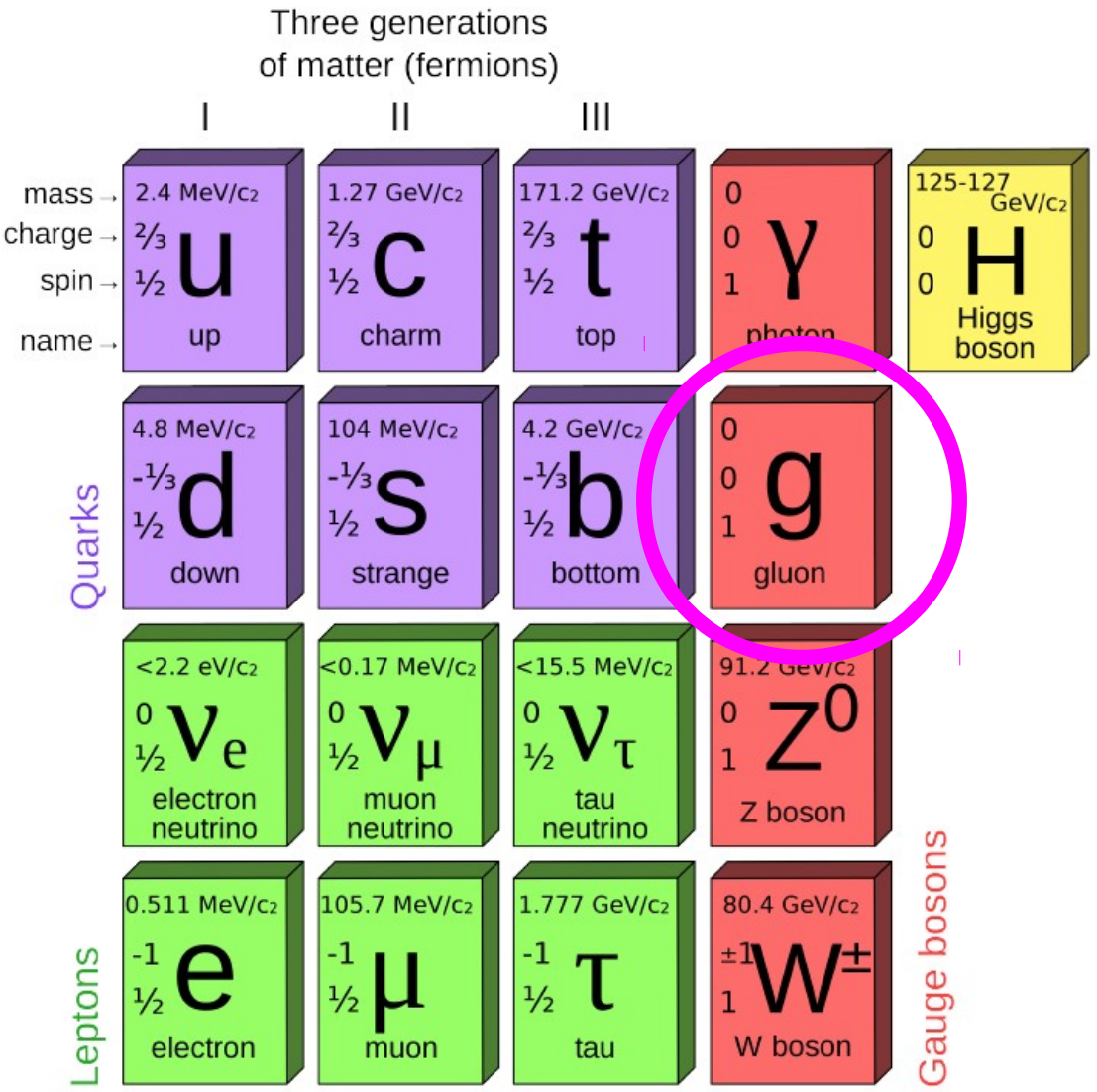
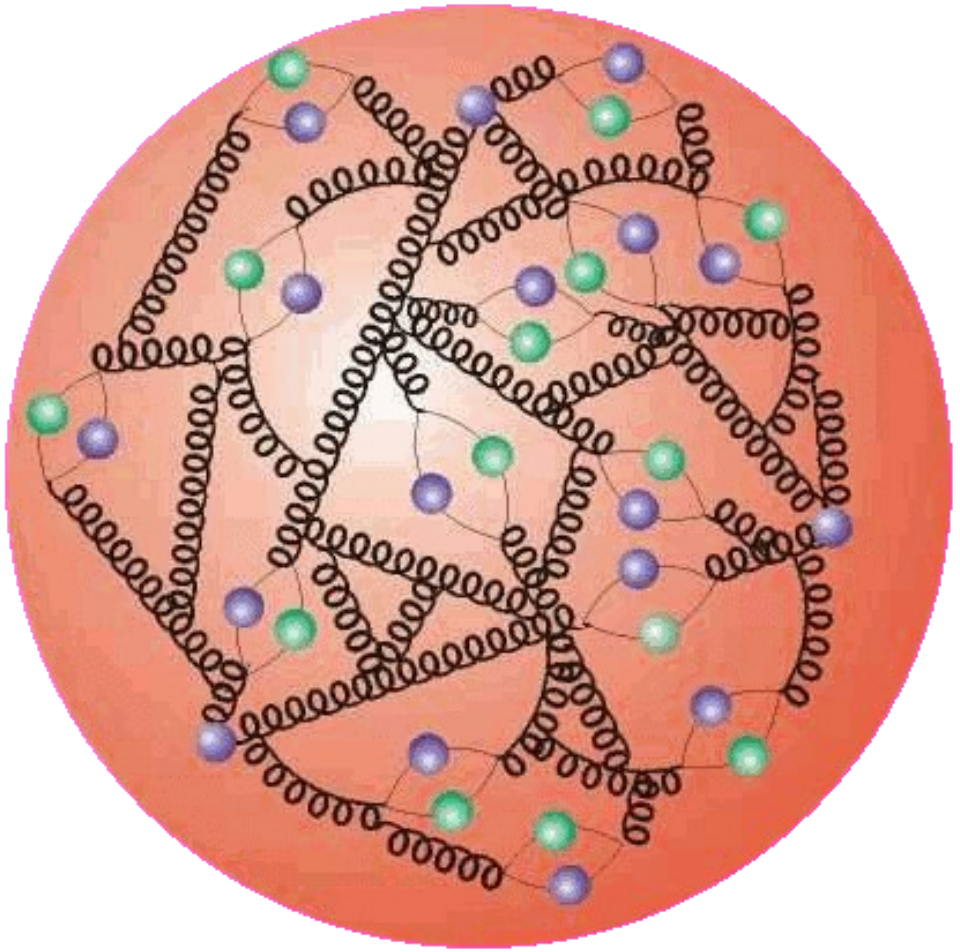
# Strong force dynamics



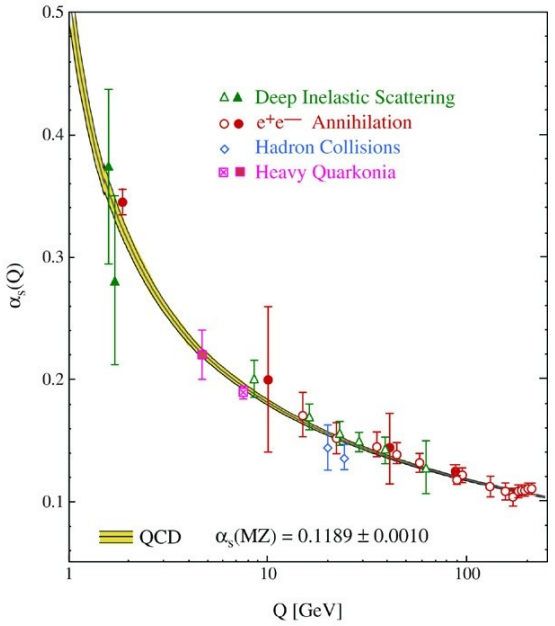
# Many difficult aspects about the strong force

- The strong interaction is very complex!

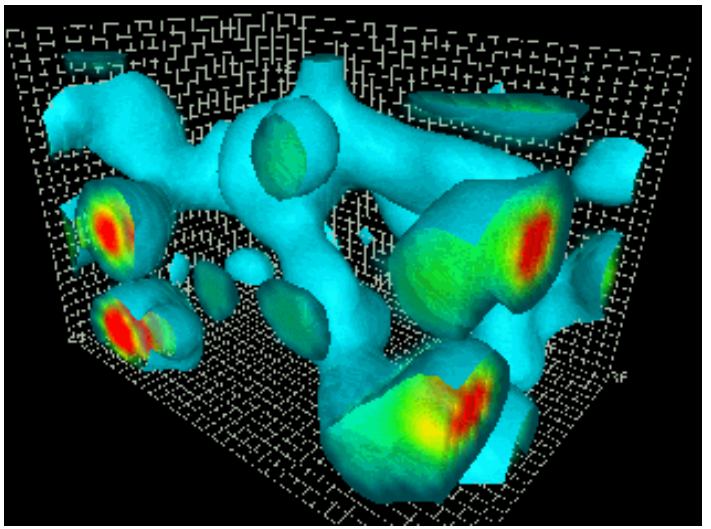


**CONFINEMENT**

**Quarks and gluons couples strong:**




**Complex vacuum:**



# Feynman diagram

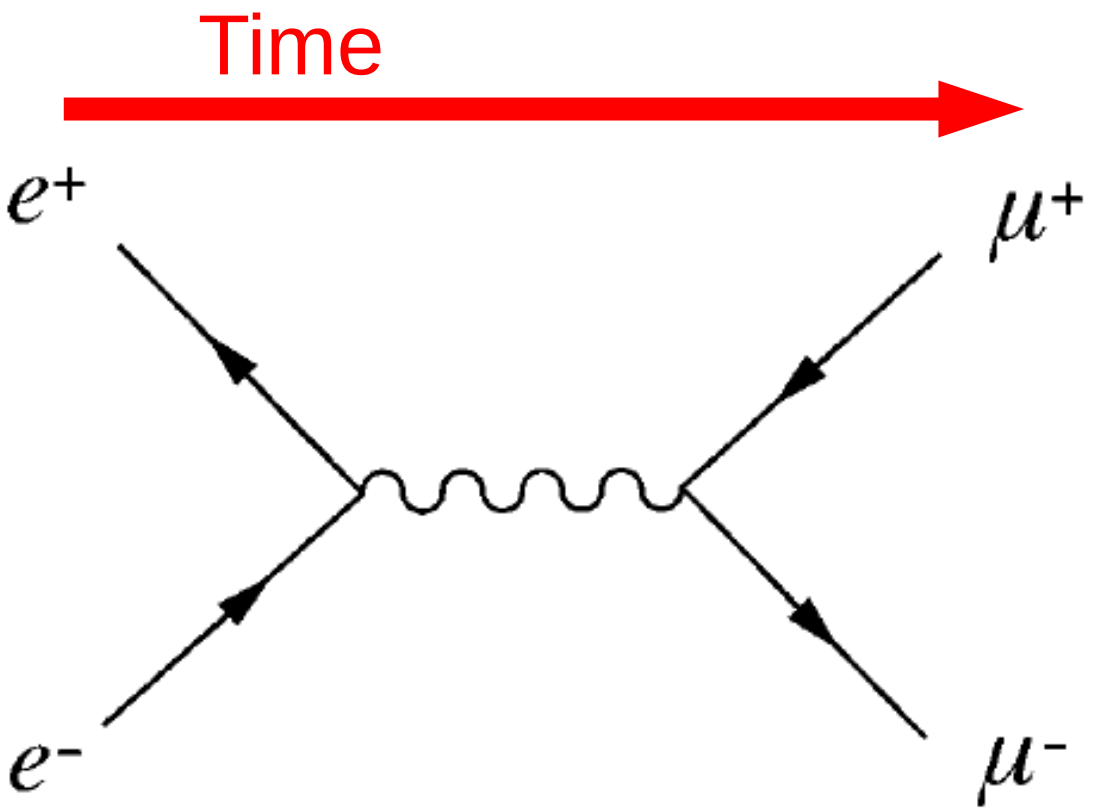



Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

# Feynman diagram
# A calculational tool!

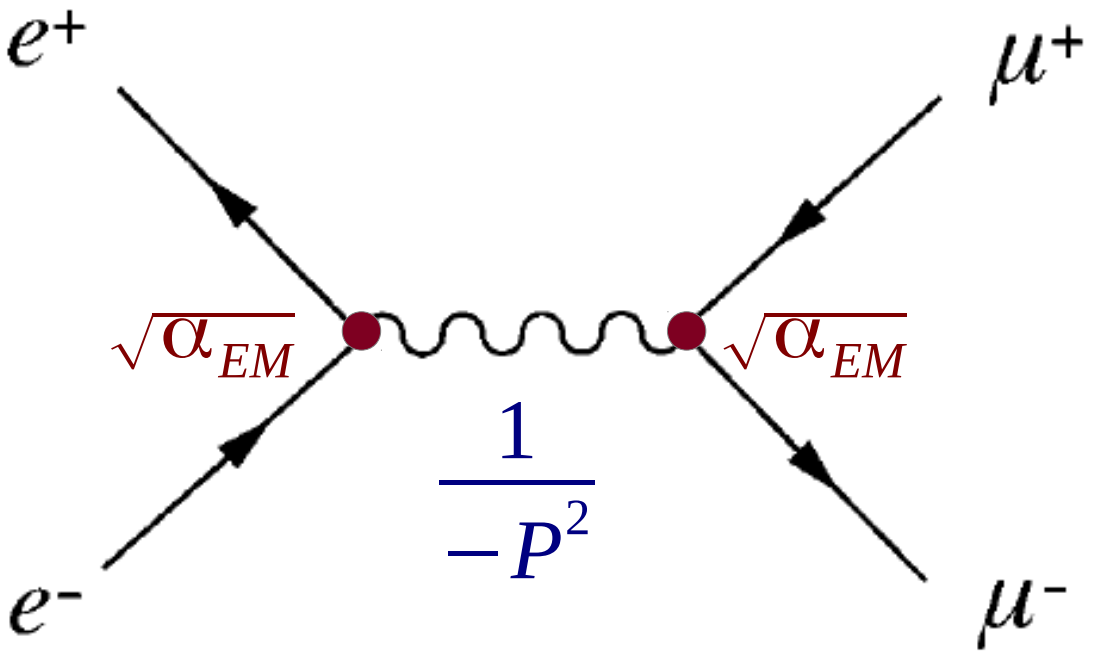



Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

Amplitude $A \propto \frac{\alpha_{EM}}{-P^2}$ Probability $P \propto \frac{\alpha_{EM}^2}{P^4}$

# Feynman diagram of quark-quark scattering

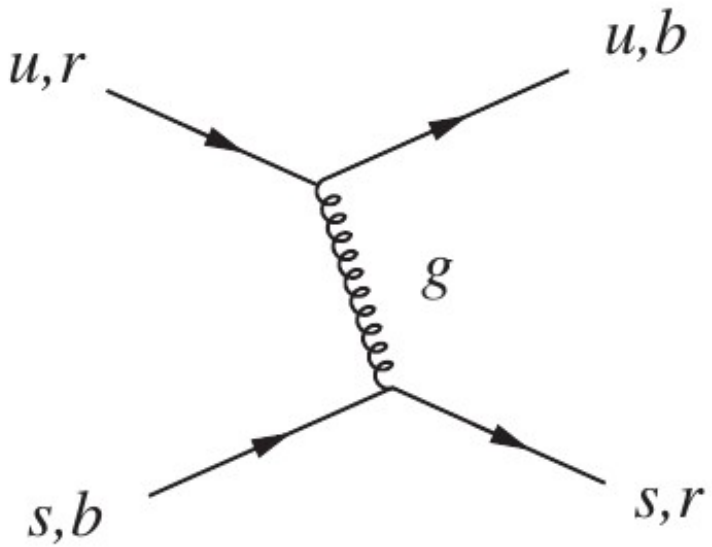



Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour *u* or *s* is unchanged on gluon emission, but the colour state can change, as shown.

# Color flow

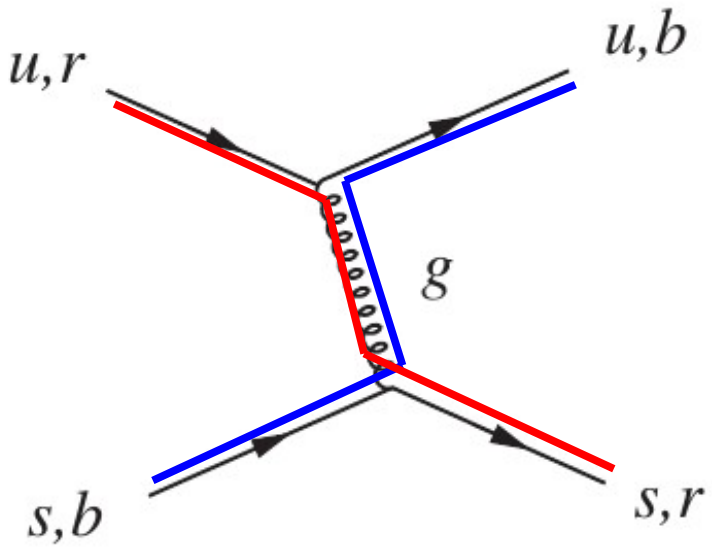



Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour *u* or *s* is unchanged on gluon emission, but the colour state can change, as shown.

# Special QCD processes because gluons are colored!

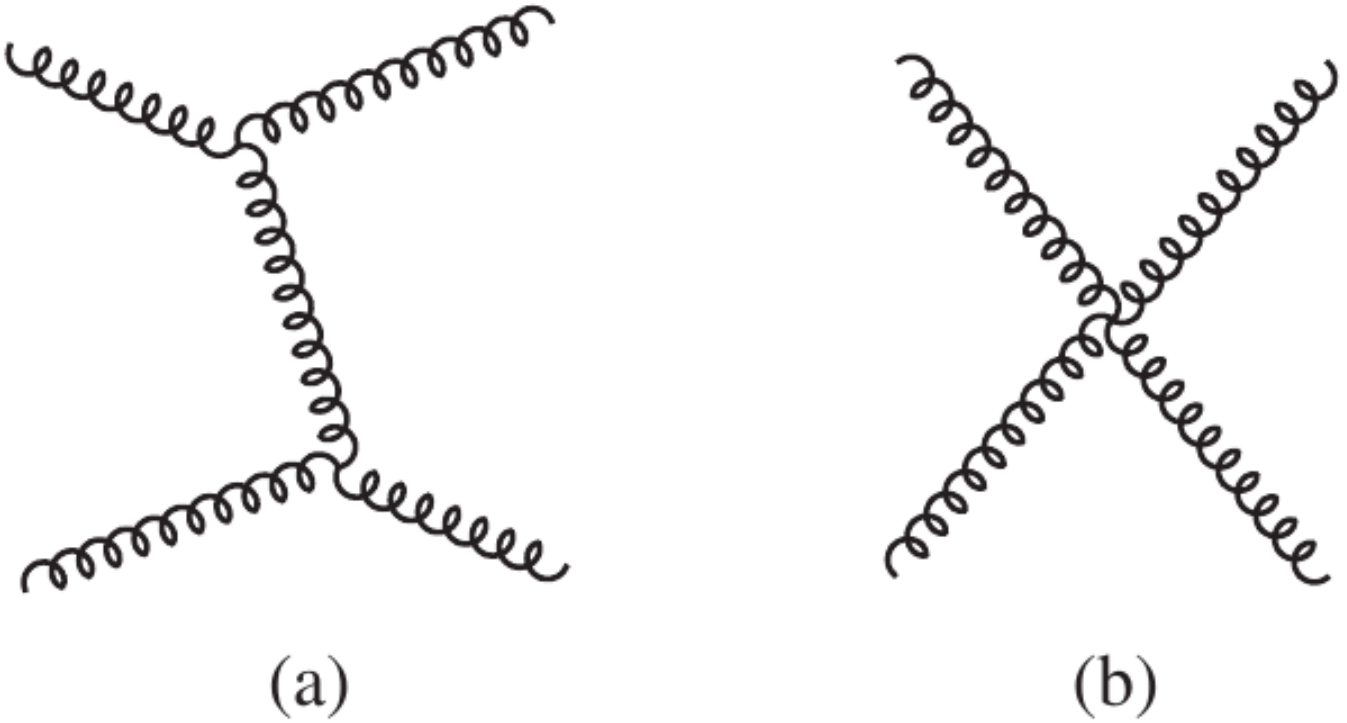



Figure 7.2 The two lowest-order contributions to gluon–gluon scattering in QCD.

# The strong coupling

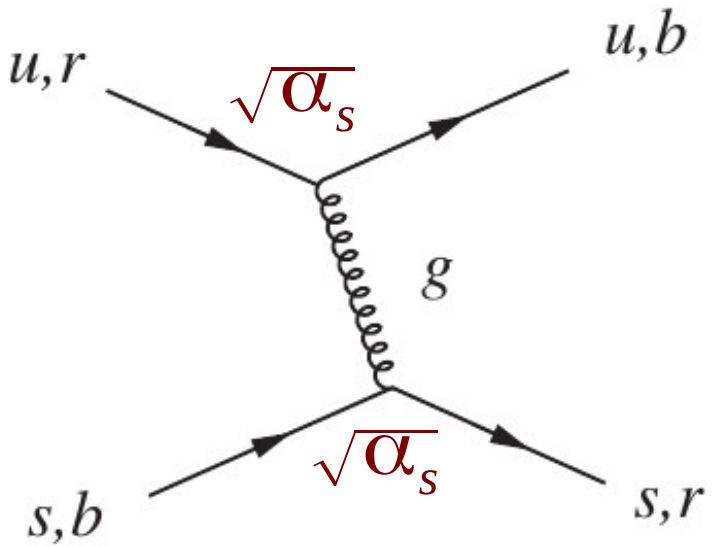
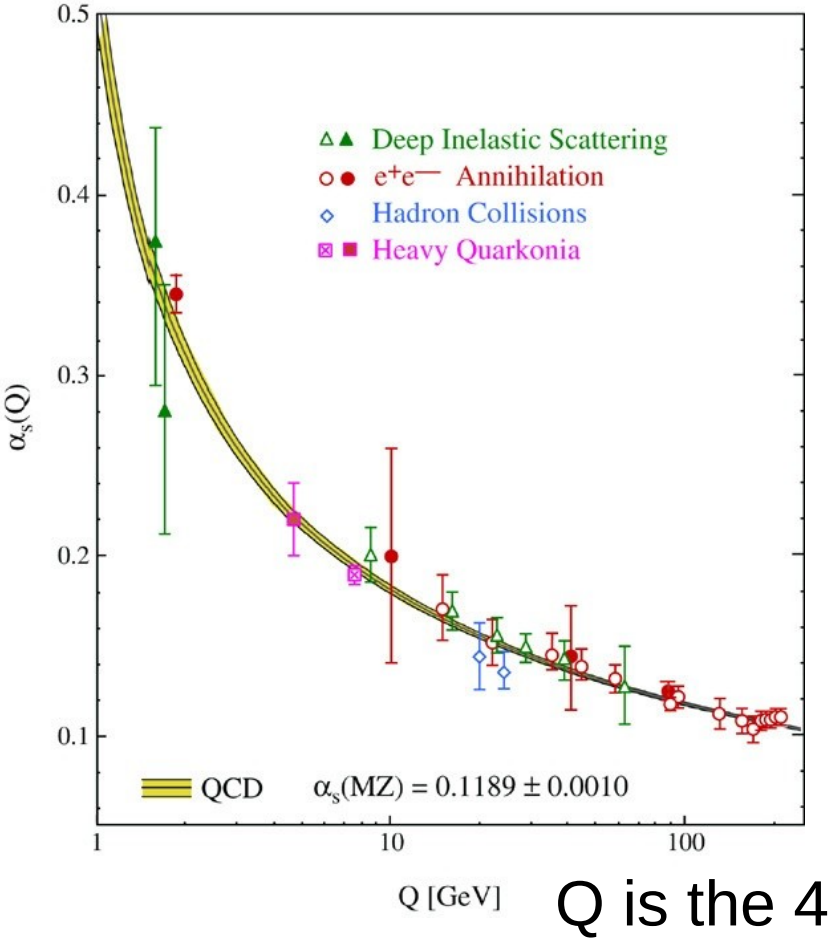



Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour *u* or *s* is unchanged on gluon emission, but the colour state can change, as shown.

# The coupling is not fixed but runs!

$\alpha_s$




Q is the 4 momentum transfer

In fact it becomes ~1 at the scale $\Lambda_{QCD}$~200 MeV

# Screening/running of the coupling in electromagnetic collisions

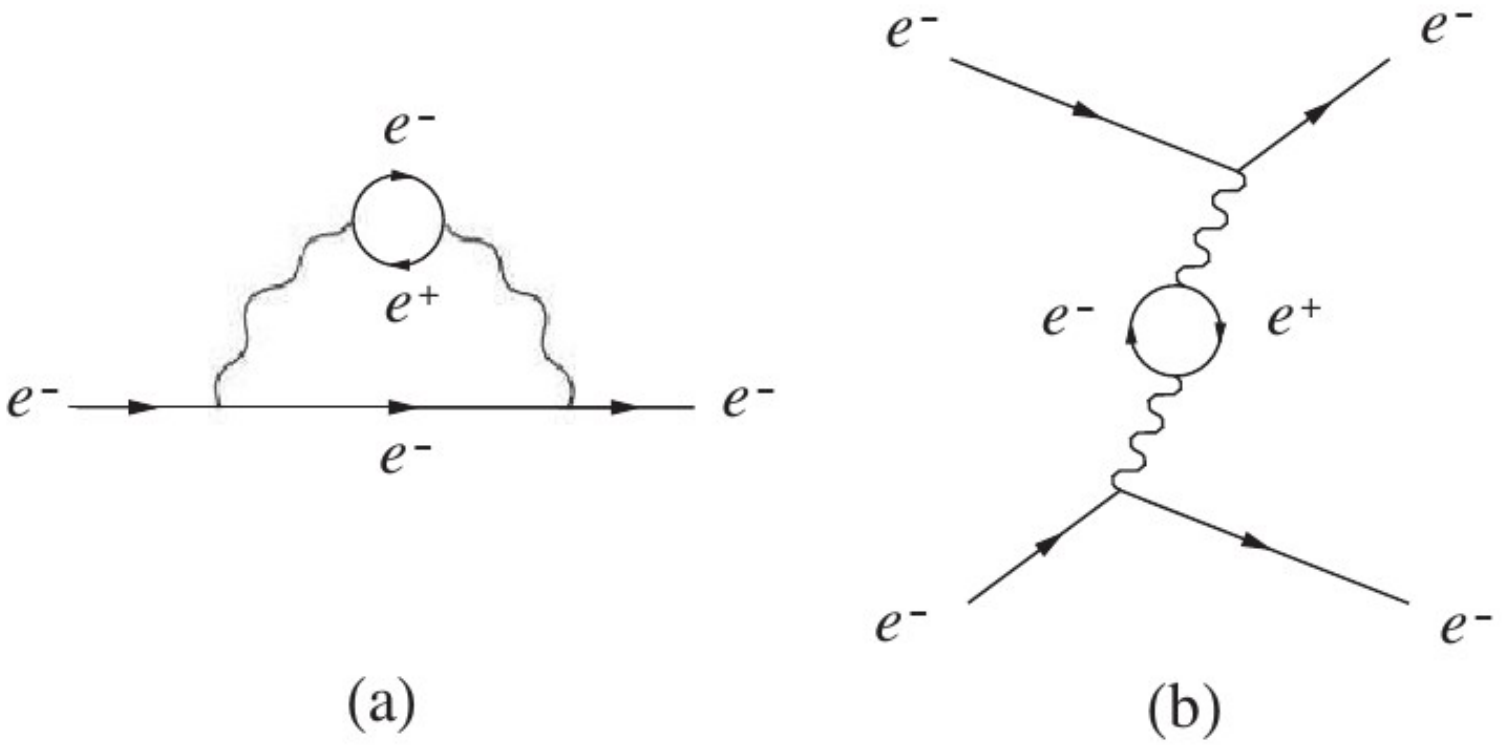
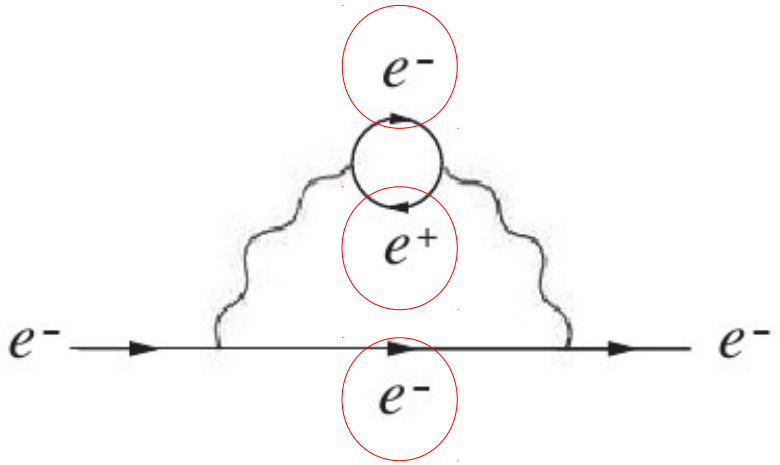



Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

# Due to (polarized) fluctuations the vacuum screens the charge! (vacuum ~ dielectric medium)

Notice the order: -, +, -!



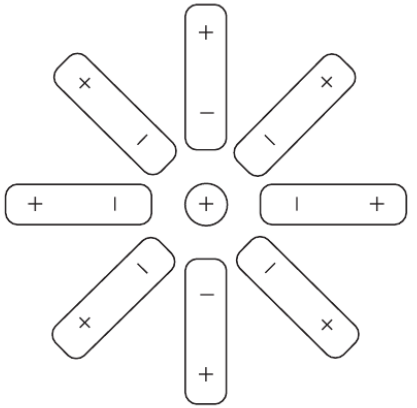



Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

The effect is measurable:
At low energy; α ~ 1/137
At high energy transfers (mZ): α ~ 1/127
<u>This change is fully described by the theory!</u>

# In QCD there is anti-screening! (bare/"naked" charge is smaller!)

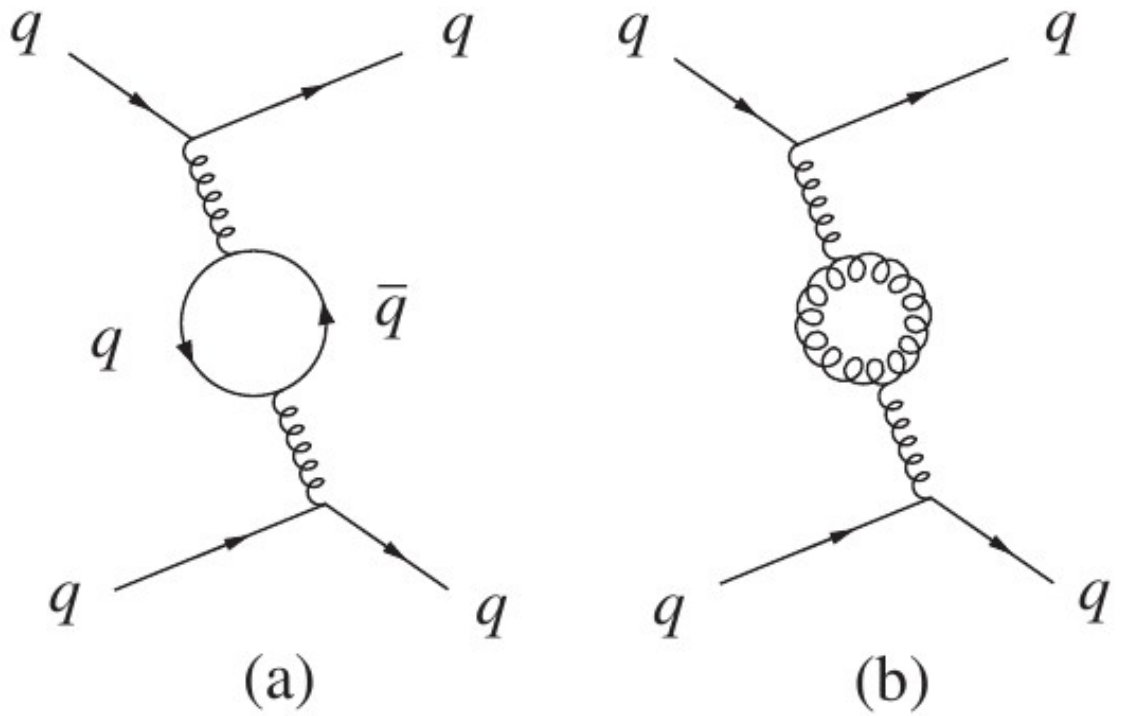



Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

# From Leif's notes

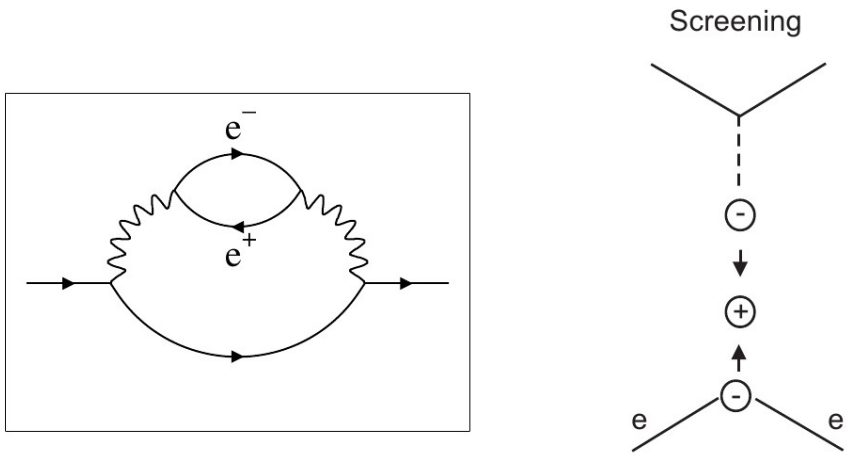



Figure 3.59: *Illustration of screening of the electric charge of the electron via the creation of a virtual $e^+e^-$ pair.*

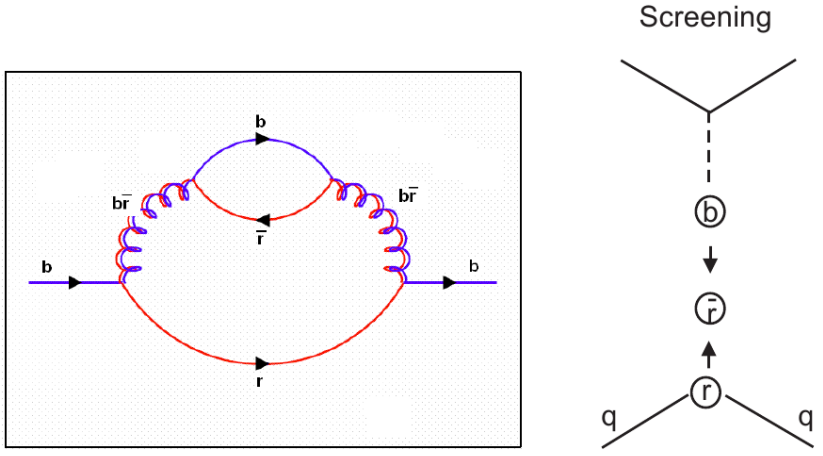



Figure 3.60: *Illustration of screening of the colour charge of a quark via the creation of a virtual $q\bar{q}$ pair.*

NB! In the first calculation (that later gave the nobel prize) they found the wrong sign and gluons was also screening.

So this is not easy to understand.

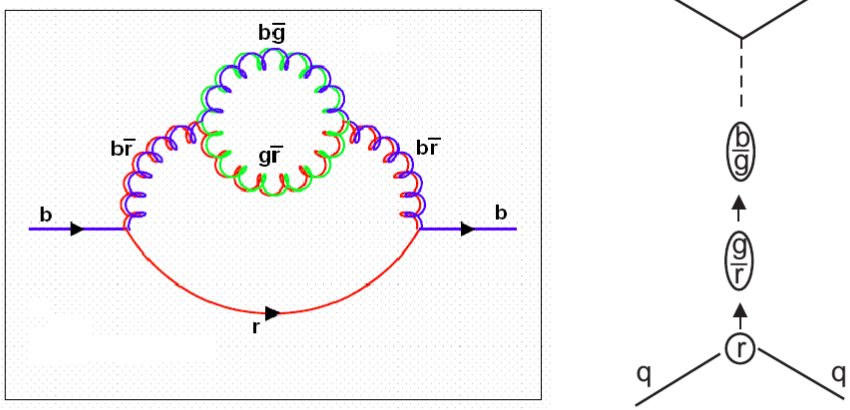
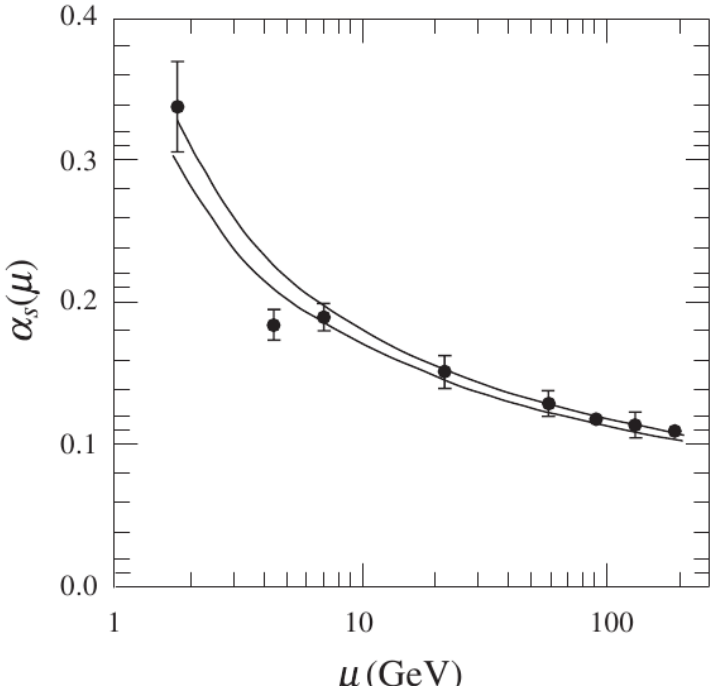


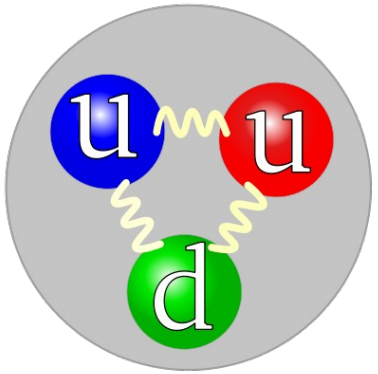

Figure 3.61: *Illustration of antiscreening of the colour charge of a quark via the creation of a virtual pair of gluons.*

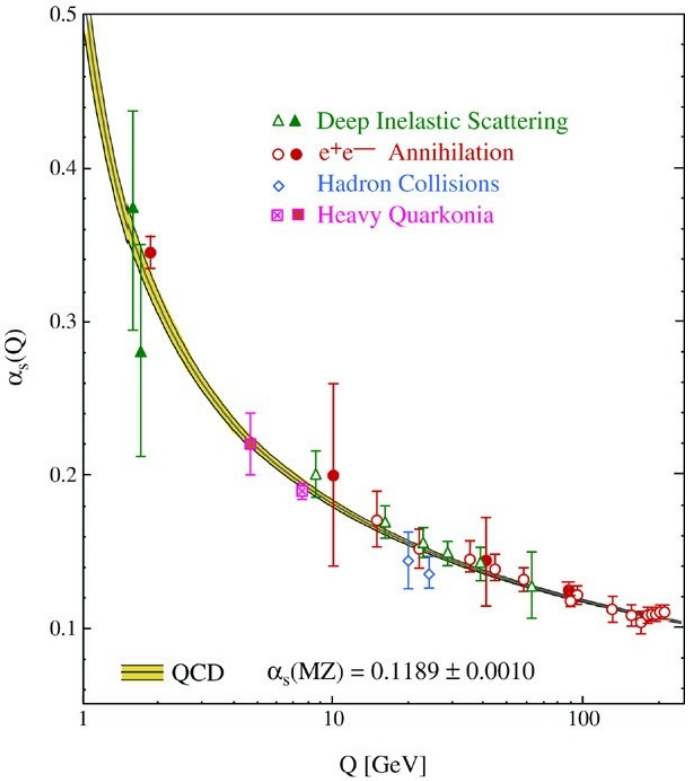
# Full result for QCD

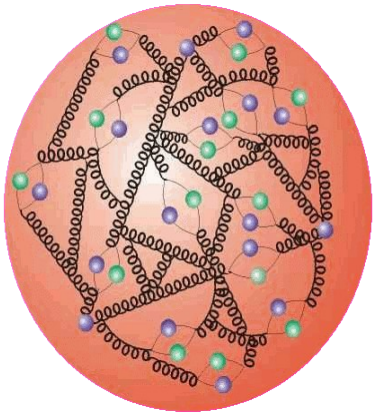



$$\alpha_s(\mu) = \alpha_s(\mu_0)\left[1 + \frac{(33 - 2N_f)}{6\pi}\alpha_s(\mu_0)\ln(\mu/\mu_0)\right]^{-1} \qquad (7.6)$$

# *2 limits of QCD: soft and hard!*



**CONFINEMENT**

Non-perturbative physics
(know the equations but not how to solve them)
Example: **Hadrons** and their production
Solution: phenomenological model, e.g. Lund string model

**ASYMPTOTIC FREEDOM**

Perturbative physics
(theoretical predictions)
Example: Quark scatterings → **jets**

# Example of 2 jet event

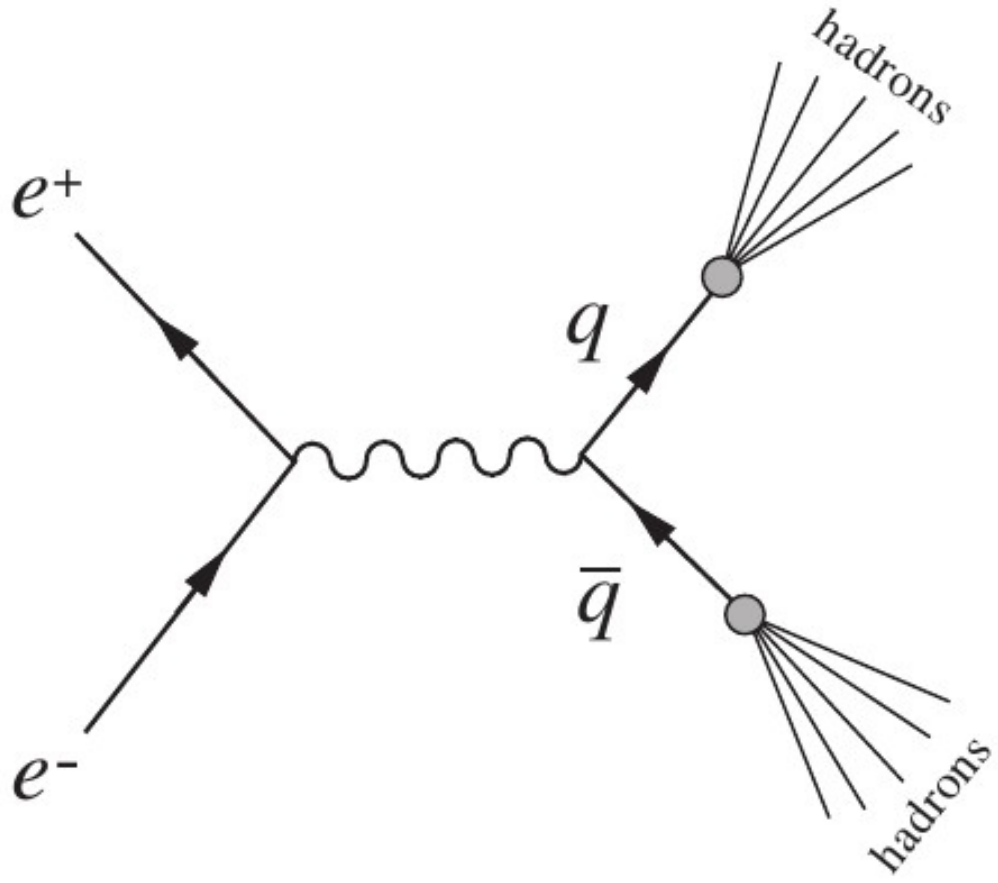
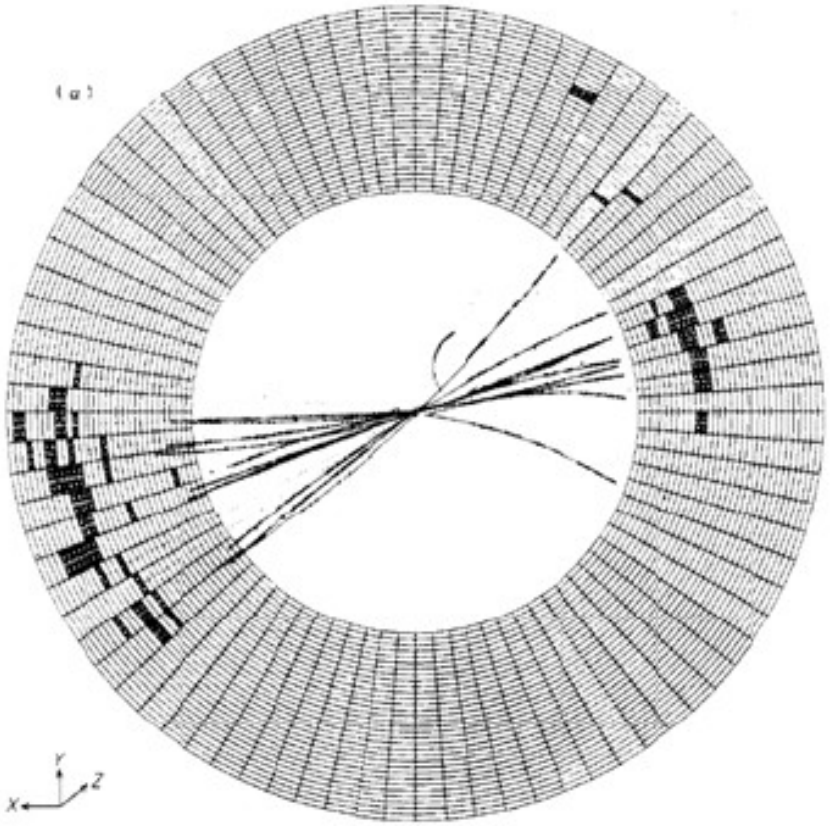



Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

# 2 jet event in $e^+ + e^-$



# What about the ratio?

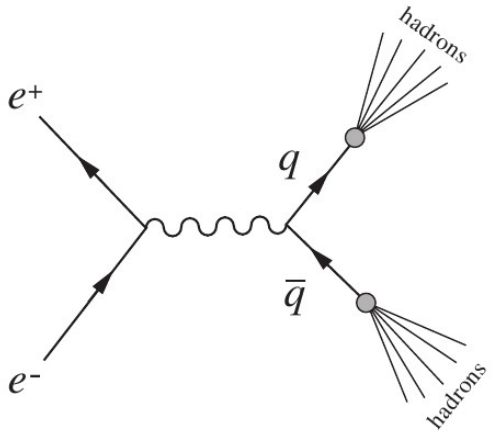



Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

$$\frac{\qquad\qquad}{\qquad\qquad} = ?$$

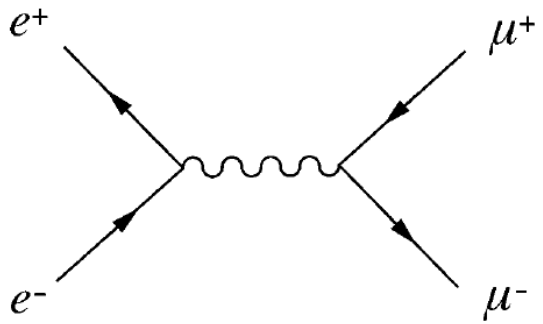
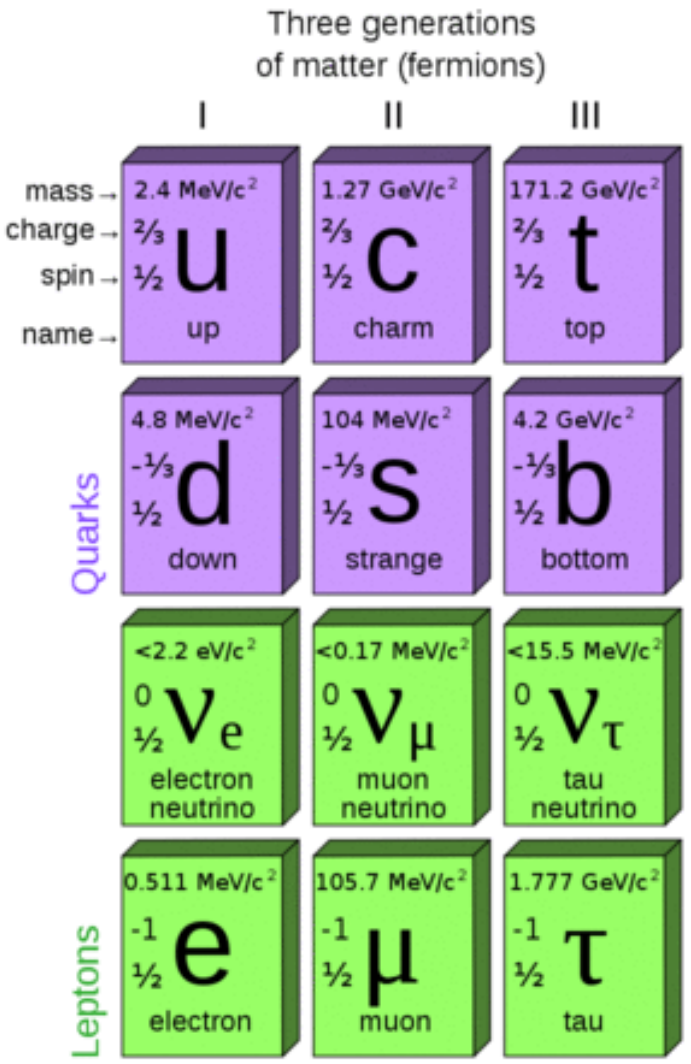



Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \to \mu^+ + \mu^-$.

# The charge difference




**q=+2/3**

**q=-1/3**

**q=-1**

- Due to different charges:
- A ~ q
- P ~ $q^2$
- Pqq ~ 4/9 + 1/9 + 1/9 + 4/9 + 1/9

  (up to threshold)
- Pμμ ~ 1
- Ratio:  11/9

# What about the ratio?

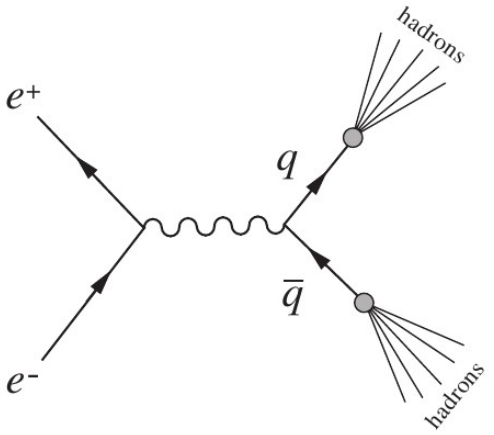



Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

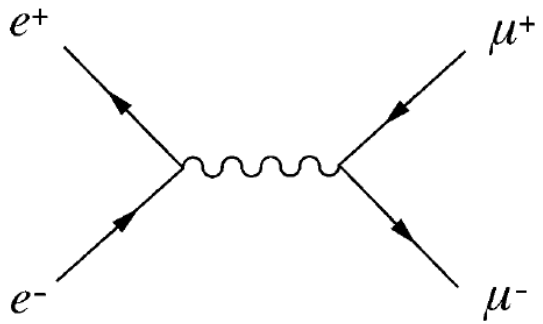



Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \to \mu^+ + \mu^-$.

R ≠11/9

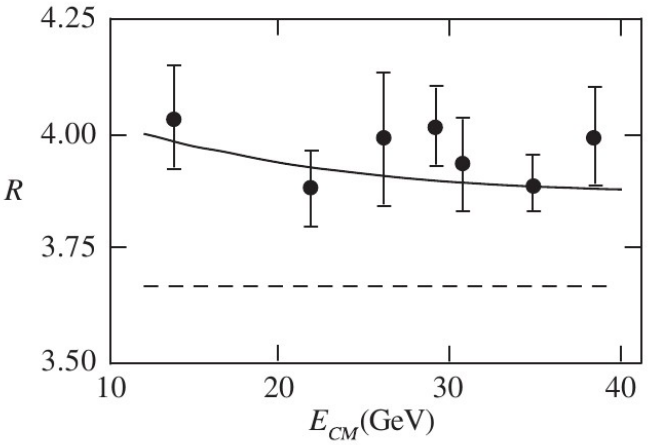
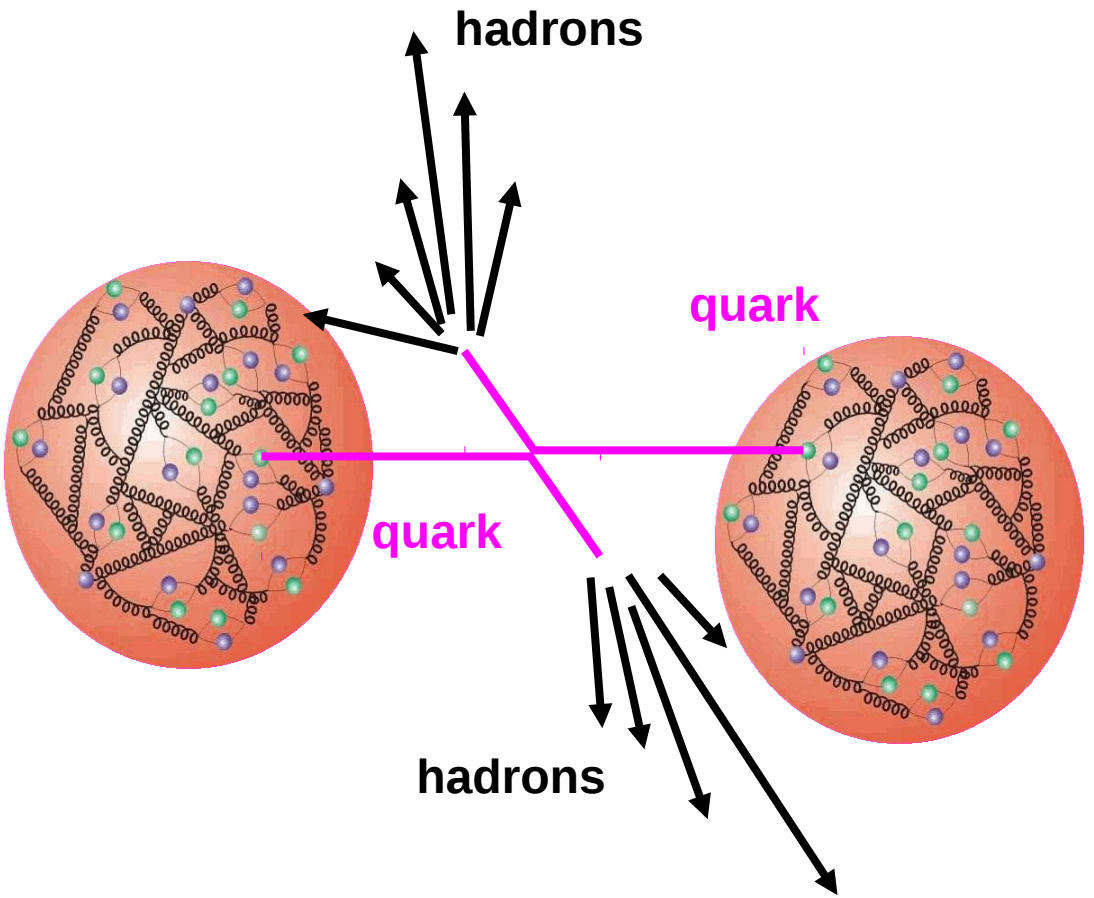


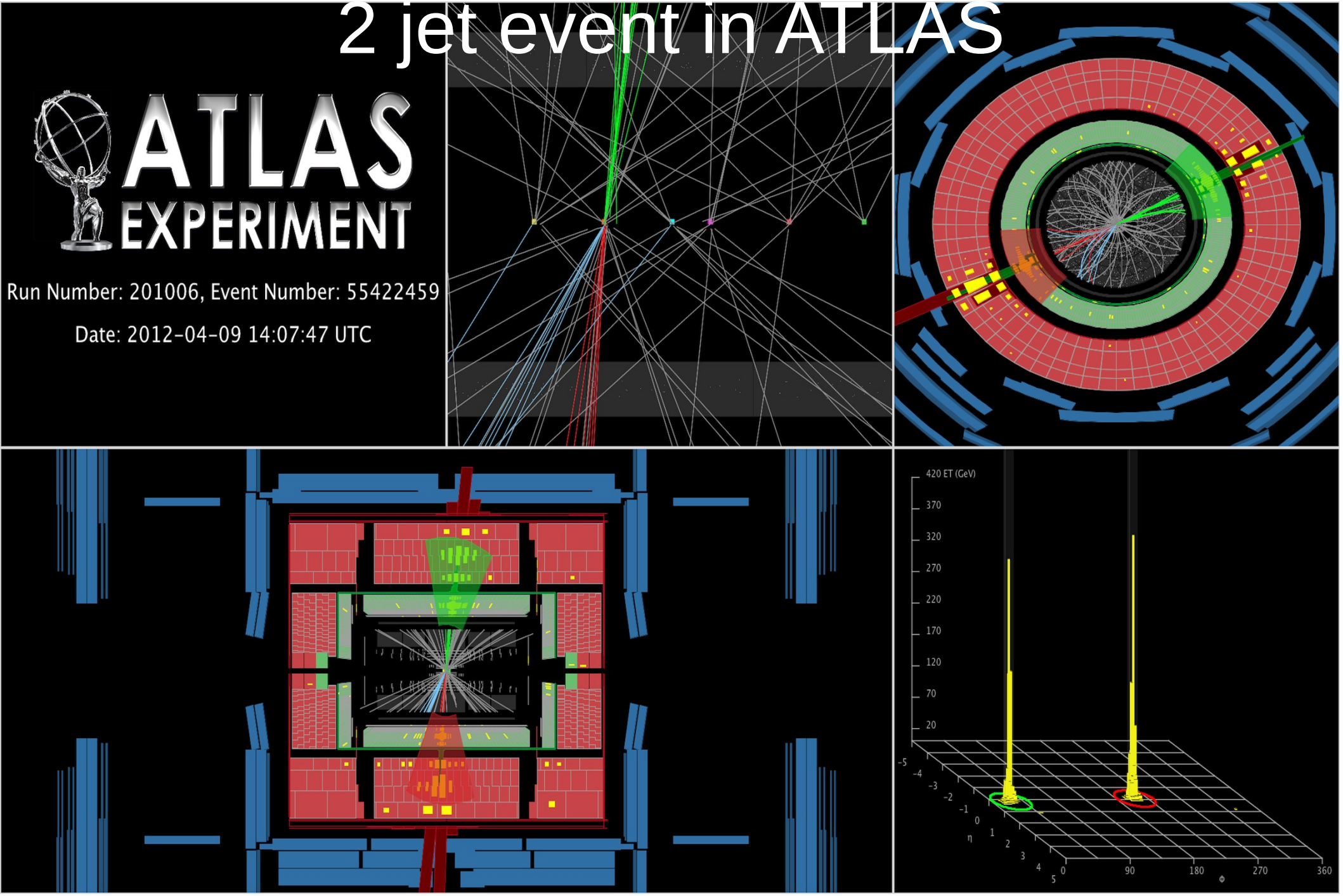

Figure 7.16 Comparison between the measured values of the cross-section ratio $R$ of Equation (7.18) and the theoretical prediction (7.22) for three colours, $N_C = 3$. The dashed line shows the corresponding prediction (7.21) omitting small contributions of order $\alpha_s$. (Data from the compilations of Wu, 1984, and Behrend *et al.*, 1987.)

There are 3 types of quark(charge)s: red, green, blue!

# Proton-proton 2 jet event



# 2 jet event in ATLAS



# 3 jet event: hard gluon

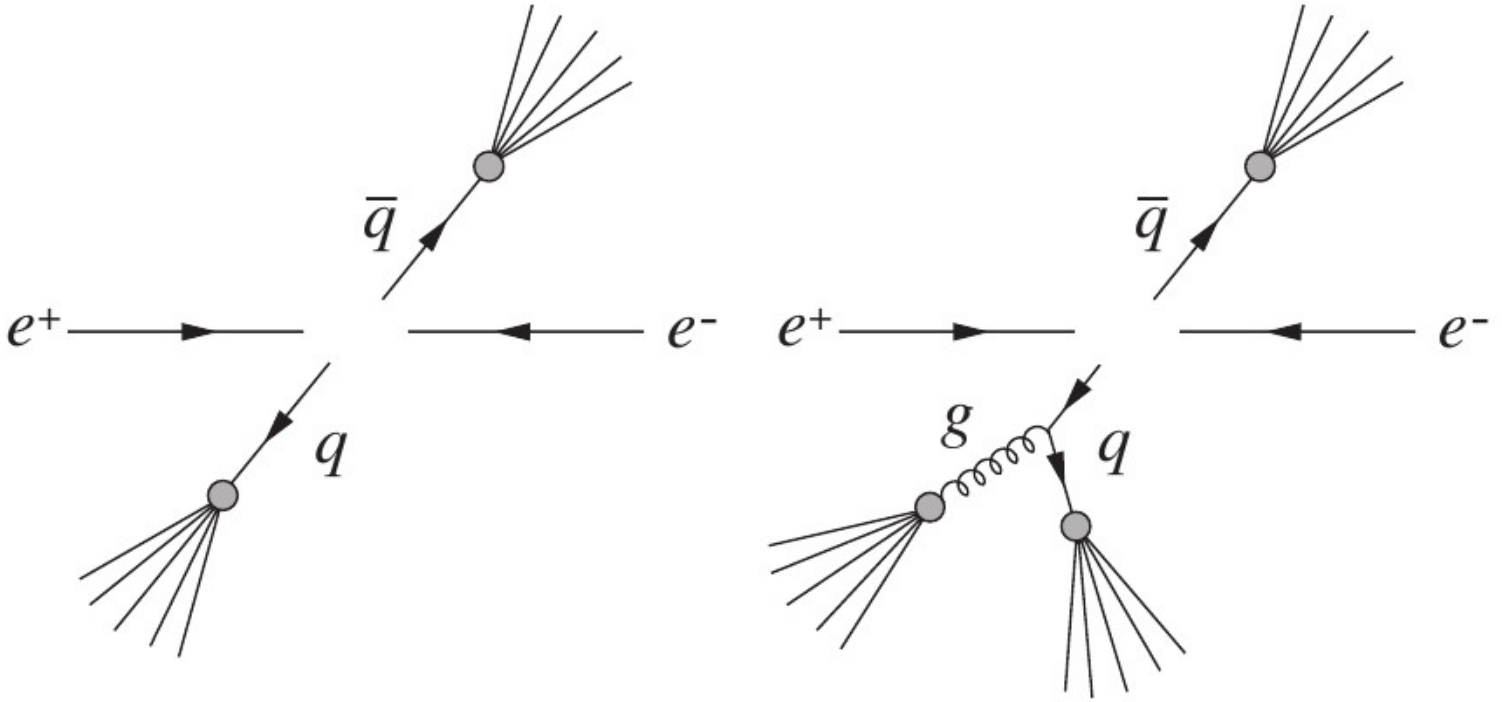
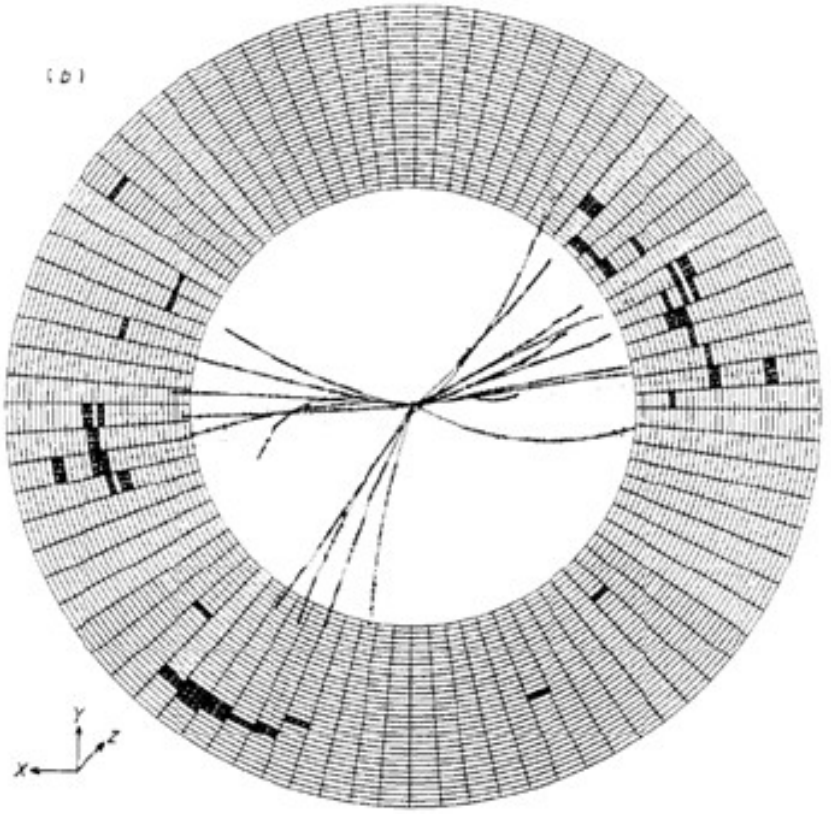



Figure 7.13 Schematic diagrams representing (a) two-jet and (b) three-jet formation in electron–positron annihilation in the centre-of-mass frame.

# 3 jet event in $e^+ + e^-$

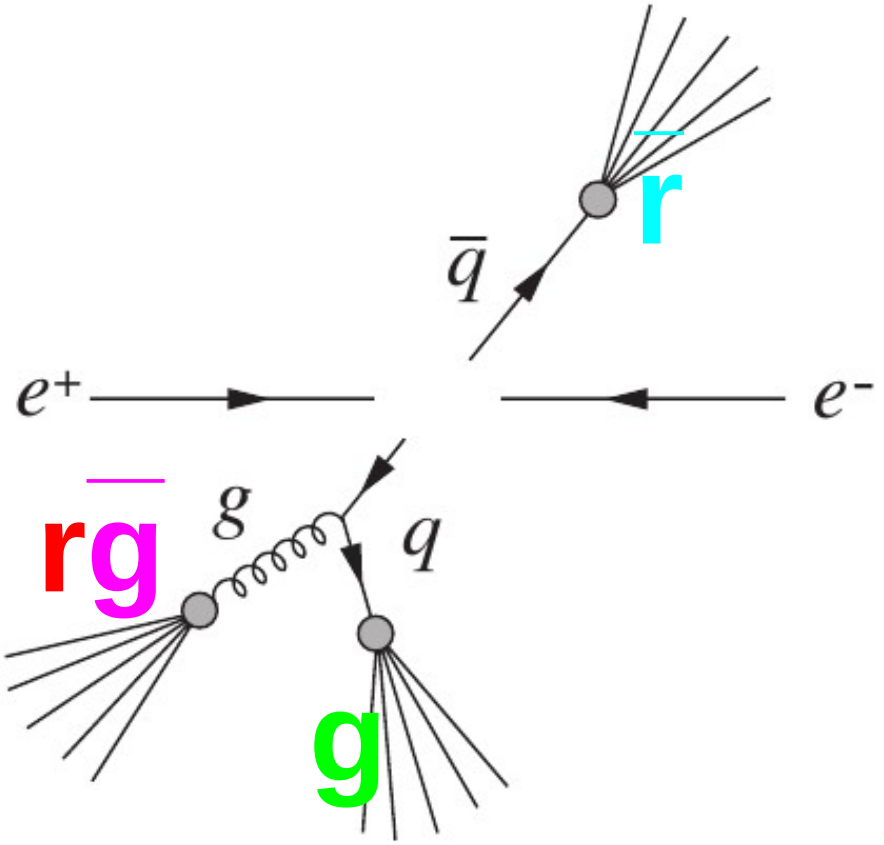


# Do you understand it? The 4 essential points

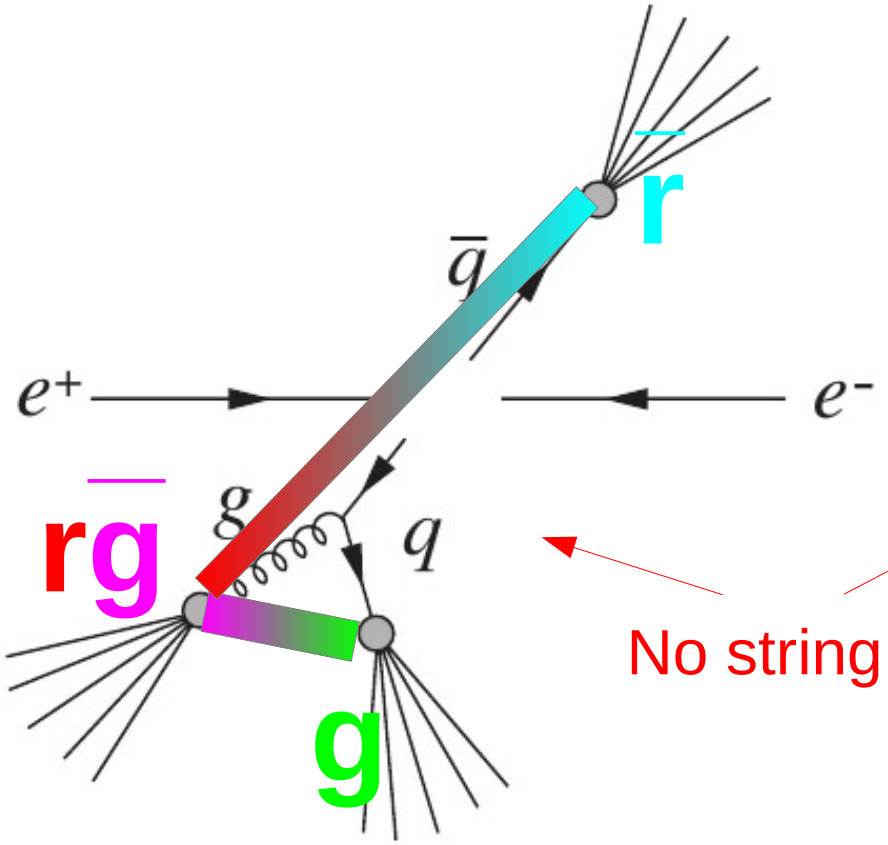
- What is the difference between the EM and the strong interaction?
- Why is the strong force strong?
- What is confinement?
- What is assymptotic freedom?

# A deeper look at fragmentation

# What happens when you have a 3 jet event – Think time:-)



# What happens when you have a 3 jet event!




No string!

Leading 2. 3.
q q g

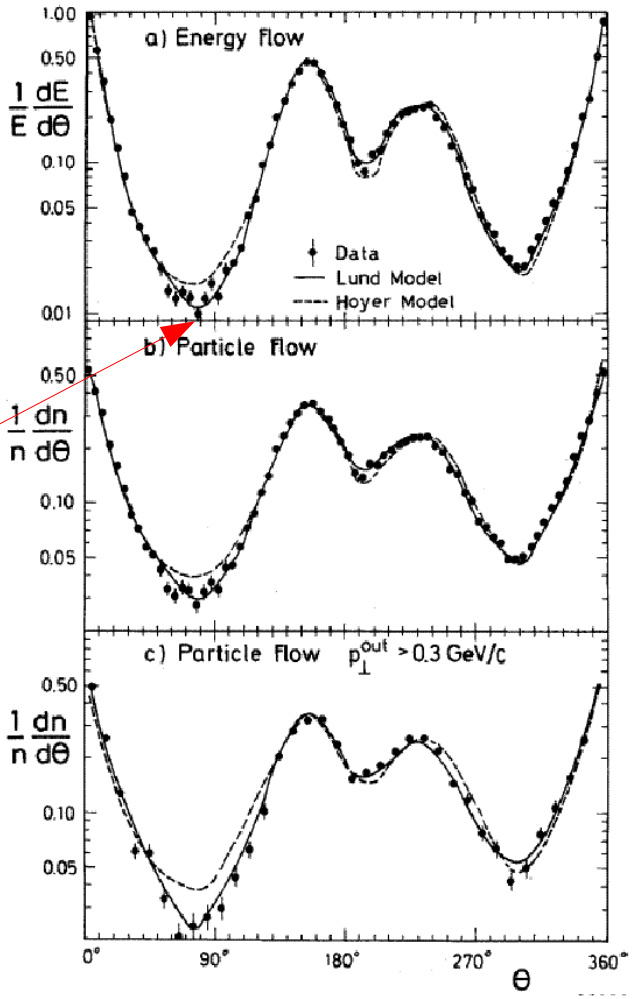
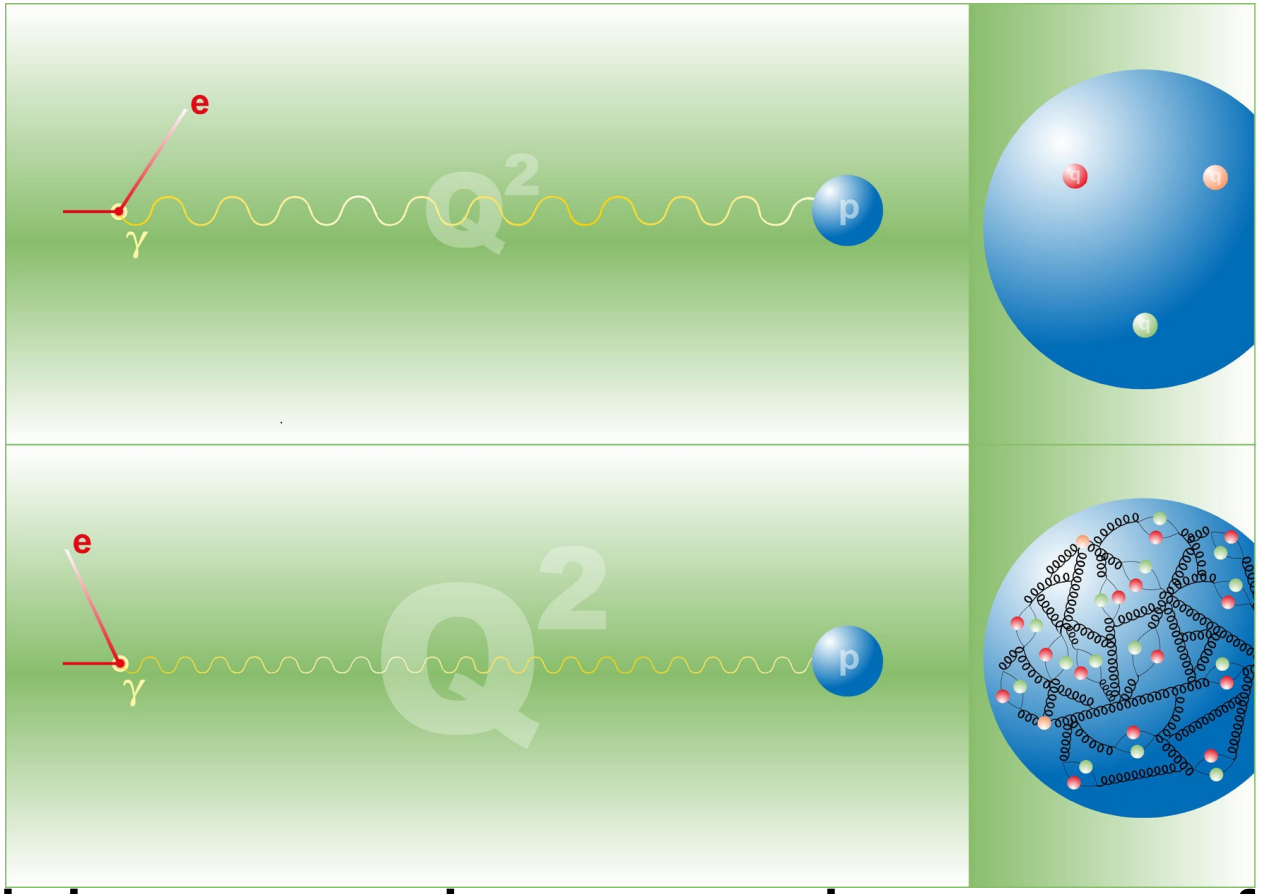



Figure from Leif's notes

# 3 small exercises

- a) Draw a series of Feynman diagrams for an Ω (sss) decay to a p (uud)
- b) If the pion was very light could a $\Sigma^0$ (uds) decay strongly to a Λ (uds)
- c) Draw a Feynman diagram for a p-p collision in which there is a Λ in the final state (via a strong process and conserving strangeness)
- d) How can a color neutral J/ψ be produced by gluons?

# Deep inelastic scattering




- At high energy the proton is a soup of quarks and gluons
  - We can use the electron to probe the proton structure

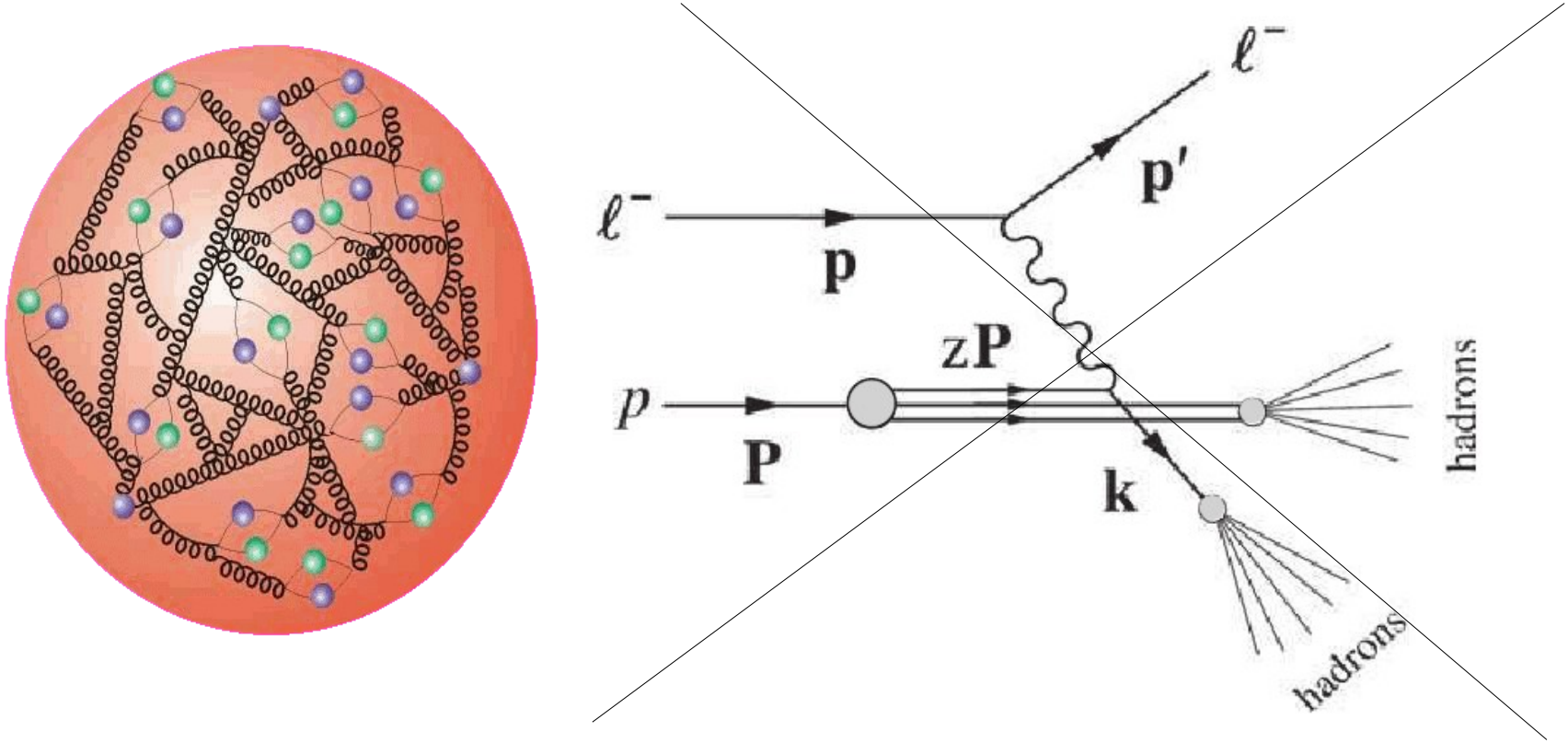
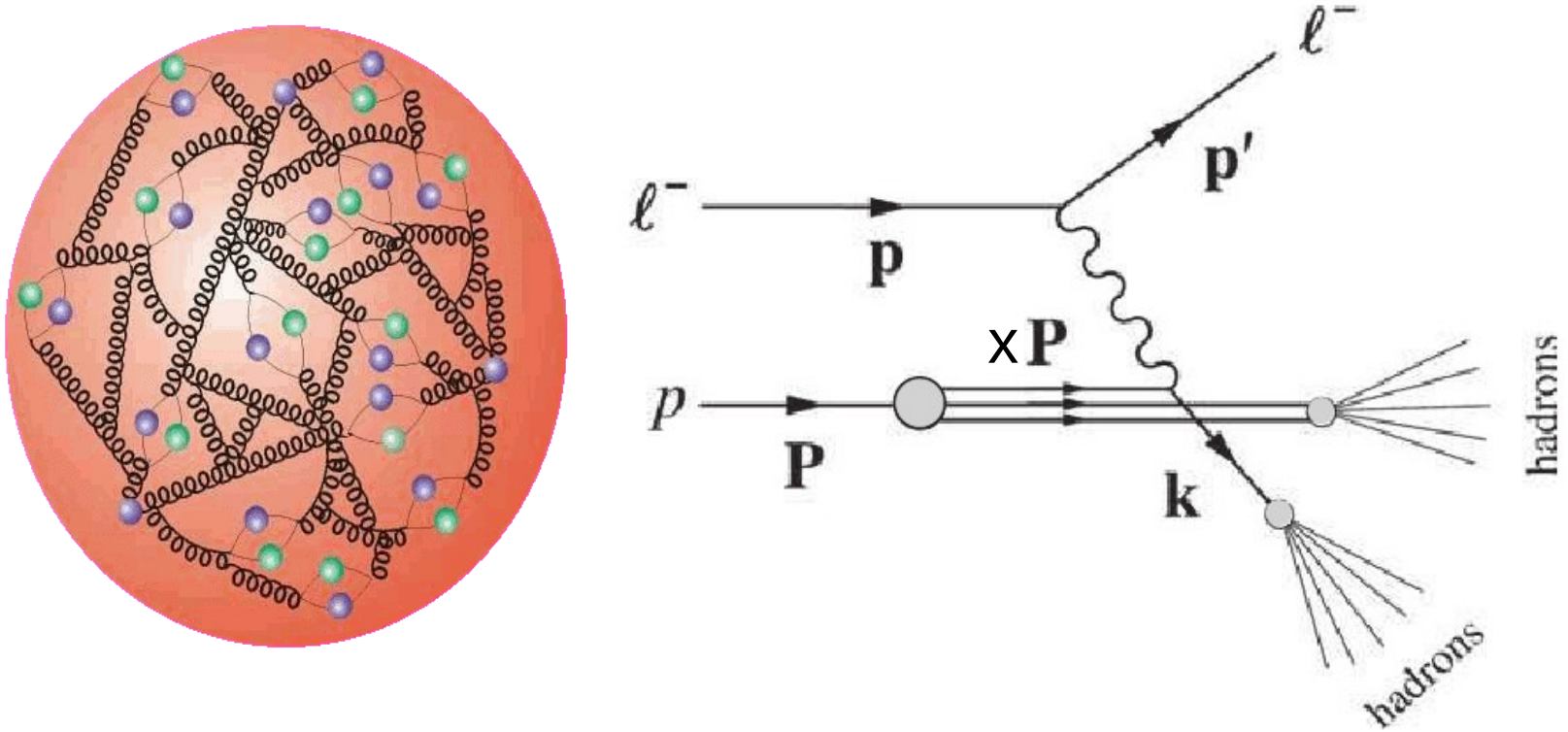



Figure 7.20 Dominant contribution to deep inelastic lepton–proton scattering in the quark model, where $\ell = e$ or $\mu$.

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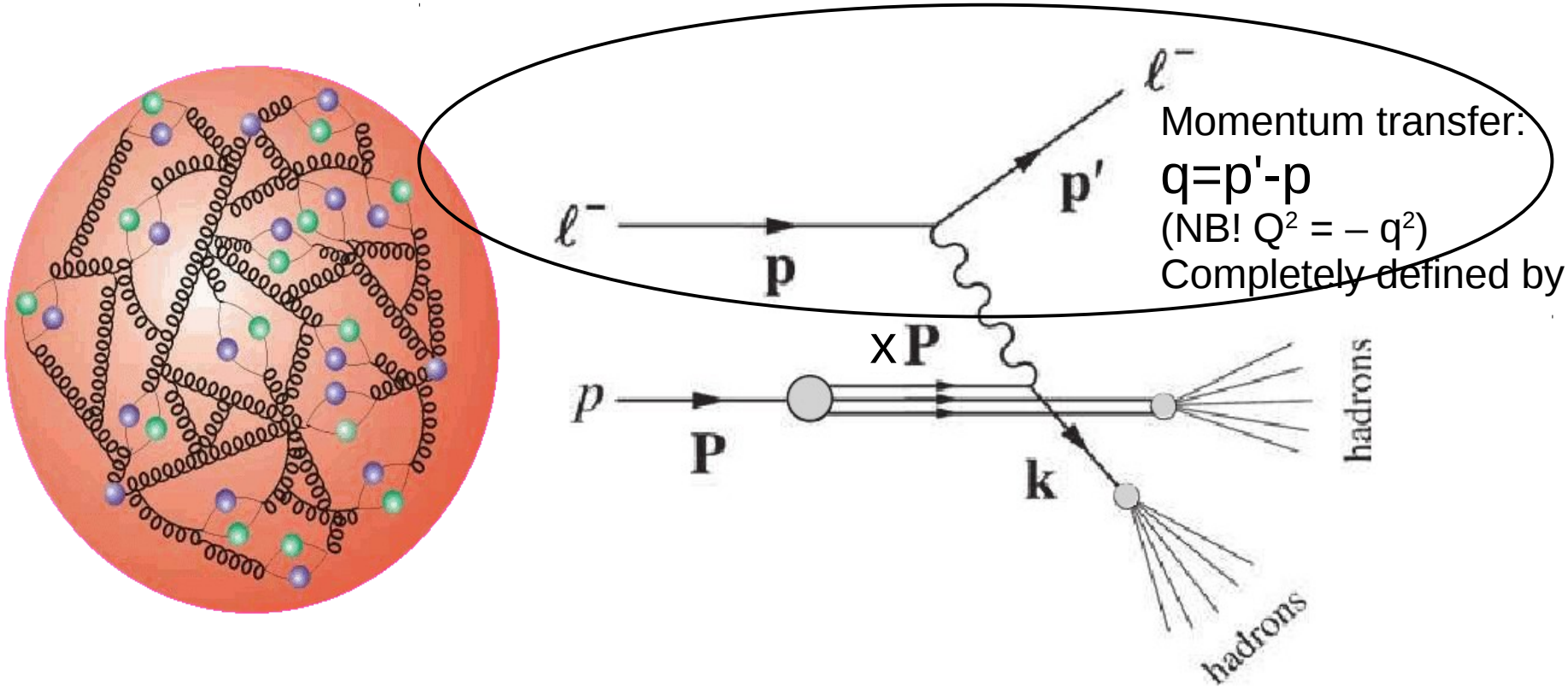


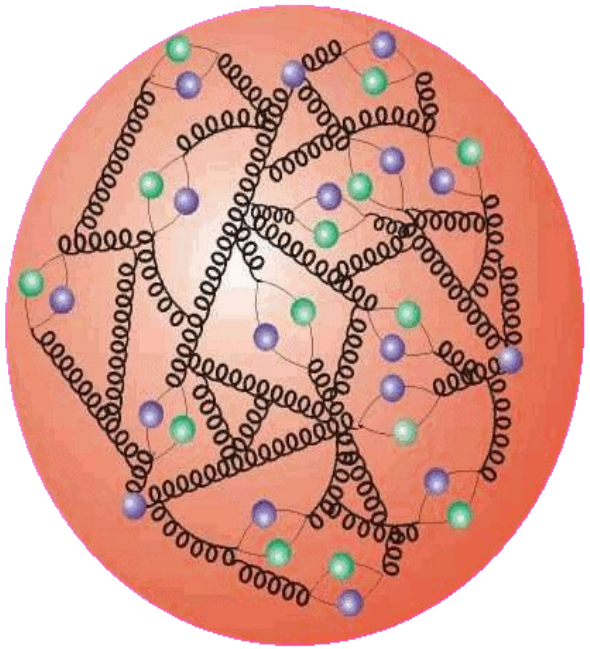

Momentum transfer:

$q=p'-p$

(NB! $Q^2 = -q^2$)

Completely defined by lepton!

Figure 7.20 Dominant contribution to deep inelastic lepton–proton scattering in the quark model, where $\ell = e$ or $\mu$.



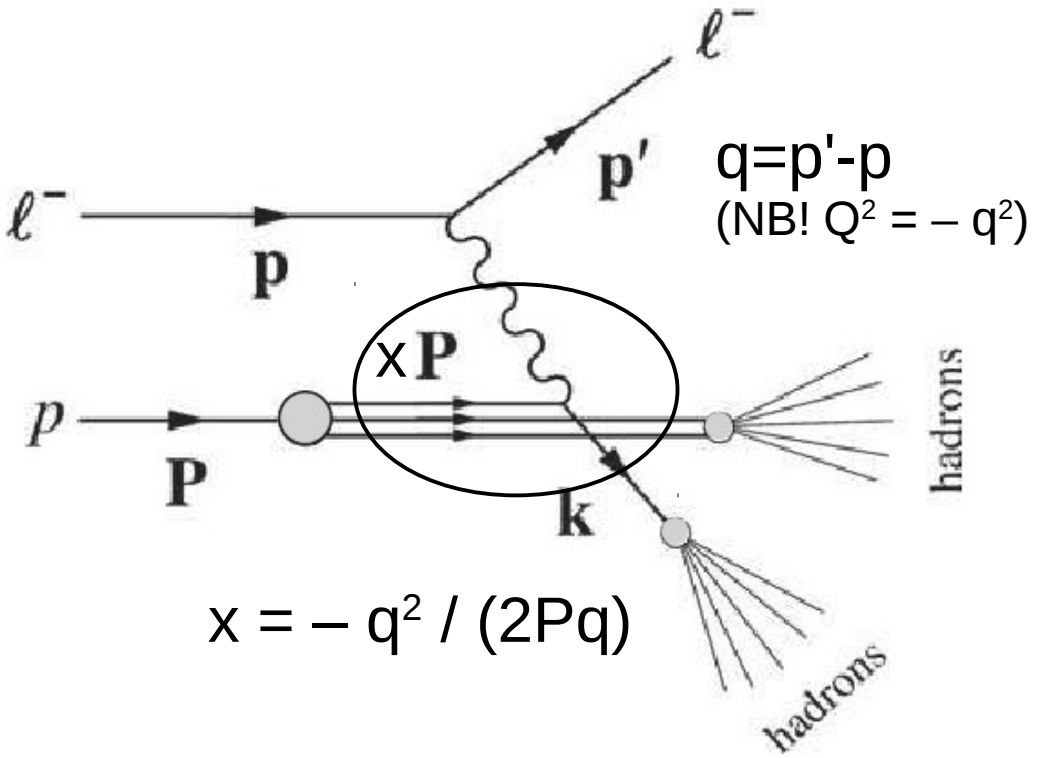



Figure 7.20 Dominant contribution to deep inelastic lepton–proton scattering in the quark model, where $\ell = e$ or $\mu$.

NB!

Because of <u>asymptotic freedom</u> we can treat the parton as a real particle instead of the part of a complicated.

The scattering itself is therefore elastic!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\mathrm{d}\Omega'} = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\frac{1}{\nu}\left[\cos^2(\theta/2)\,F_2\left(x,Q^2\right) + \sin^2(\theta/2)\,\frac{Q^2}{xM^2}F_1\left(x,Q^2\right)\right].$$

(7.53)

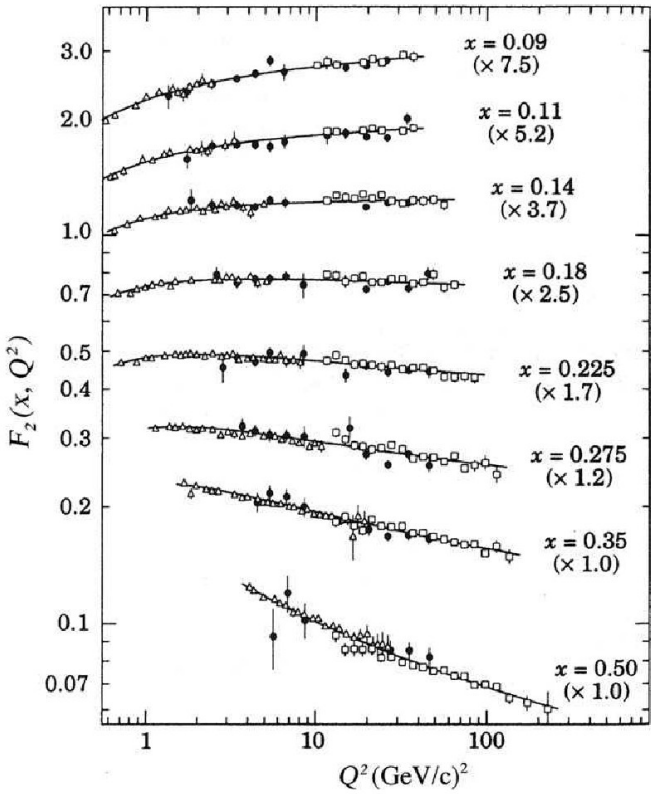
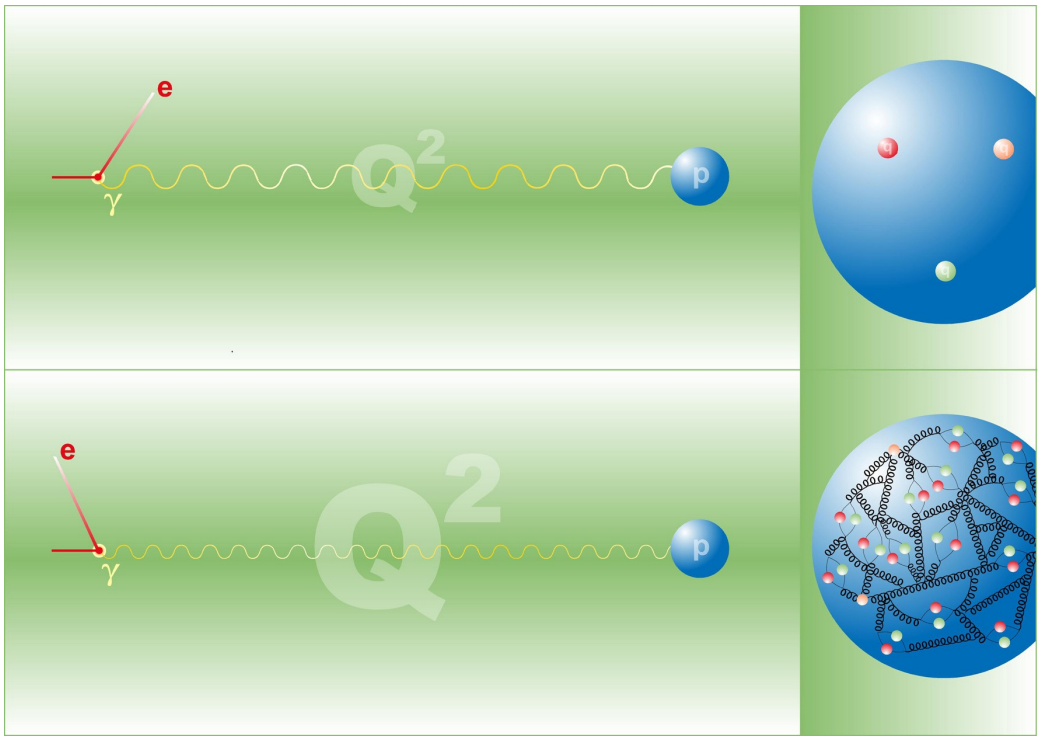
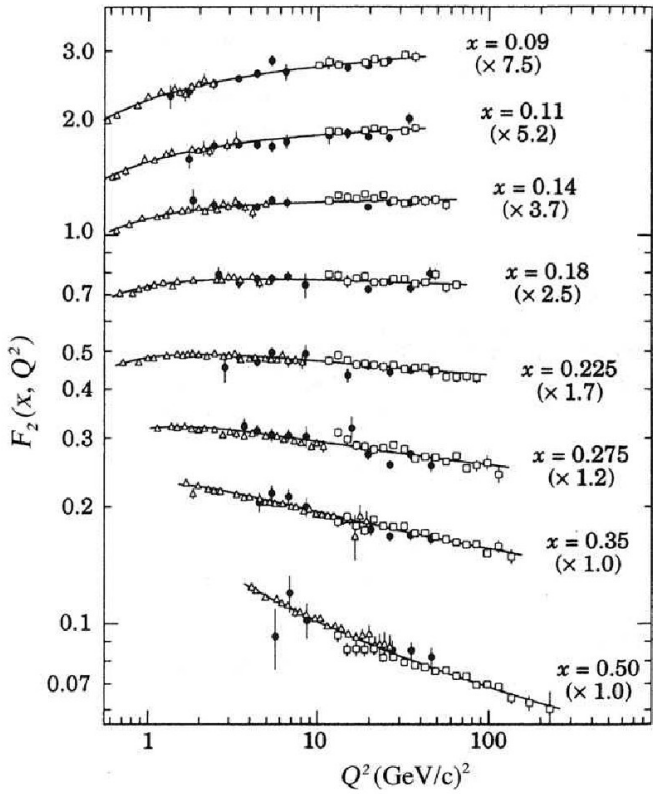



Figure 7.21 Measured values of the structure function $F_2(x, Q^2)$ from a deep inelastic scattering experiment using muons. The data points at the lower $x$ values have been multiplied by the factors in brackets so that they can be displayed on a single diagram. (Reprinted Figure 32 with permission from L. Montanet *et al.*, *Phys. Rev. D*, **50**, 1173. Copyright 1994 American Physical Society.)




# What do we learn?

# No Q dependence → Quarks are pointlike particles

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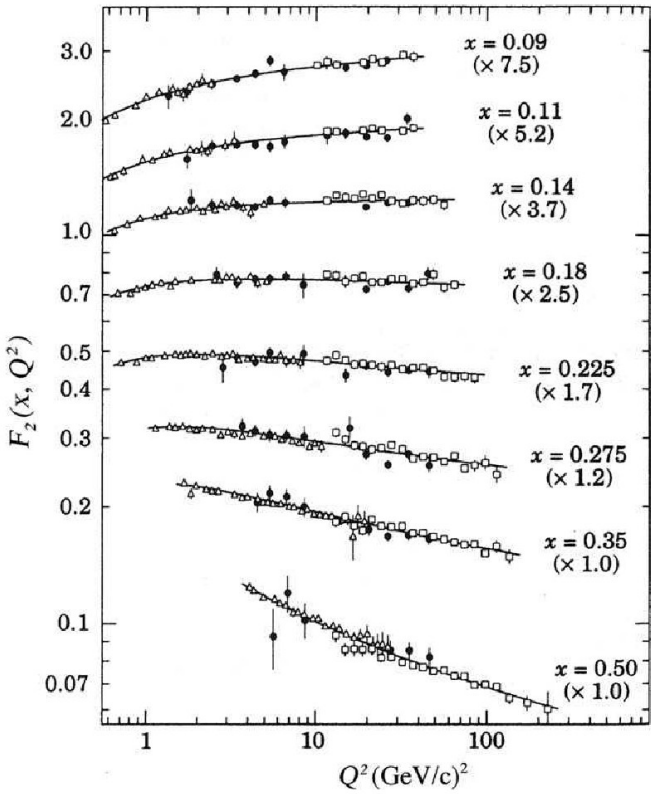
# The small Q dependence is due to gluons

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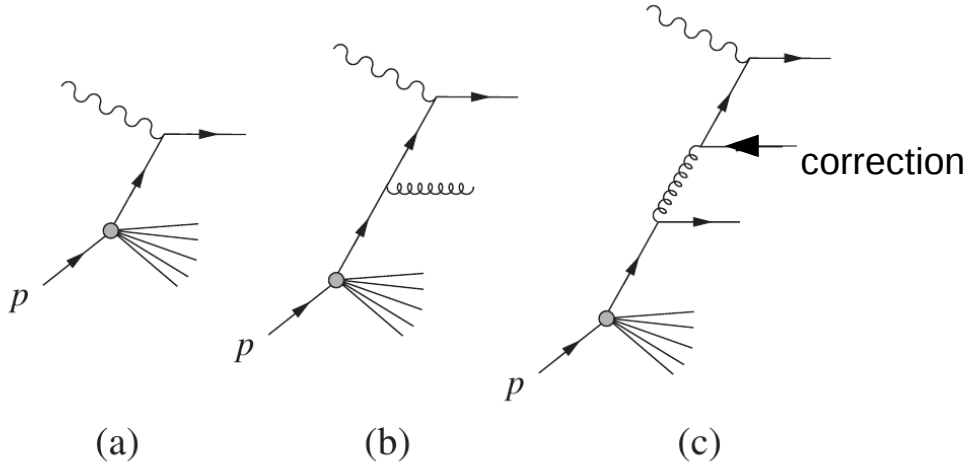



Figure 7.22 (a) The interaction of the exchanged photon with the struck quark in the parton model, together with (b, c) two of the additional processes that occur when quark–gluon interactions are taken into account.

# Number of quarks grows at small x

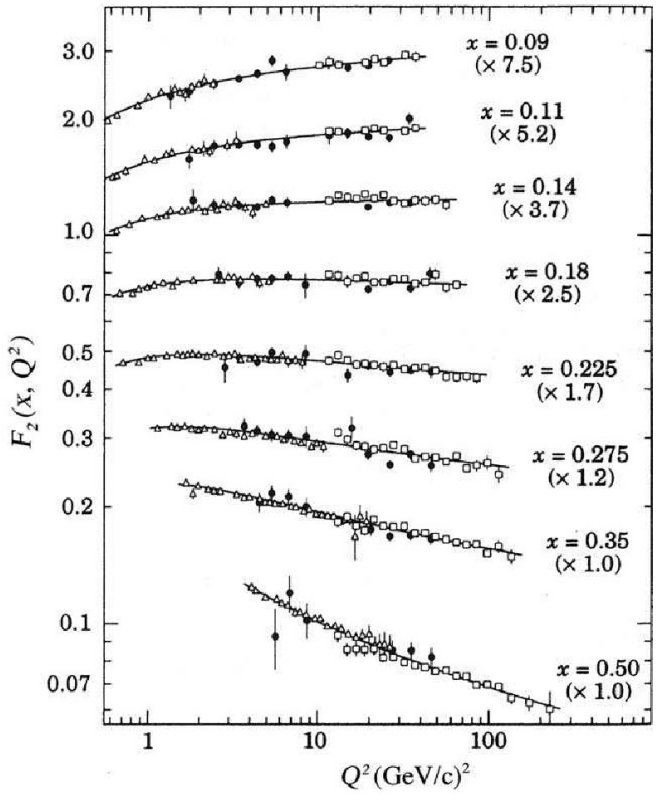
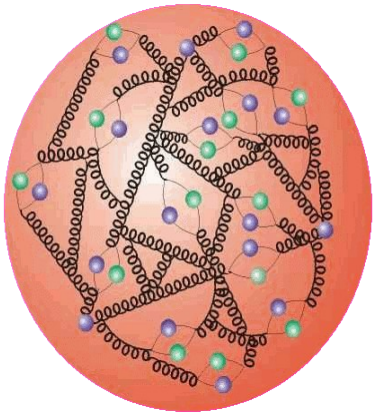
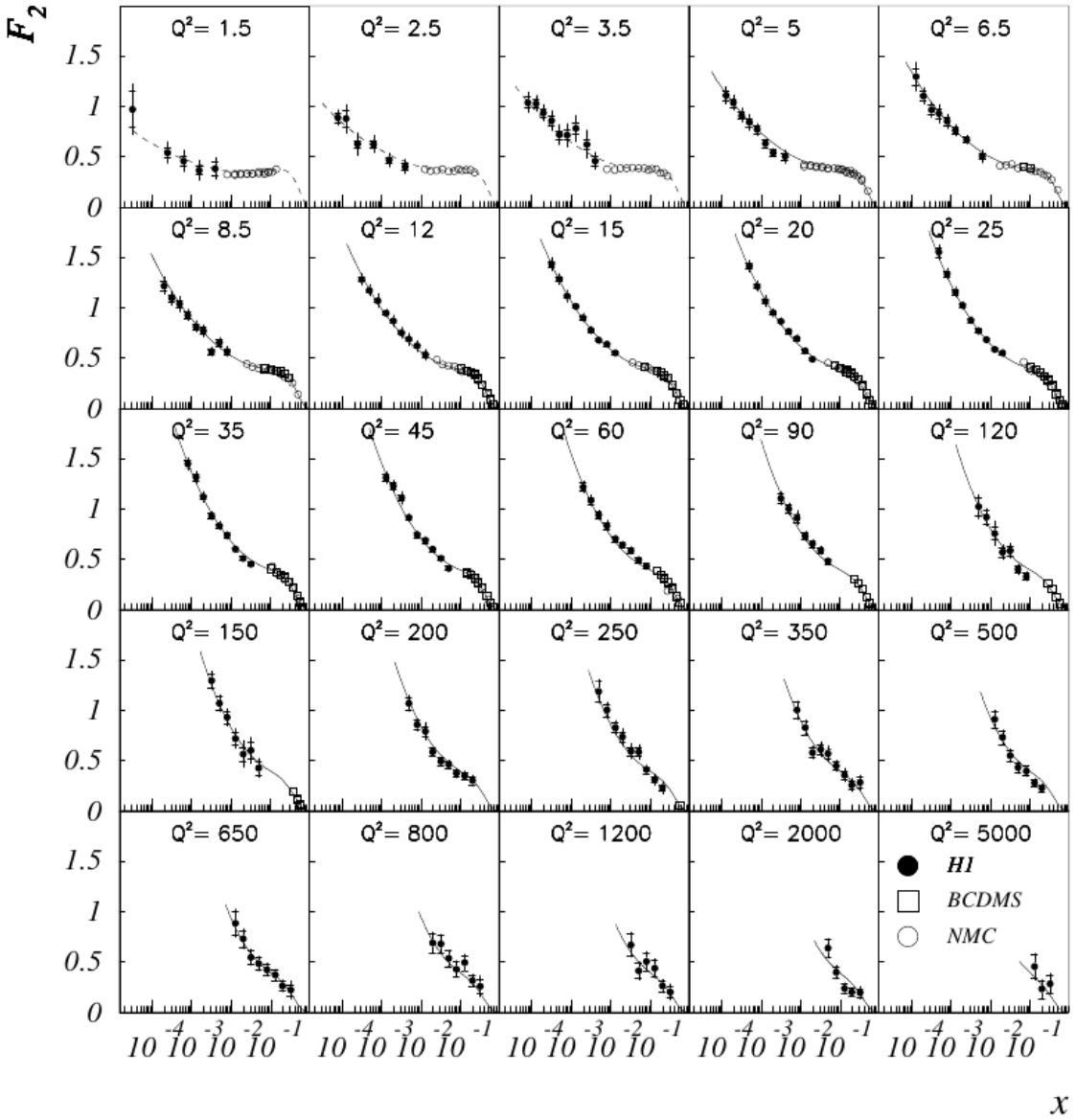


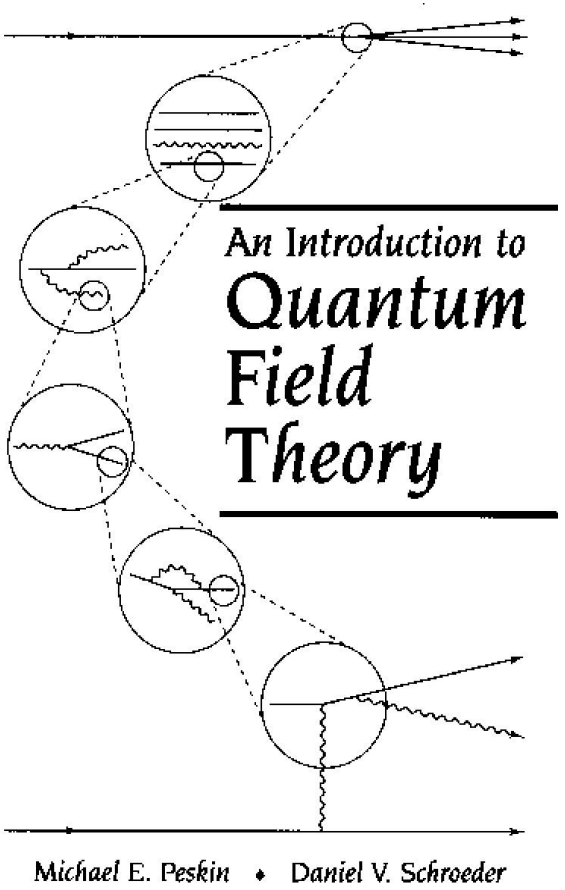

Figure 7.21 Measured values of the structure function $F_2(x, Q^2)$ from a deep inelastic scattering experiment using muons. The data points at the lower $x$ values have been multiplied by the factors in brackets so that they can be displayed on a single diagram. (Reprinted Figure 32 with permission from L. Montanet *et al.*, *Phys. Rev. D*, **50**, 1173. Copyright 1994 American Physical Society.)

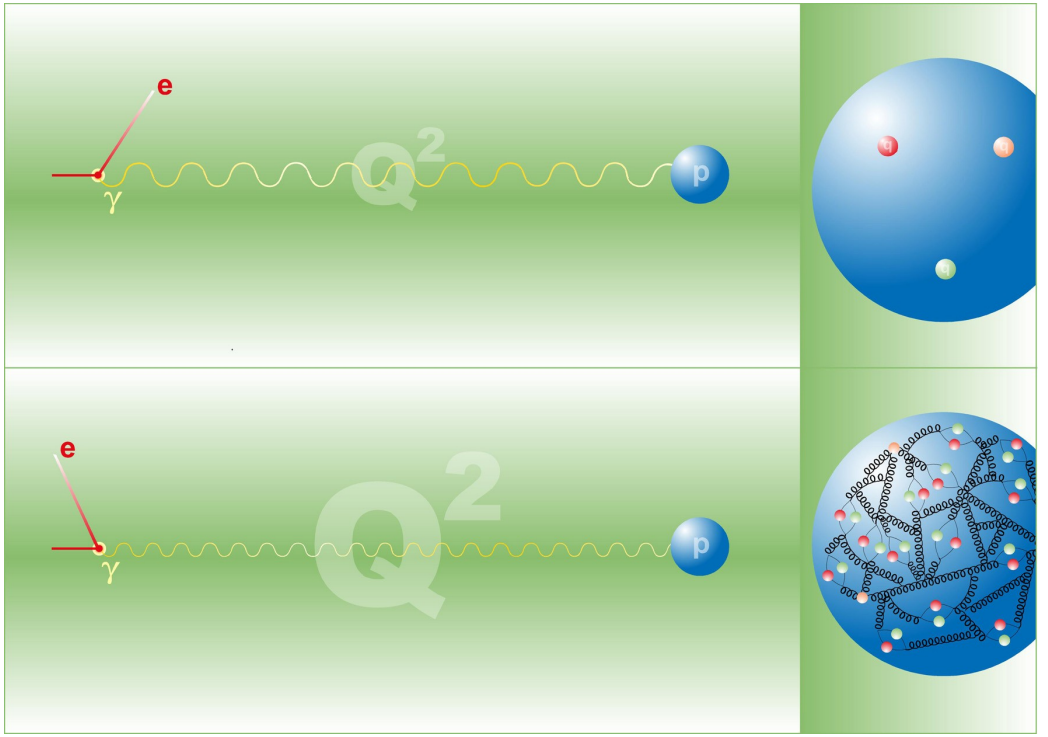


# F2 from Leif's notes



# The proton structure depends on the scale at which you resolve it



# Interpreting the result in the quark model

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\mathrm{d}\Omega'} = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\frac{1}{\nu}\left[\cos^2(\theta/2)\,F_2\left(x,Q^2\right) + \sin^2(\theta/2)\,\frac{Q^2}{xM^2}F_1\left(x,Q^2\right)\right]. \tag{7.53}$$

$$F_2(x,Q^2) = \sum_a e_a^2\, x f_a(x), \tag{7.56}$$

~~$F_1(x,Q^2) = 0 \quad (\text{spin} - 0)$~~ (7.57a)

and

$$2xF_1(x,Q^2) = F_2(x,Q^2) \quad (\text{spin} - \tfrac{1}{2}), \tag{7.57b}$$

$$F_2\left(x,Q^2\right) \approx \sum_a \left[e_a^2\, x f_a(x) + e_a^2\, x f_{\bar{a}}(x)\right],$$

# Result: information about the proton structure

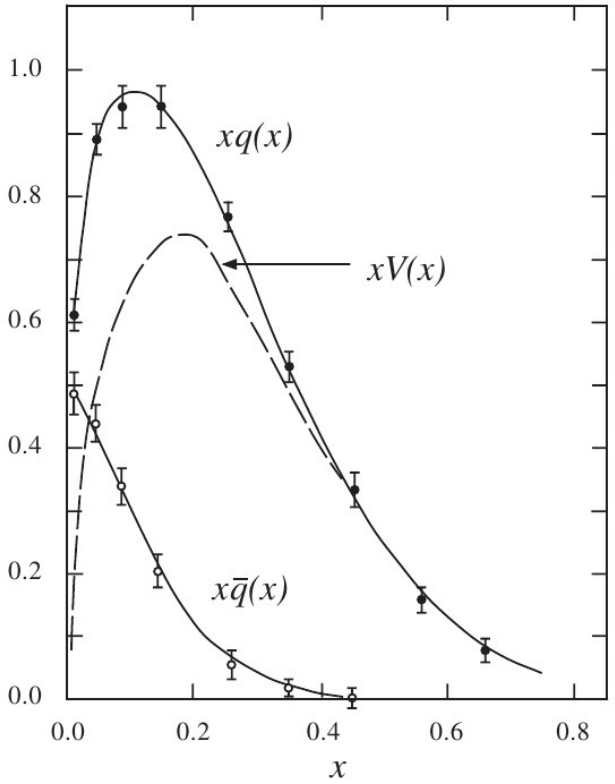
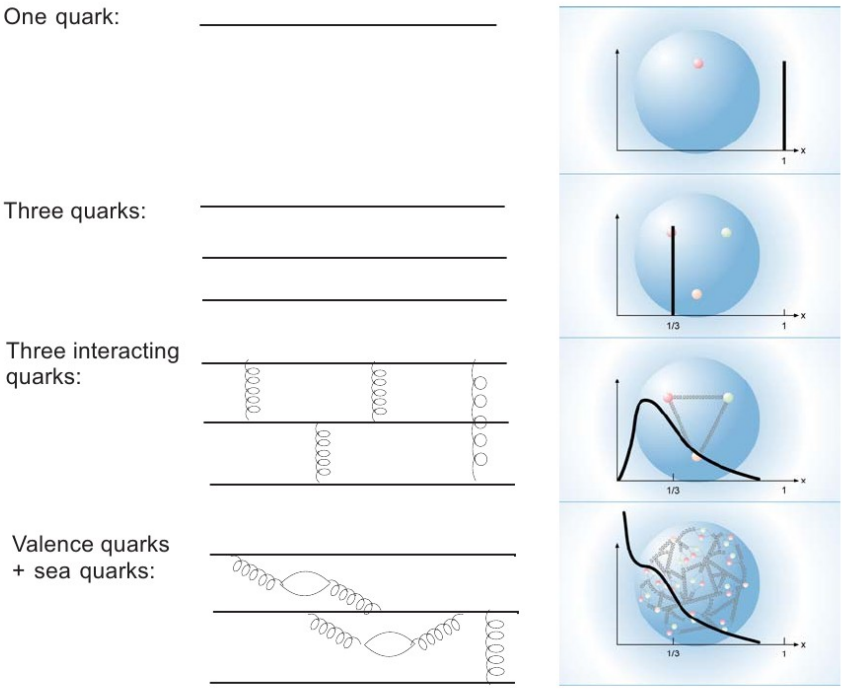
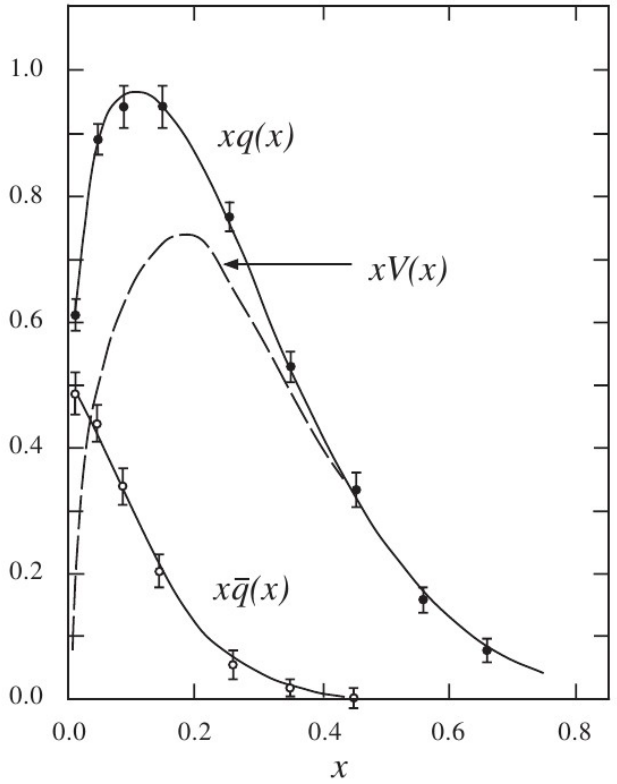


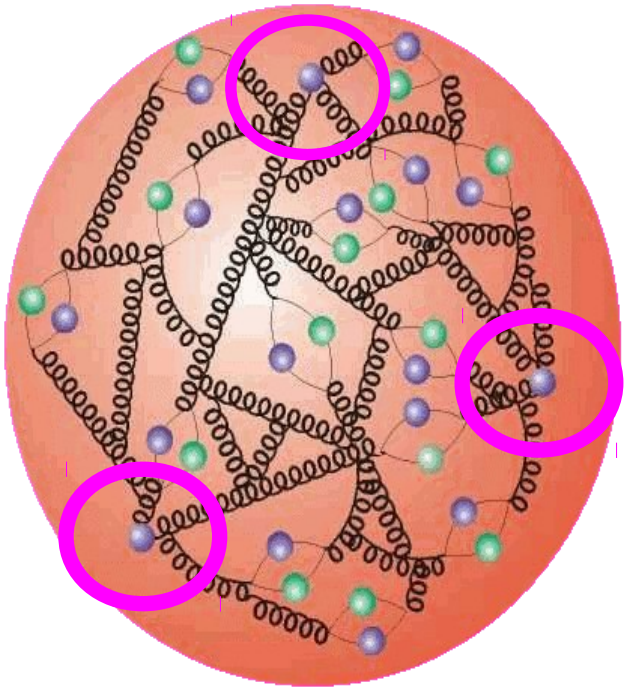

Figure 7.23 Quark and antiquark distributions (7.59a), together with the valence qua distribution (7.59b), measured at a $Q^2$ value of about $10\,\mathrm{GeV}^2$, from neutrino experimer at CERN and Fermilab.



# Result: ~50% of energy carried by valence quarks

$Q^2$~10GeV$^2$



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