# 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 physics

Today

- Lecture 11 (4 slides/page) - Fragmentation, running couplings, particle decays
  - Halzen and Martin,pp. 16-26
  - Griffiths, pp. 298-301
  - Williams, pp. 221-227
  - Perkins, pp. 44-46

Previous lecture

- 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

# Data: E.M. coupling constant, $\alpha_{EM}$

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

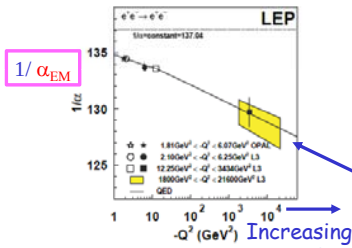



Figure 6: Summary of LEP results on the measurement of the running of the electromagnetic coupling. The band represents the L3 measurement at high $Q^2$. The full symbols represent the OPAL and the L3 measurements at low and intermediate $Q^2$. The open symbols are the reference values to which the measurement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

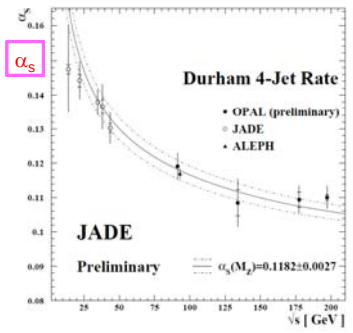
$1/\alpha_{EM}$

Increasing energy² of probe

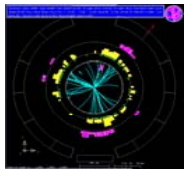
☺ Confusion warning! Often presented as: coupling [or 1/(coupling)] vs. distance [or energy² ]

- 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, $\alpha_s$

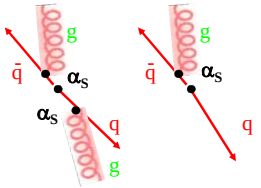



$\alpha_s$



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

"parton level" pictures



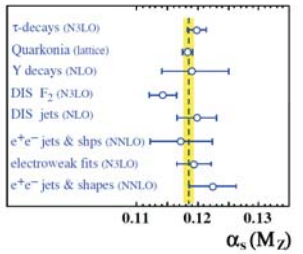

4-jet event

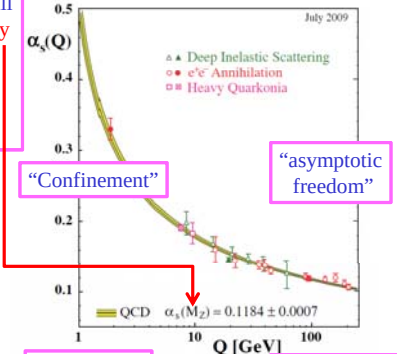
3-jet event

- $\alpha_s$ is strong force coupling constant
- Ratio of rate of 3-jet vs. 4-jet events
  - Directly related to $\alpha_s$
  - Analogous to "R", many factors cancel
- Momentum scale-dependent value
  - Centre-of-mass energy in $e^+e^-$ collisions

# $\alpha_s$ Summary

Consistent value of $\alpha_s$ 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 $\alpha_s$ varies with energy, not its actual value




"Confinement"

"asymptotic freedom"

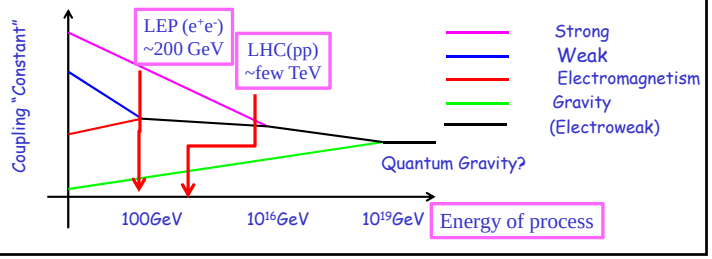
Long range (low energy)

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]

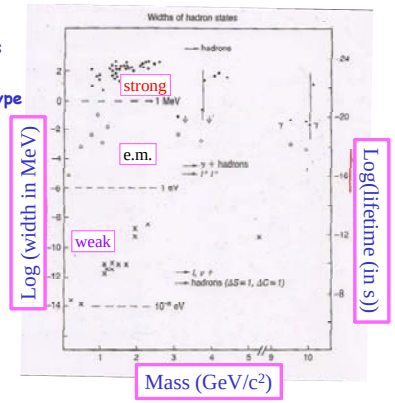
# Running Coupling Constants

- Coupling "constants" are said to "run" (change their strength) with energy
- For electromagnetism, the coupling "constant", $\alpha_{EM}$, 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, $\alpha_s$, decreases with energy




# 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 | ✓ | ✓ | ✓ |