined by type of interactions allowed
- Strength of interaction reflected in lifetime of decaying particle
- Many hadronic resonances, lifetimes
  - $\tau \sim 10^{-23}$s
  - Deduced from width, $\Gamma \sim 10\text{-}100$ MeV
  - These are Strong Interaction decays
- Some much longer lived hadrons
  - $\tau \sim 10^{-10}$s
  - Can be measured directly
  - These are Weak Interaction decays
- Some with intermediate lifetimes (e.m.)



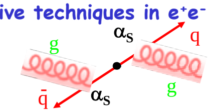
Conservation Rules

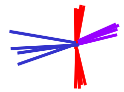
Interaction	Symbol	SI	EM	WI
Energy	E	✓	✓	✓
Momentum	P	✓	✓	✓
Angular Mom^n.	J	✓	✓	✓
Charge (e.m, colour)	Q	✓	✓	✓
Fermion number		✓	✓	✓
Quark number		✓	✓	✓
Baryon number	B	✓	✓	✓
Lepton number	L	✓	✓	✓
Electron number	L_e	✓	✓	✓
Muon number	L_m	✓	✓	✓
Tau number	L_t	✓	✓	✓
Quark flavour		✓	✓	×
Isospin	I	✓	×	×
Parity	P	✓	✓	×
Charge Conjugtion	C	✓	✓	×
Time reversal	T	✓	✓	×
Matter-Antimatter	CP	✓	✓	×
Quantum Field Theory	CPT	✓	✓	✓

✓ conserved
× Not *necessarily* conserved

Strong Coupling "constant", α_S

- α_S the fundamental, universal QCD parameter
- Standard Model predicts "momentum scale", Q ($\sim\sqrt{s}$) 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 $\mathcal{O}(10^{-5})$

Data: E.M. coupling constant, α_{EM}

XXVI Physics in Collision, Búzios, Rio de Janeiro, 6-9 July 2006

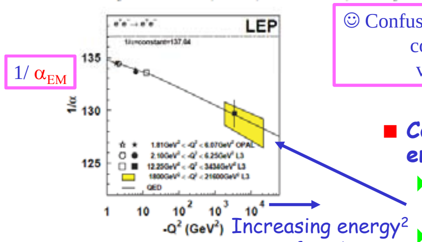
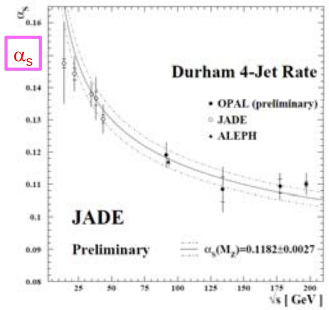


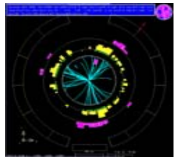
Figure 6: Summary of LEP results on the measurement of the running of the electromagnetic coupling. The band represents the L3 measurement at high Q^2. The full symbols represent the OPAL and the L3 measurements at low and intermediate Q^2. The open symbols are the reference values to which the measurement are anchored, as discussed in the last section of the text. The solid line shows the QED predictions of Reference [5].

☺ Confusion warning! Often presented as: coupling [or 1/(coupling)] vs. distance [or energy^2]

- Coupling decreases as energy increases
  - From ~1/137 (usual energies)
  - To 1/127 (~90 GeV centre-of-mass)
- Example of recent compilation of data
- Many others similar in literature

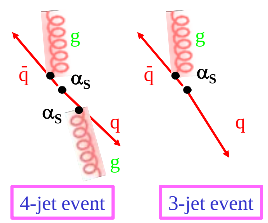
Data: strong coupling constant, α_S





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

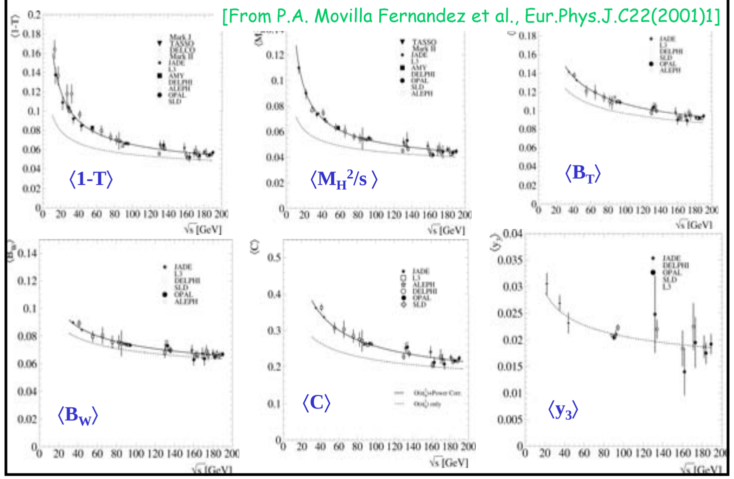
"parton level" pictures



- 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
  - Centre-of-mass energy in e^+e^- collisions

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

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



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