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

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)

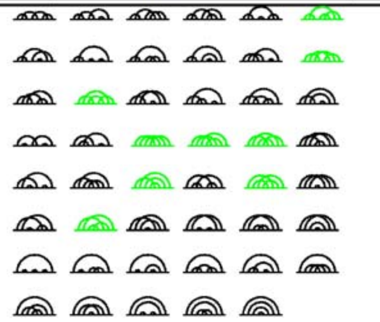
- Concepts advanced, will not do any more than skim surface (apologies!)
  - Interested in details, will put further references on web

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

the 47 4-loop electron self-masses without electron loops



green = reduced to master integrals (work in progress. . .)

S.Laporta, Numerical calculation of electron g-2 at 4 loops in QED, CentroFermi, Rome, 30 Nov 2007 Page 10

Example of numerical value of a Master Integral

$$= M_{139} = -\frac{5}{2\epsilon^4} - \frac{45}{4\epsilon^3} - \frac{4255}{144\epsilon^2} - \frac{106147}{1728\epsilon} - 141.72215618664768694996791$$
$$- 521.14654568600250441775466\epsilon - 3347.99336507828861178653341\epsilon^2$$
$$- 17951.37747748099449310976222\epsilon^3 - 101753.81653311731821395603\,86\epsilon^4 + \ldots$$
$$\epsilon = \frac{4-D}{2}$$

S.Laporta, Numerical calculation of electron g-2 at 4 loops in QED, CentroFermi, Rome, 30 Nov 2007 Page 15

Contribution of a 4-loop quadruple-cross diagram

$$= \{23299 \text{ integrals}\} = \sum_{j=1}^{140} \frac{p_j(D)}{q_j(D)} M_j(D)$$ 140 Master Integrals

M_1 M.I. with 11 denominators

$p_1(D)$ =polynomial of degree 11

$q_1(D) = 5(D-1)(D-2)(D-3)(5D-16)(5D-18)(5D-22)$

M_{140} M.I. with 4 denominators (factorizes into 4 1-loop tadpoles)

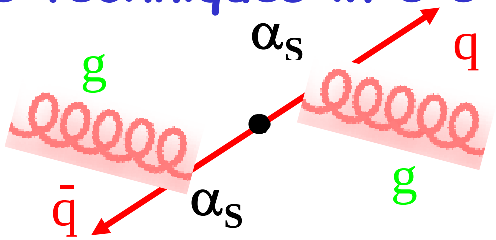
$p_{140}(D)$ =polynomial of degree 58

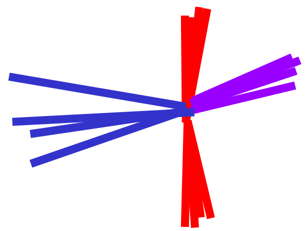
$$q_{140}(D) = 5184000D(D+4)(D+2)(D-1)^2(D-3)^5(D-4)^4$$
$$(D-5)^3(D-6)(D-8)(2D-5)^2(2D-7)^4(2D-9)^2(2D-11)$$
$$(2D-13)(3D-8)^2(3D-10)^3(3D-11)^2(3D-13)(4D-11)$$
$$(5D-12)(5D-13)(5D-14)(5D-16)(5D-17)(5D-18)$$
$$(5D-19)(5D-21)(5D-22)(7D-16)(10D^2-59D+86)$$

S.Laporta, Numerical calculation of electron g-2 at 4 loops in QED, CentroFermi, Rome, 30 Nov 2007 Page 14

Strong Coupling "constant", α_s

- α_s the fundamental, universal QCD parameter
- Standard Model predicts "momentum scale", Q (~$\sqrt{s}$) 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^-

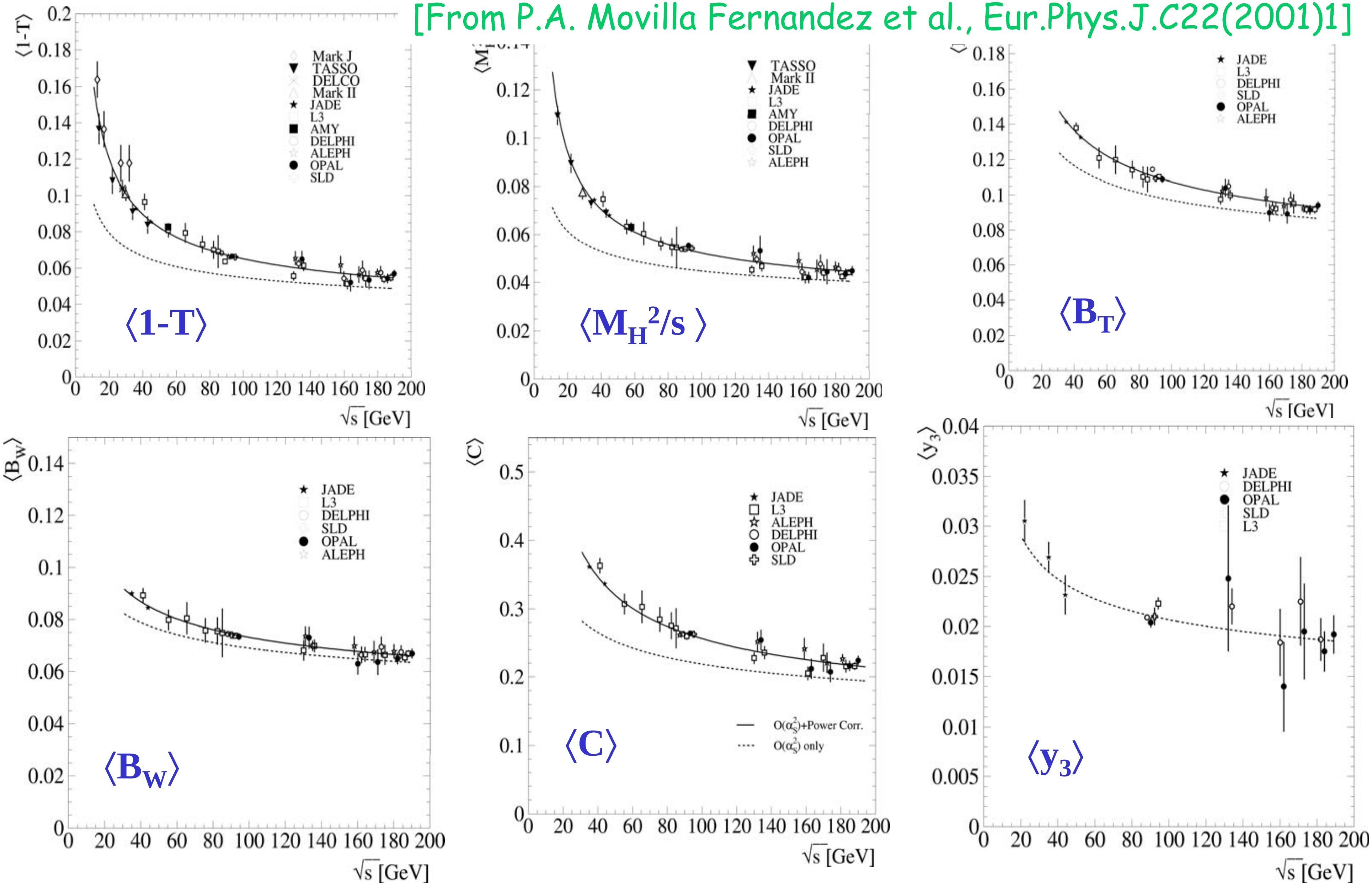




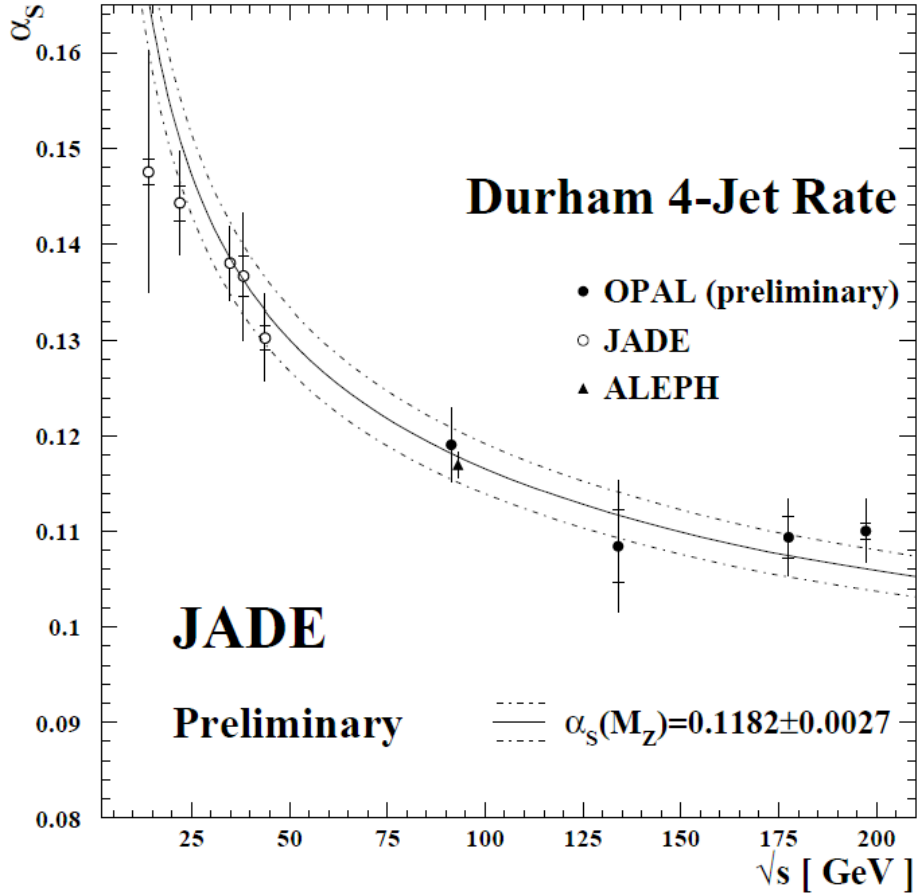
- Precision low, $\mathcal{O}$(%) cf. electroweak $\mathcal{O}(10^{-5})$

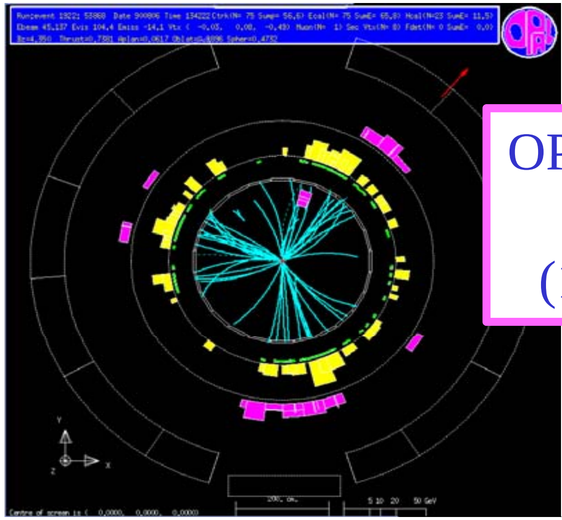
Global α_s measurements, various e^+e^- observables

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

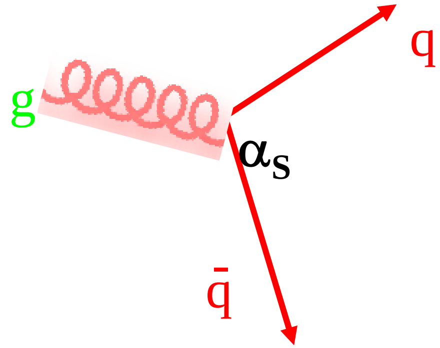


Strong coupling constant





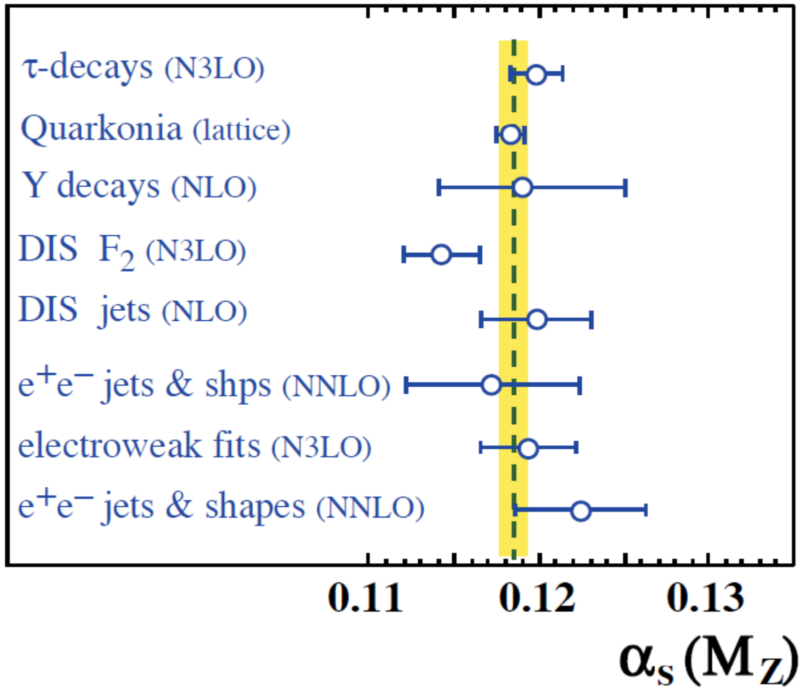
OPAL Detector
at LEP
(1989-2001)

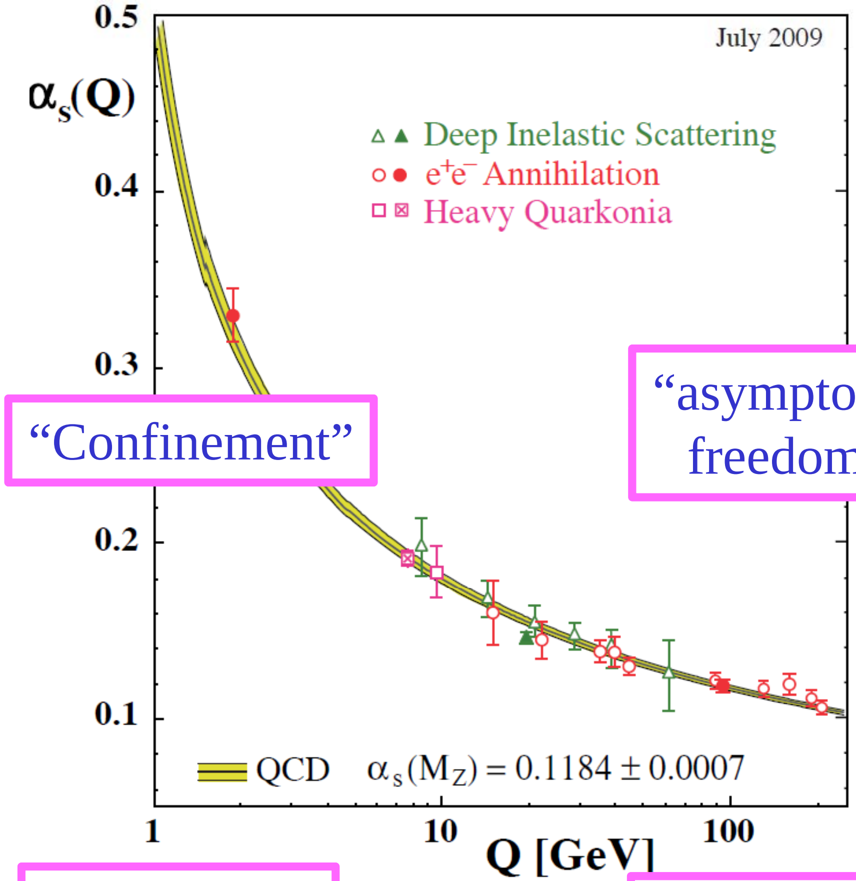


- α_S is strong force coupling constant
- Momentum scale-dependent value
  - Illustrate by measurement at different centre-of-mass energies in e^+e^- collisions

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]