

Outline

■ Relativistic Kinematics

- ▶ (4-momentum)² invariance, invariant mass
- ▶ Hypothesis testing, production thresholds
- ▶ Cross-sections, flux and luminosity, accelerators
- ▶ Particle lifetime, decay length, width

Today

■ Classification of particles

- ▶ Fermions and bosons
- ▶ Leptons, hadrons, quarks
- ▶ Mesons, baryons

- [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

■ 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

Previous
lecture

■ Electroweak Interactions

- ▶ Charged and neutral current
- ▶ W, Z, LEP experiments
- ▶ Higgs and the future

- [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

■ LHC Experiments

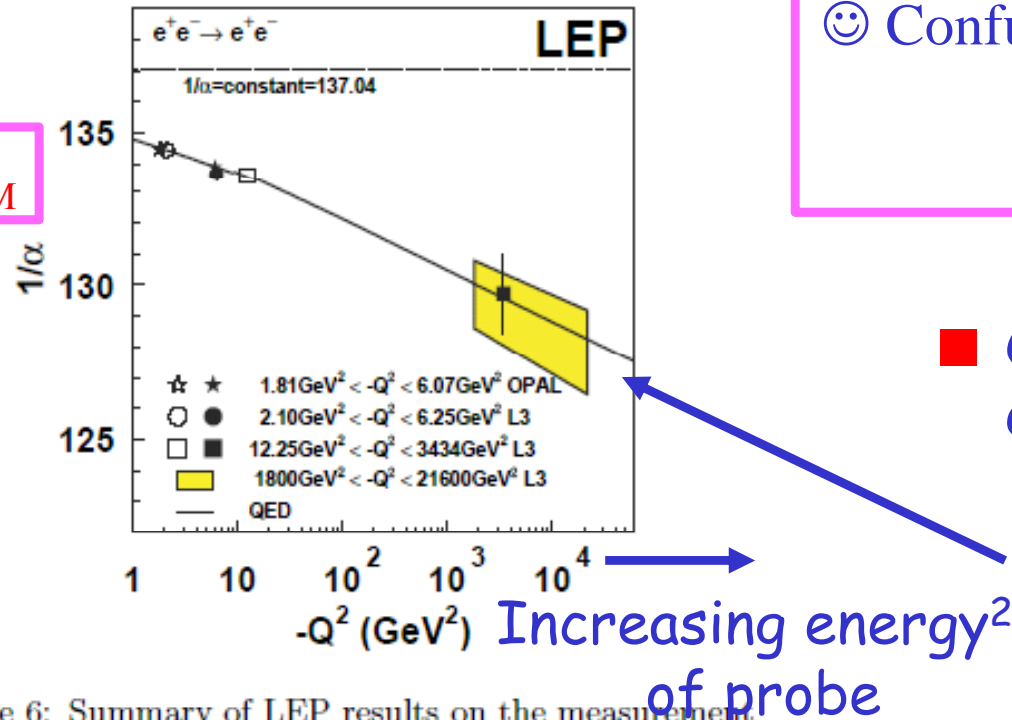
■ Future - introduction to accelerator physics

Data: E.M. coupling constant, α_{EM}

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

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

$1/\alpha_{EM}$



■ Coupling decreases as energy increases

▶ From ~1/137 (usual energies)

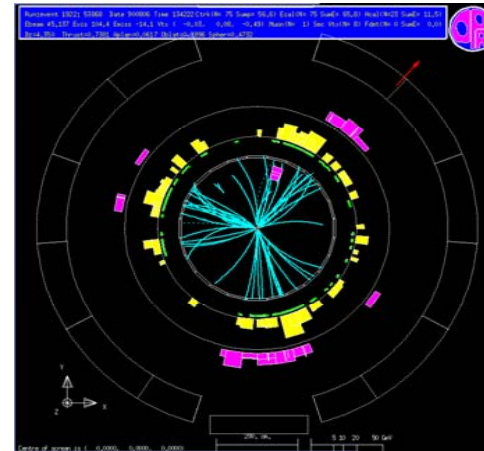
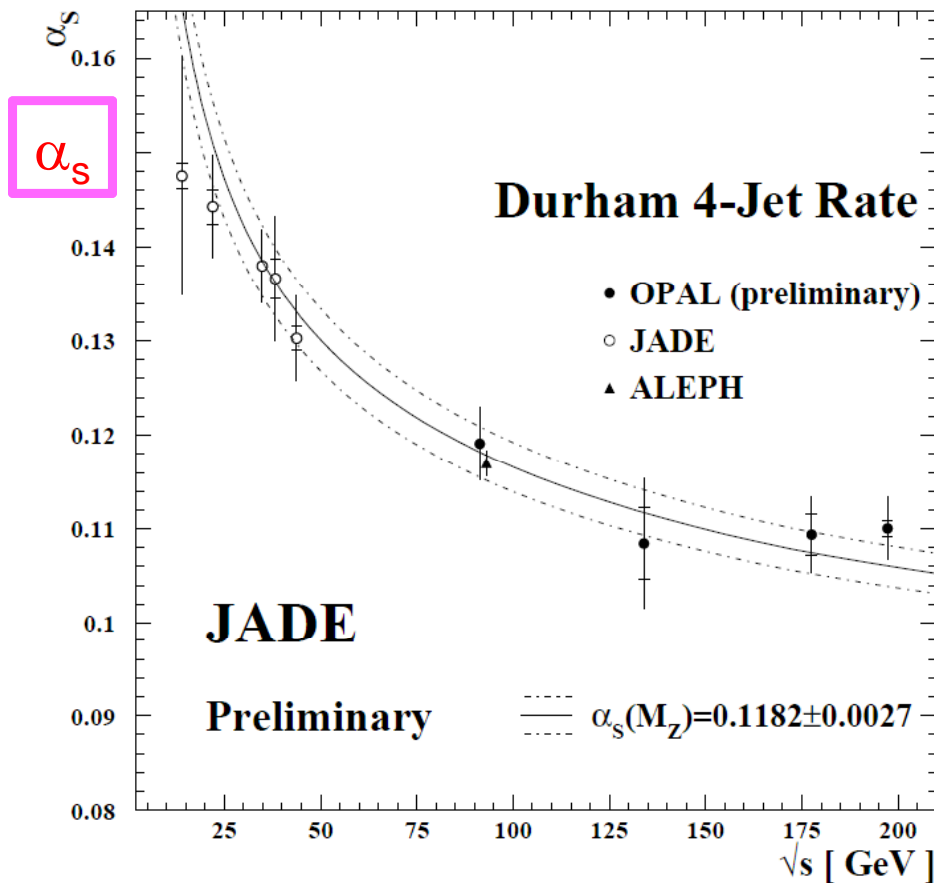
▶ To 1/127 (~90 GeV centre-of-mass)

■ Example of recent compilation of data

■ Many others similar in literature

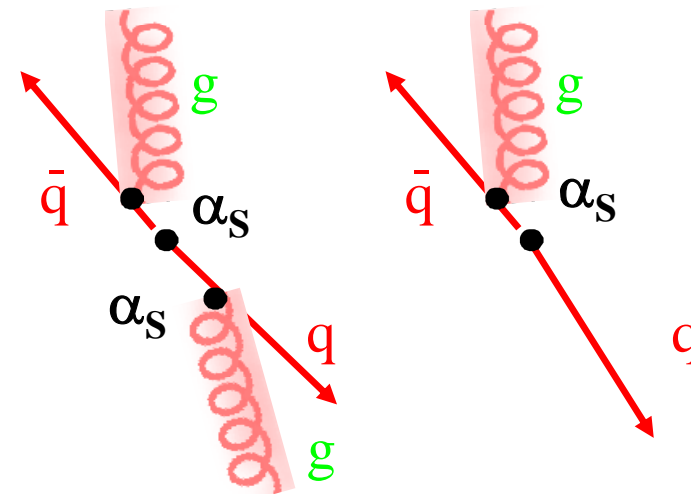
Figure 6: Summary of LEP results on the measurement of the running of the electromagnetic coupling. The band represents the L3 measurement at high Q^2 . The full symbols represent the OPAL and the L3 measurements at low and intermediate Q^2 . The open symbols are the reference values to which the measurement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

Data: strong coupling constant, α_s



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

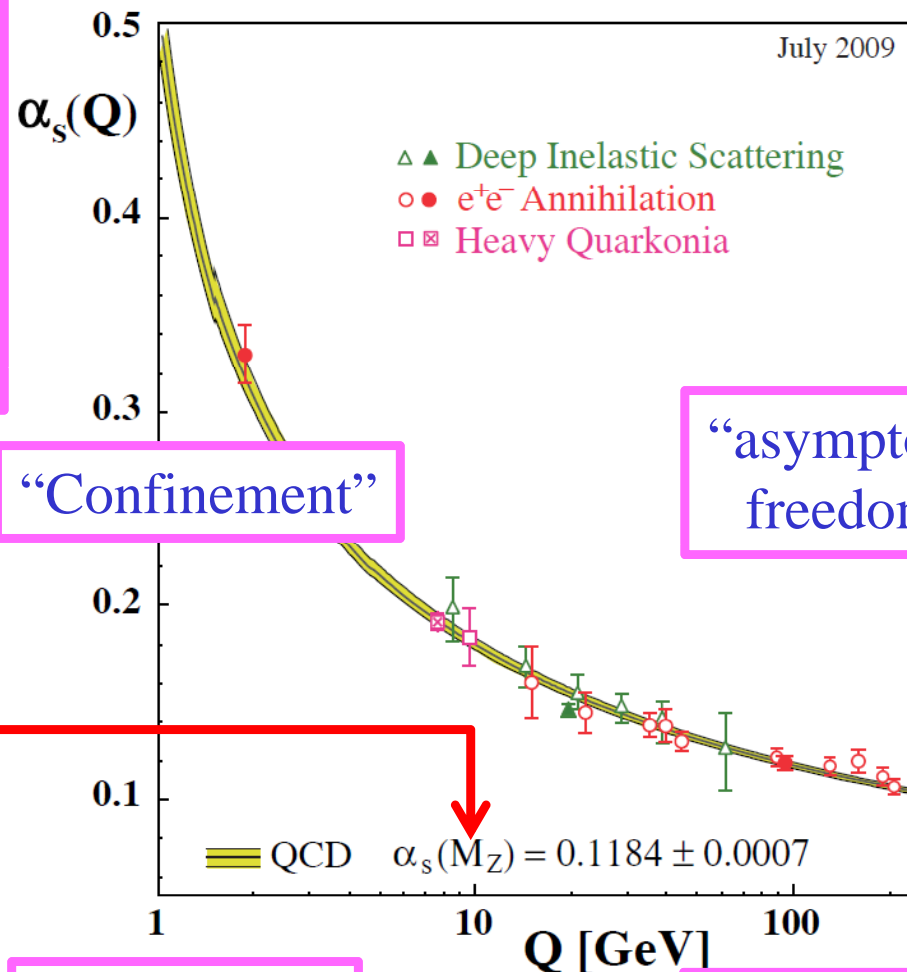
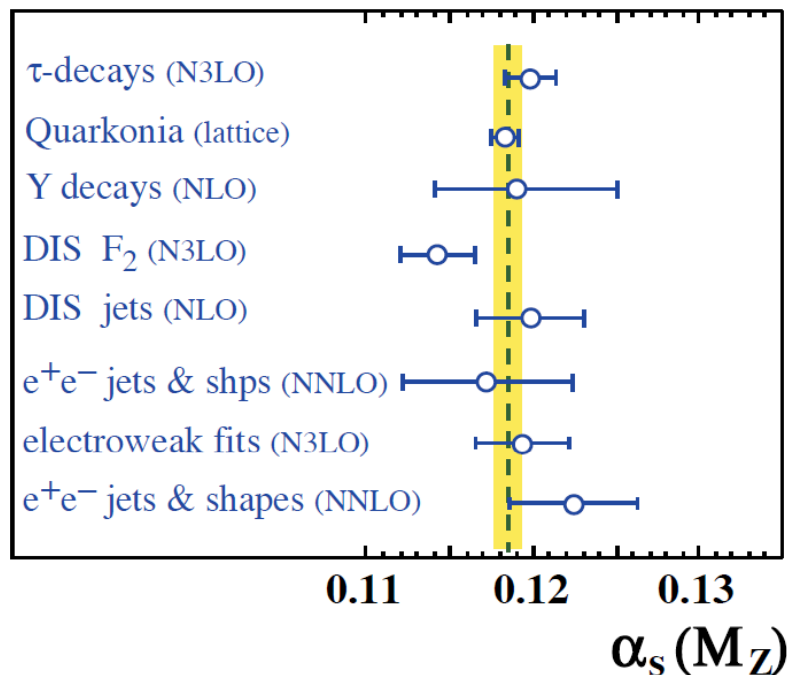
“parton level” pictures



- 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

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



“Confinement”

“asymptotic freedom”

Long range
(low energy)

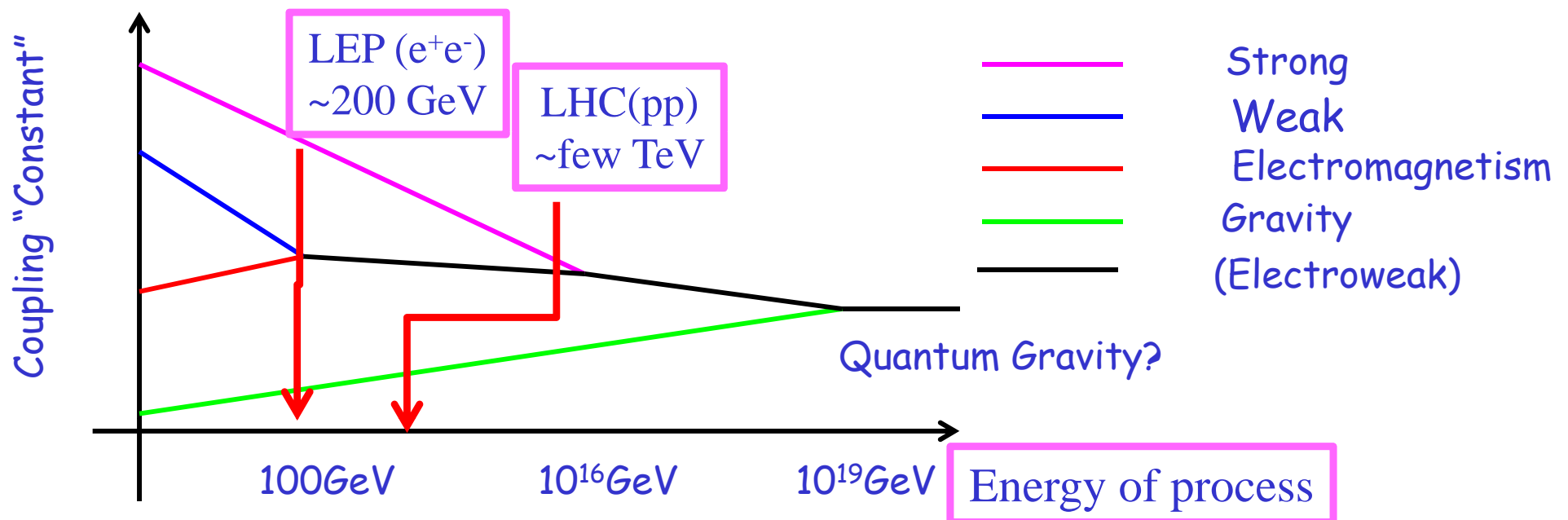
Short range
(low energy)

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

[<http://pdg.lbl.gov/2011/reviews/rpp2011-rev-qcd.pdf>]

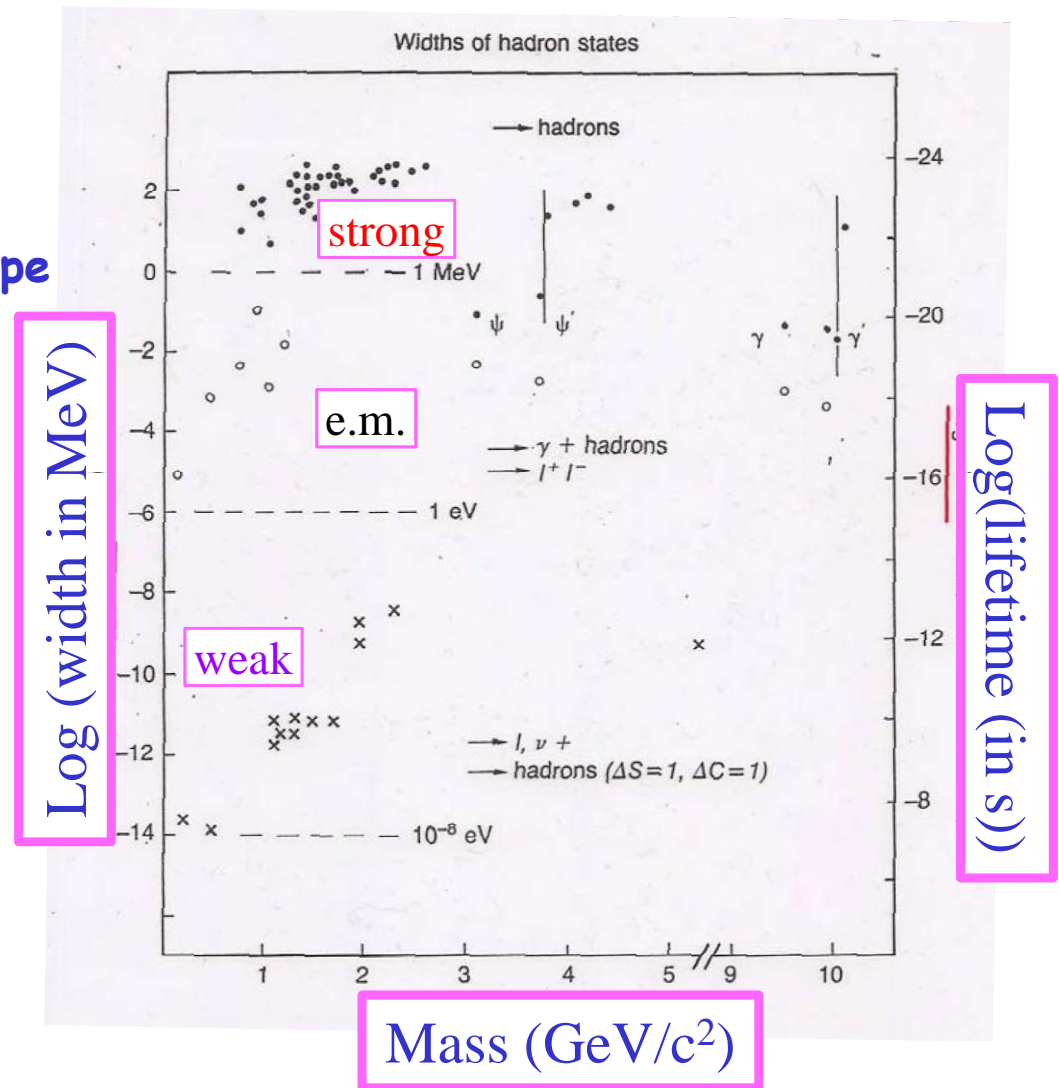
Running Coupling Constants

- Coupling “constants” are said to “run” (change their strength) with energy
- For **electromagnetism**, the coupling “constant”, 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



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
 - ▶ $\tau \sim 10^{-23}\text{s}$
 - ▶ Deduced from width, $\Gamma \sim 10\text{-}100\text{ MeV}$
 - ▶ These are **Strong Interaction decays**
- Some much longer lived hadrons
 - ▶ $\tau \sim 10^{-10}\text{s}$
 - ▶ Can be measured directly
 - ▶ These are **Weak Interaction decays**
- Some with intermediate lifetimes (e.m.)



Conservation Rules

Interaction	Symbol	SI	EM	W I
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 Conjugation	C	✓	✓	✗
Time reversal	T	✓	✓	✗
Matter-Antimatter	CP	✓	✓	✗
Quantum Field Theory	CPT	✓	✓	✓