

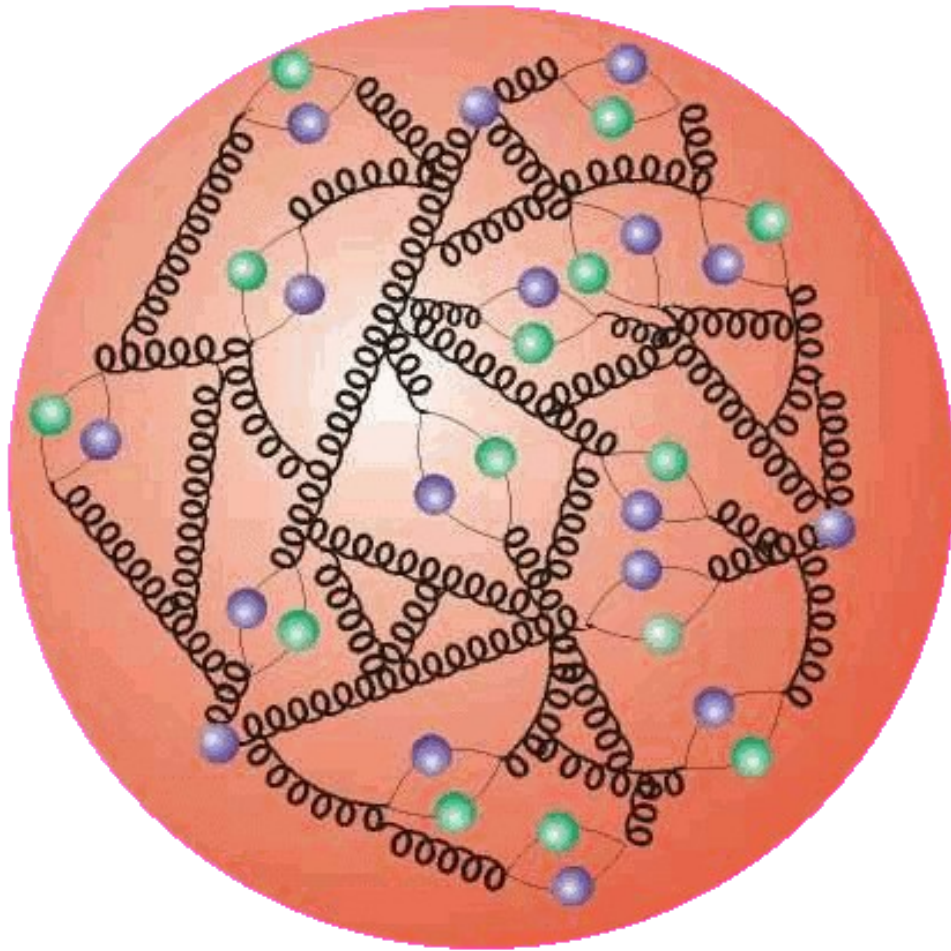
Strong force dynamics

Three generations
of matter (fermions)

	I	II	III		
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0	? GeV/c ²
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name →	u up	c charm	t top	γ photon	H Higgs boson
				g gluon	
Quarks	4.8 MeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV/c ² $-\frac{1}{3}$ $\frac{1}{2}$ b bottom		
	<2.2 eV/c ² 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV/c ² 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV/c ² 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV/c ² 0 1 Z⁰ Z boson	
Leptons	0.511 MeV/c ² -1 $\frac{1}{2}$ e electron	105.7 MeV/c ² -1 $\frac{1}{2}$ μ muon	1.777 GeV/c ² -1 $\frac{1}{2}$ τ tau	80.4 GeV/c ² ±1 1 W[±] W boson	Gauge bosons

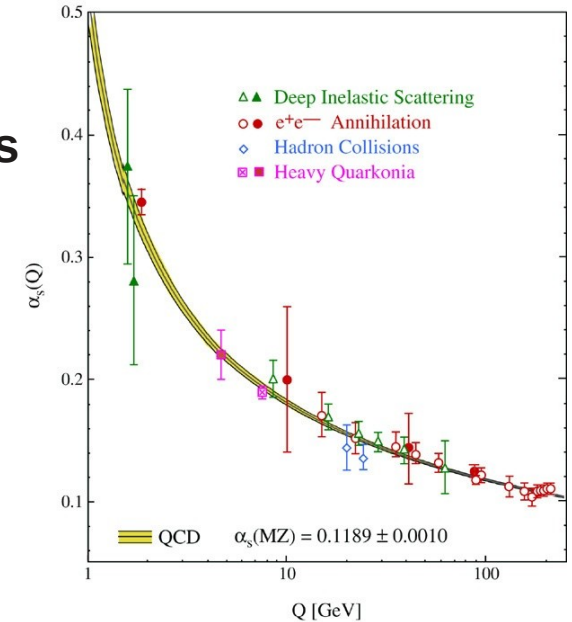
Many difficult aspects about the strong force

- The strong interaction is very complex!

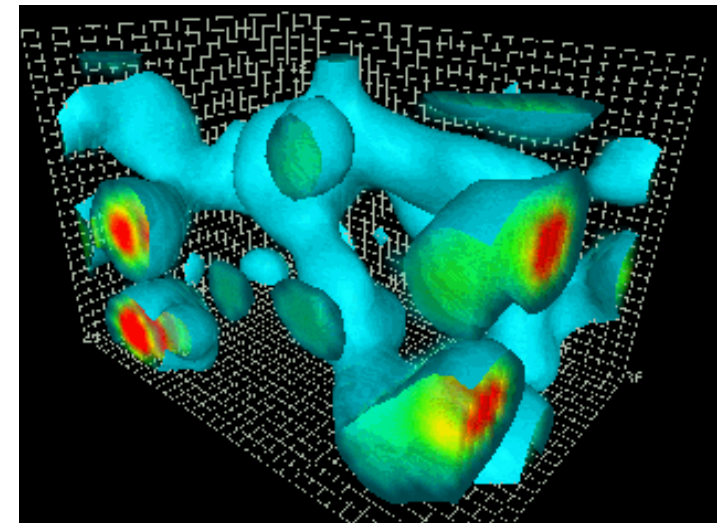


CONFINEMENT

Quarks and gluons
couples strong:



Complex
vacuum:



Feynman diagram

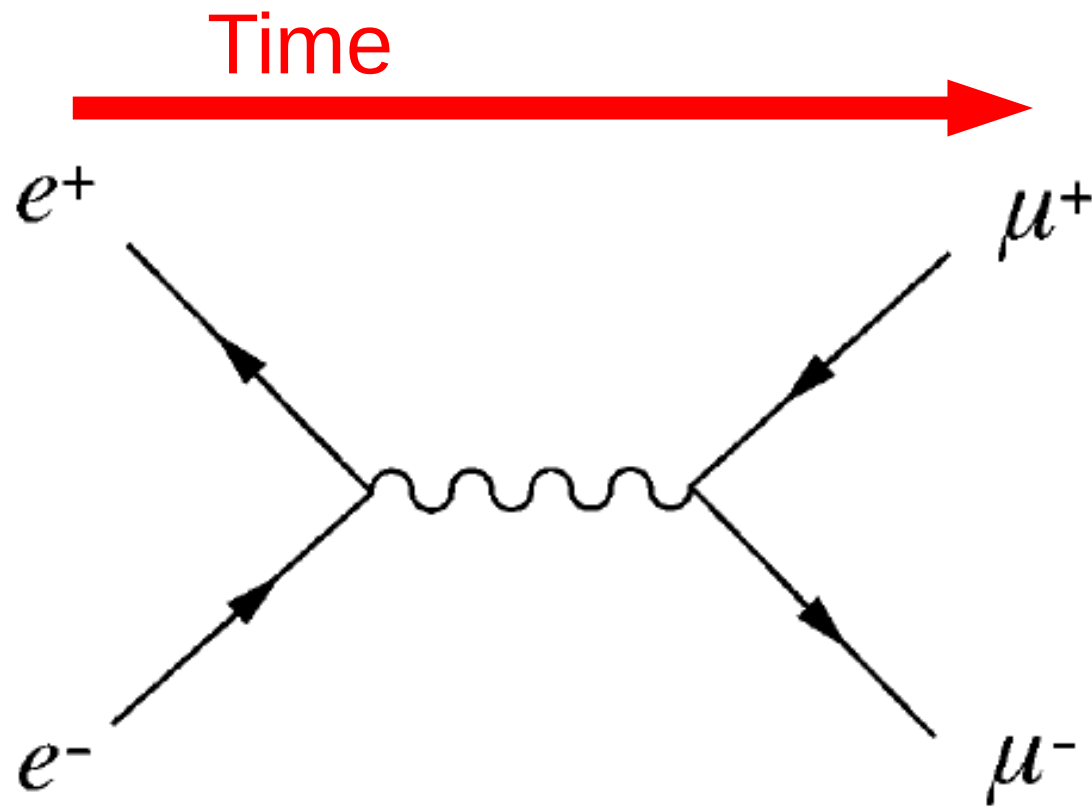


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

Feynman diagram

A calculational tool!

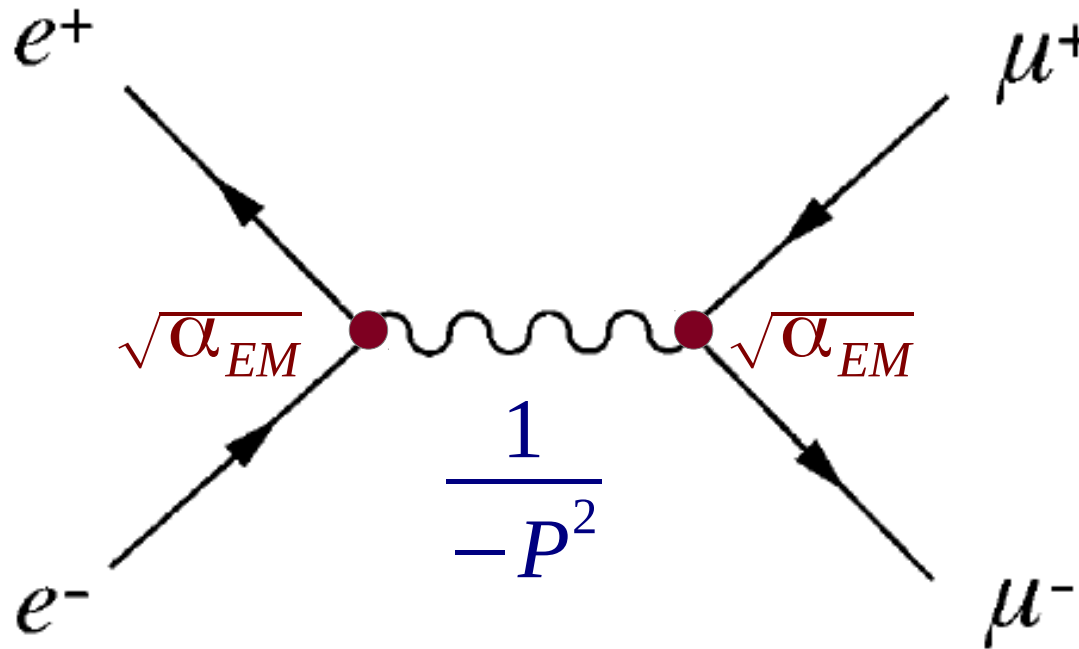


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

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

Feynman diagram of quark-quark scattering

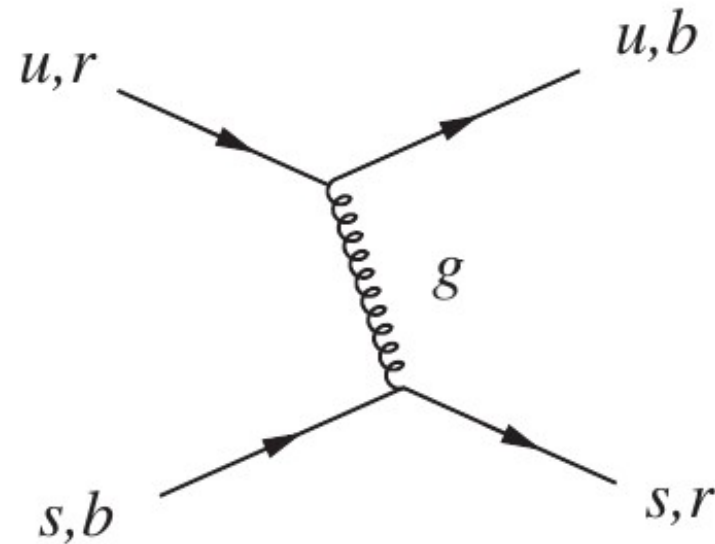


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a ‘corkscrew’ line to distinguish it from a photon. In this diagram the quark flavour u or s is unchanged on gluon emission, but the colour state can change, as shown.

Color flow

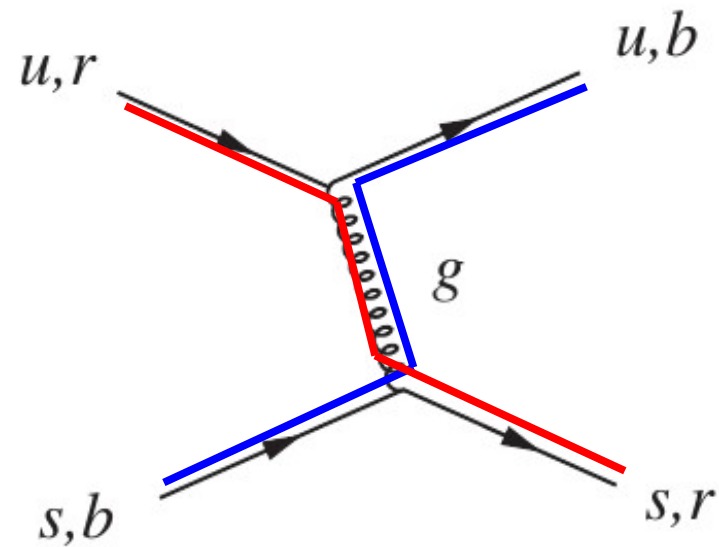


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a ‘corkscrew’ line to distinguish it from a photon. In this diagram the quark flavour u or s is unchanged on gluon emission, but the colour state can change, as shown.

Special QCD processes because gluons are colored!

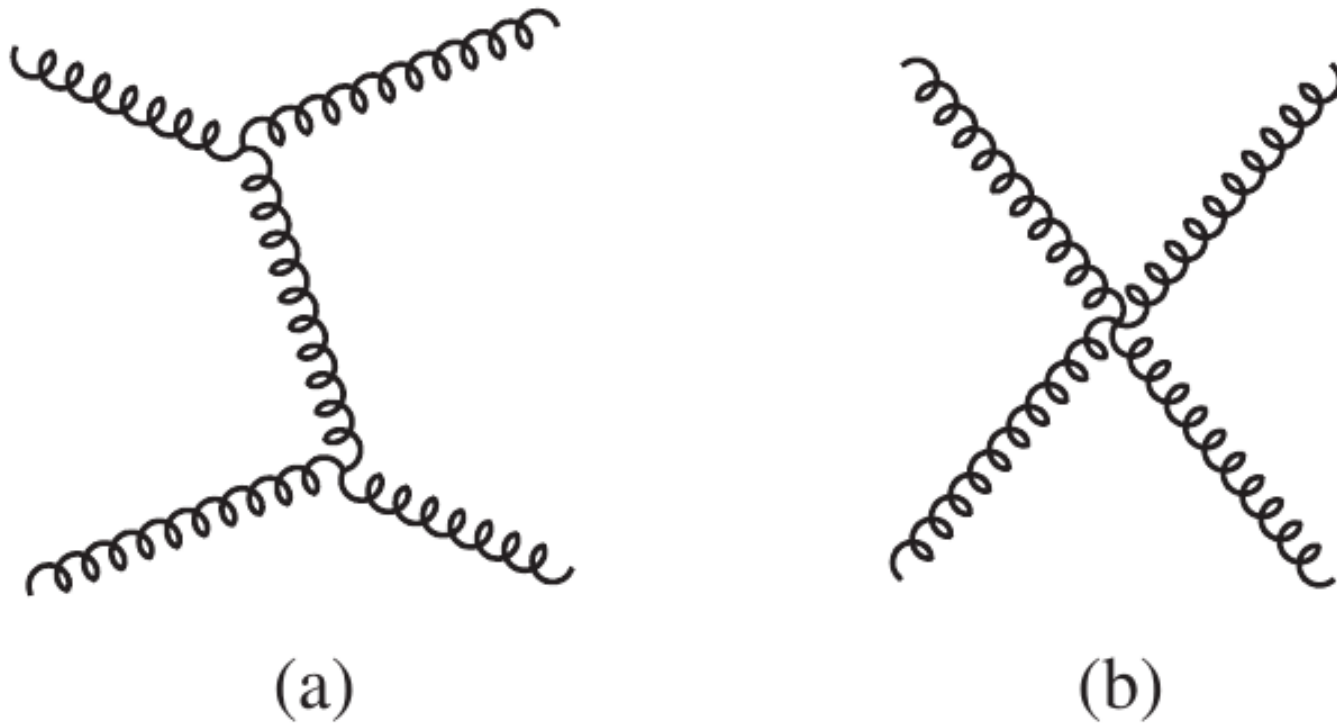


Figure 7.2 The two lowest-order contributions to gluon–gluon scattering in QCD.

The strong coupling

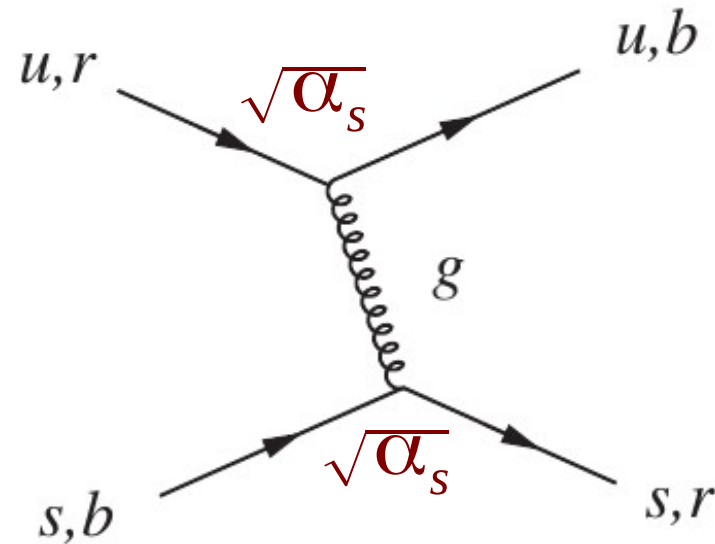
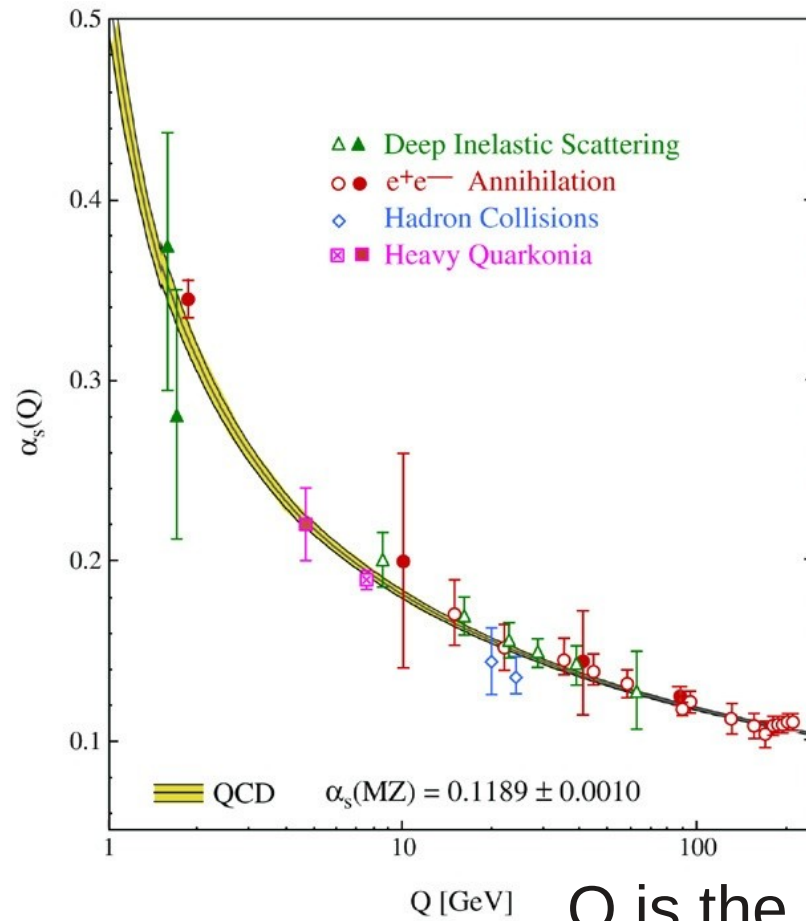


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a ‘corkscrew’ line to distinguish it from a photon. In this diagram the quark flavour u or s is unchanged on gluon emission, but the colour state can change, as shown.

The coupling is not fixed but runs!

α_s



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

Screening/running of the coupling in electromagnetic collisions

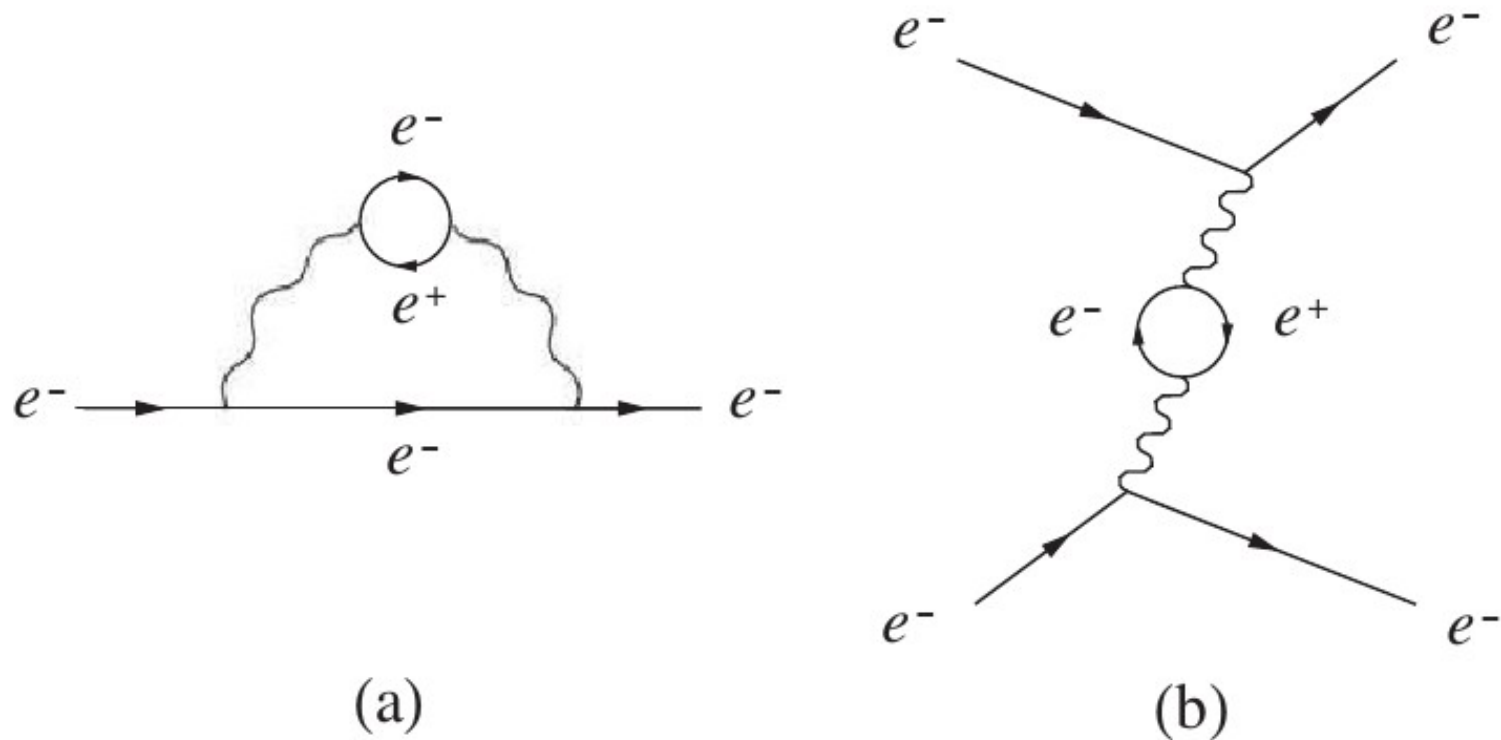


Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

Due to (polarized) fluctuations the vacuum screens the charge!
(vacuum \sim dielectric medium)

Notice the order: -, +, -!

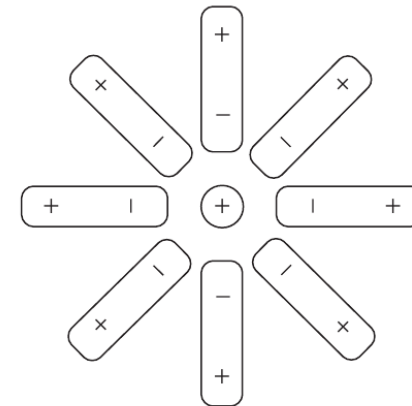
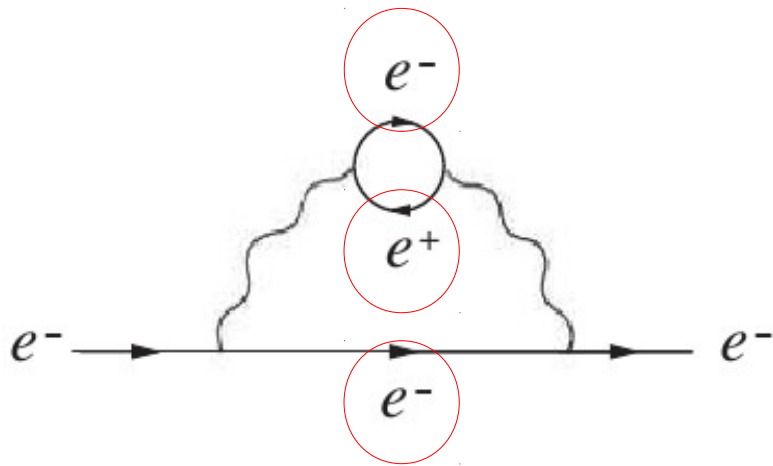


Figure 7.6 Schematic diagram representing the polarization of the molecules of a dielectric by a positive charge placed within it.

The effect is measurable:

At low energy; $\alpha \sim 1/137$

At high energy transfers (mZ): $\alpha \sim 1/127$

This change is fully described by the theory!

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

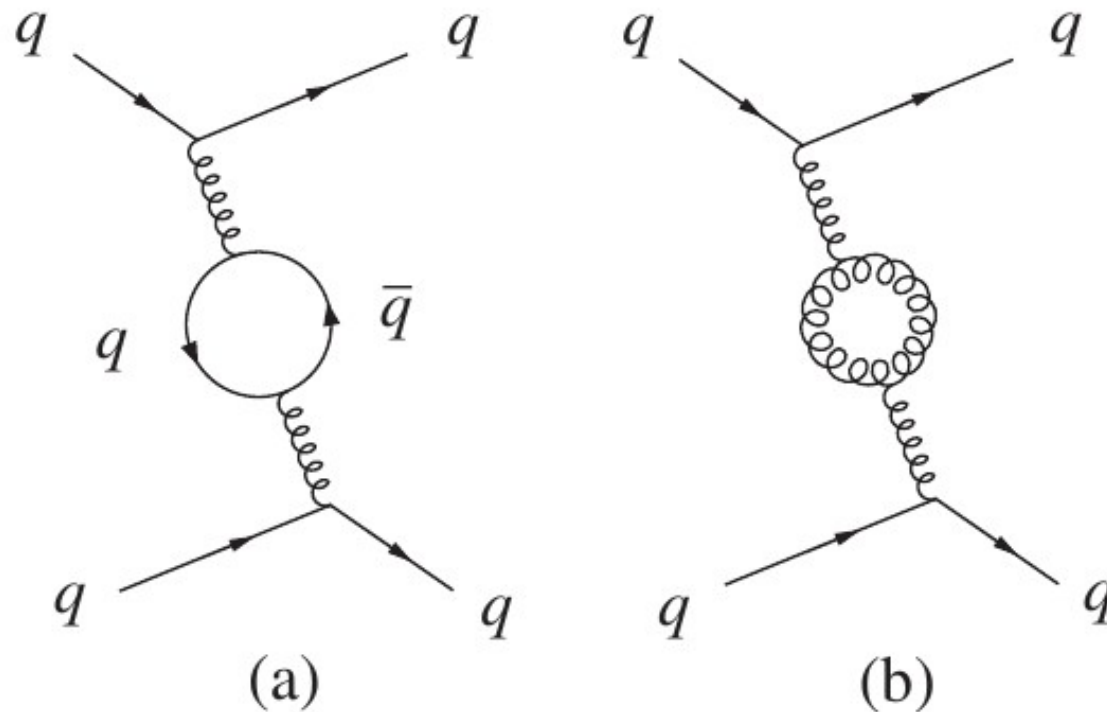
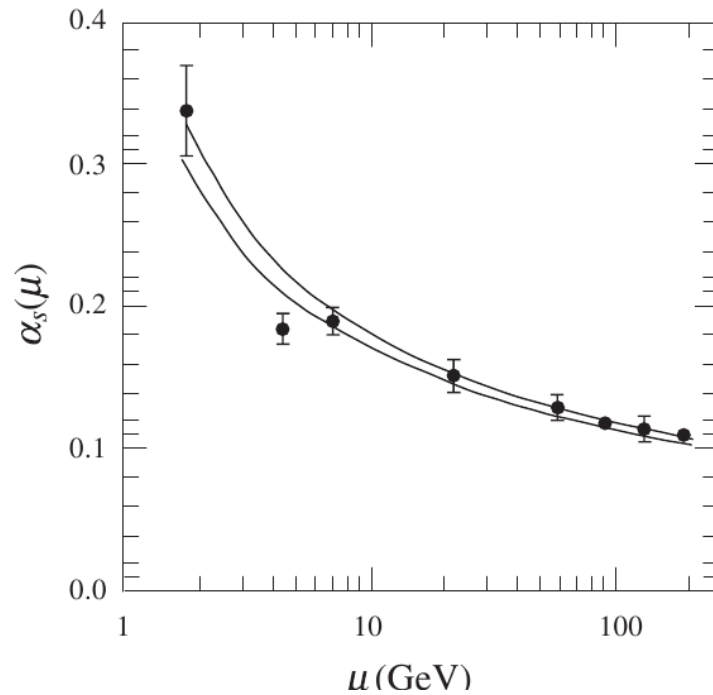


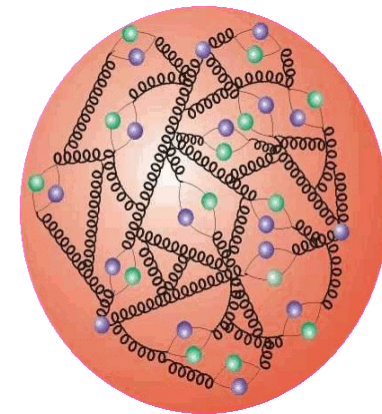
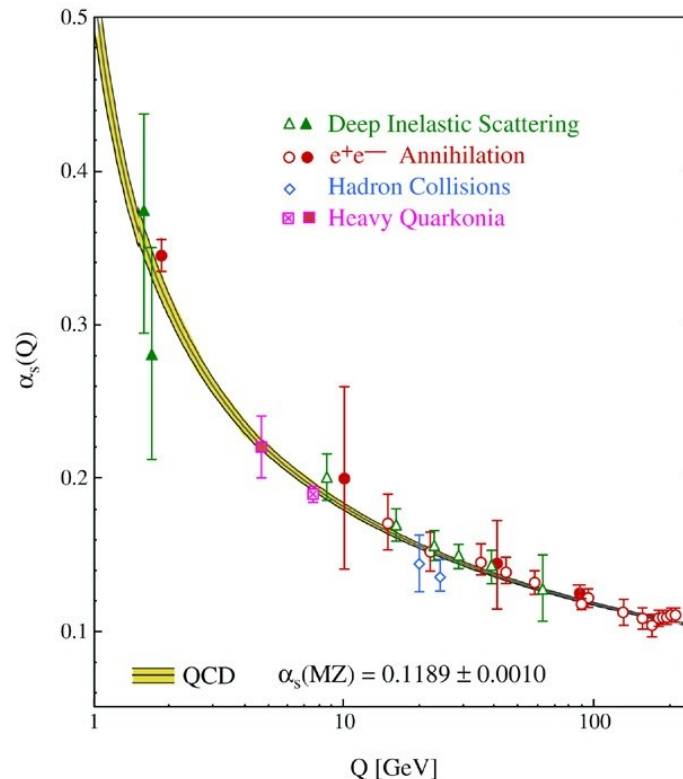
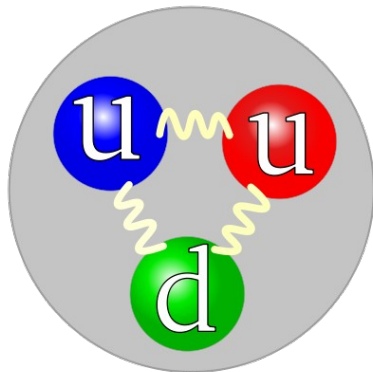
Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

Full result for QCD



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

2 limits of QCD: soft and hard!



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

Perturbative physics
(theoretical predictions)
Example: Quark scatterings

Example of 2 jet event

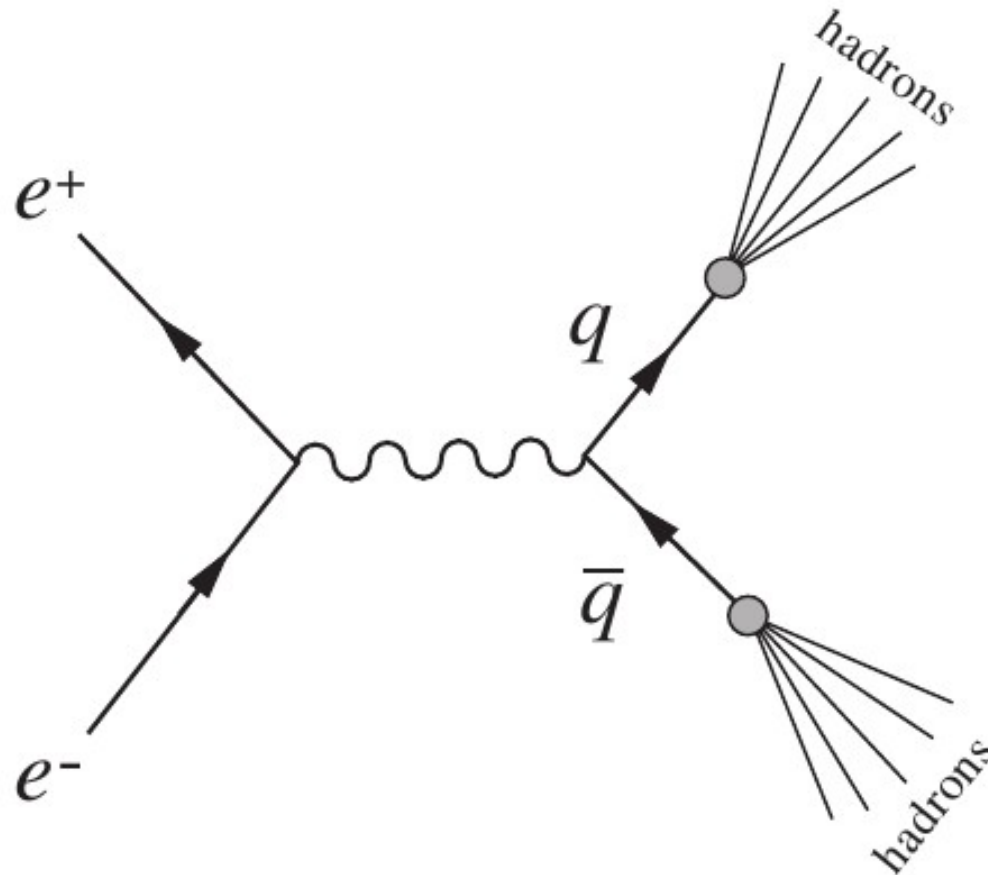
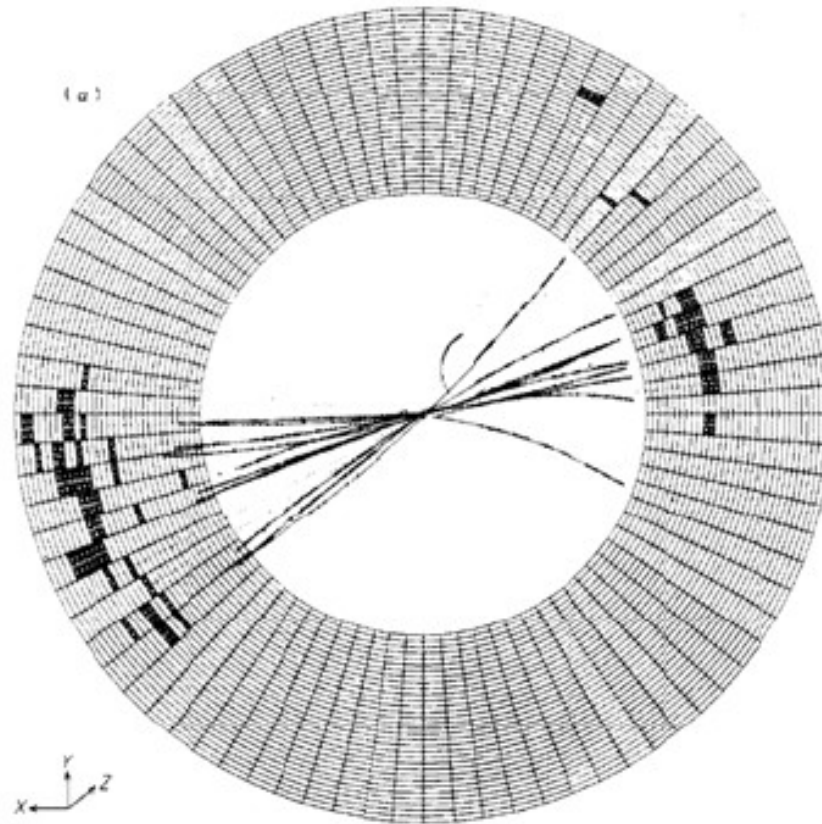


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

2 jet event in e^+e^-



What about the ratio?

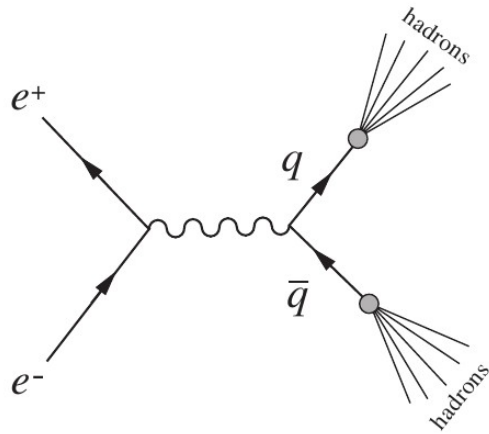


Figure 7.10 Basic mechanism of two-jet production in electron-positron annihilation.

= ?

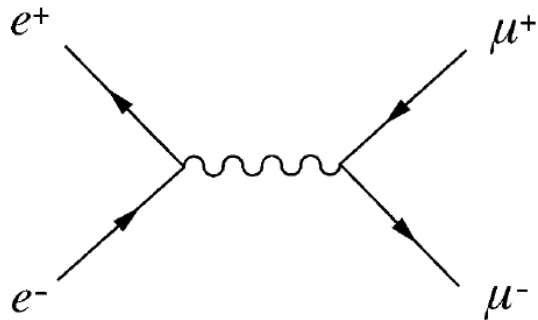


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

The charge difference

Three generations of matter (fermions)

	I	II	III
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name	u up	c charm	t top
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
Quarks	d down	s strange	b bottom
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²
	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
Leptons	e electron	μ muon	τ tau

$$q = +\frac{2}{3}$$

$$q = -\frac{1}{3}$$

$$q = -1$$

- Due to different charges:
- $A \sim q$
- $P \sim q^2$
- $P_{qq} \sim \frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9}$
(up to threshold)
- $P_{\mu\mu} \sim 1$
- Ratio: $\frac{11}{9}$

What about the ratio?

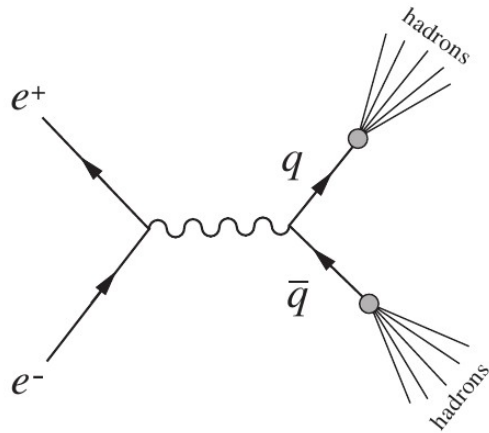


Figure 7.10 Basic mechanism of two-jet production in electron-positron annihilation.

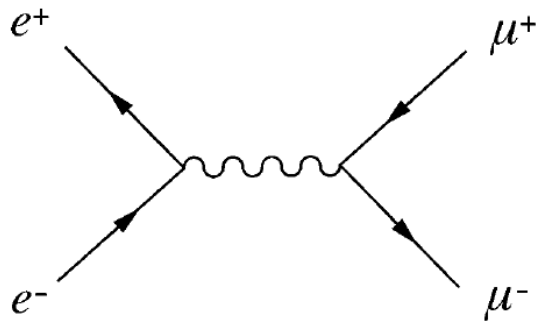


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

$R \neq 11/9$

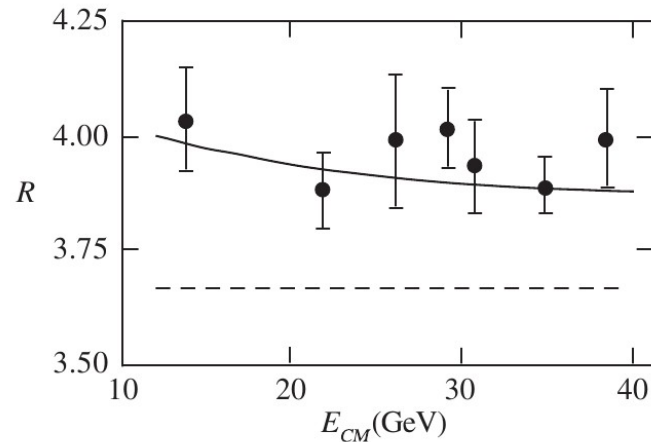
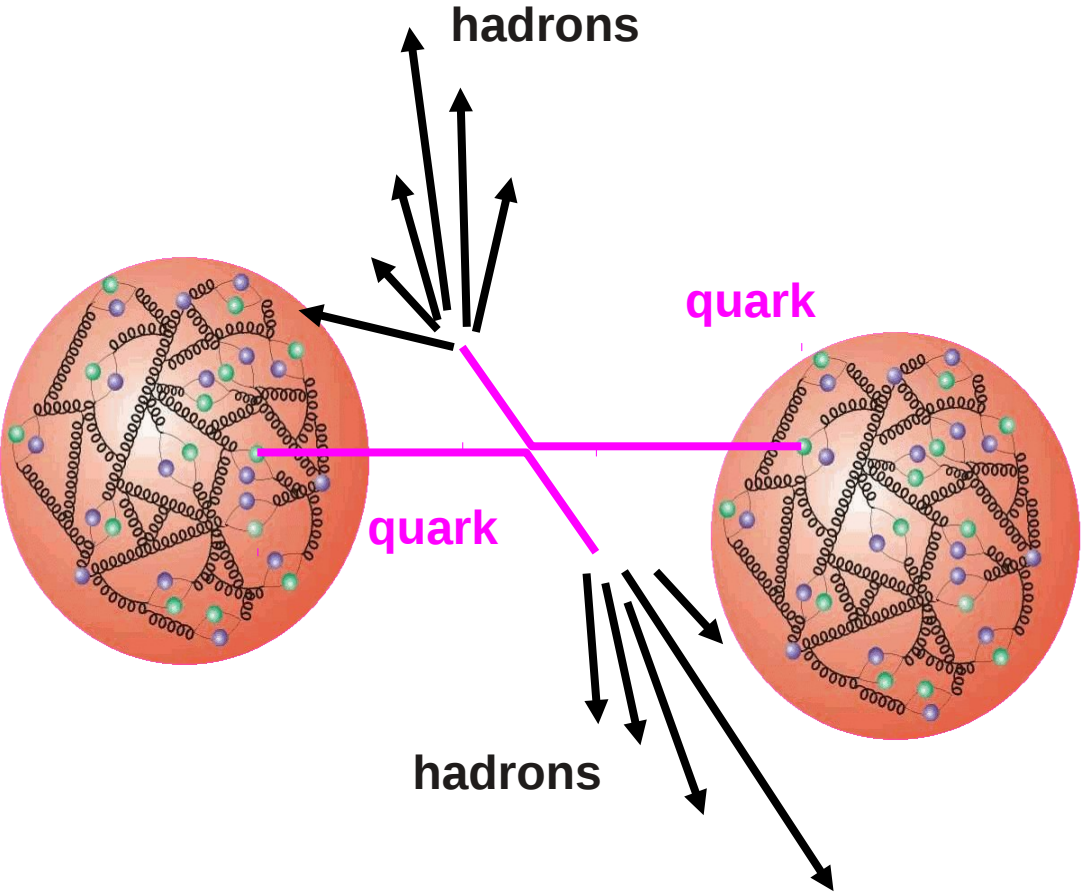


Figure 7.16 Comparison between the measured values of the cross-section ratio R of Equation (7.18) and the theoretical prediction (7.22) for three colours, $N_c = 3$. The dashed line shows the corresponding prediction (7.21) omitting small contributions of order α_s . (Data from the compilations of Wu,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

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

Proton-proton 2 jet event



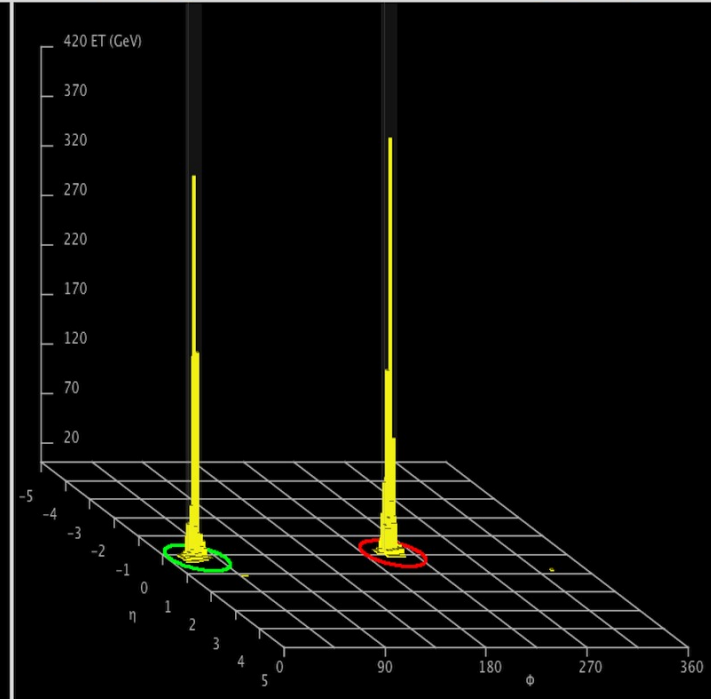
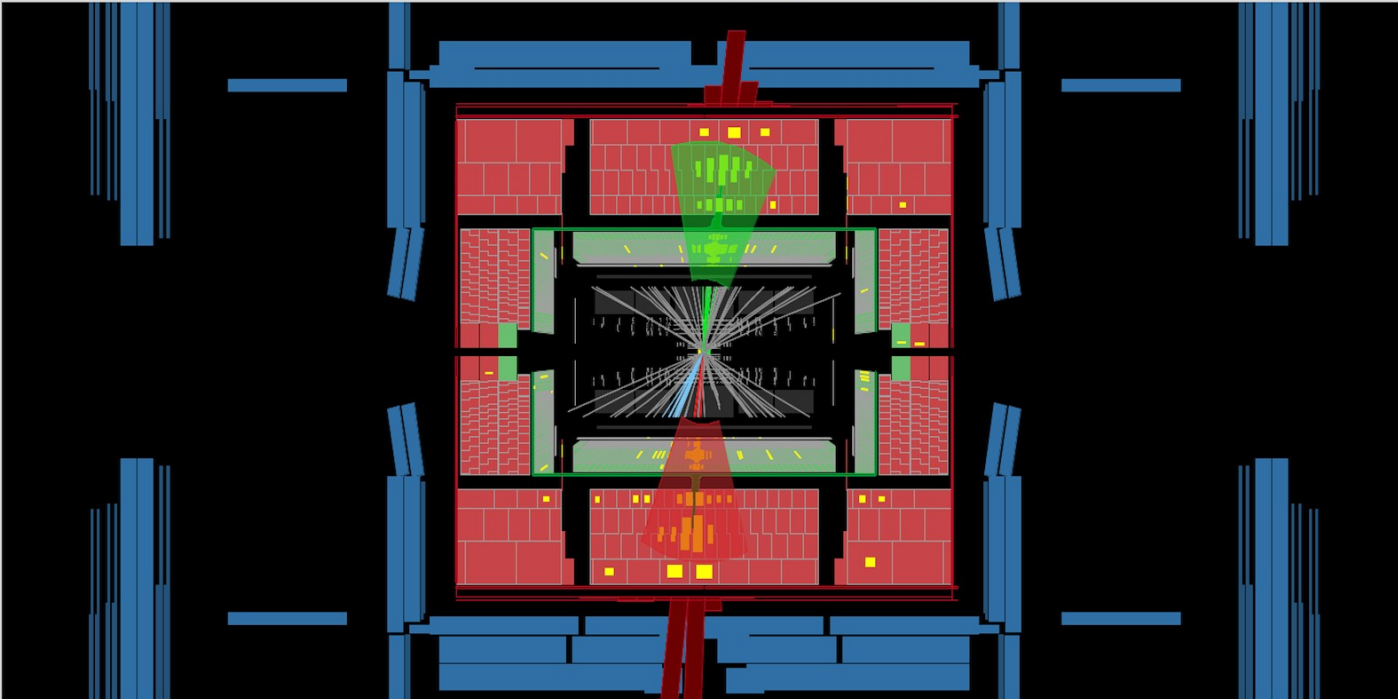
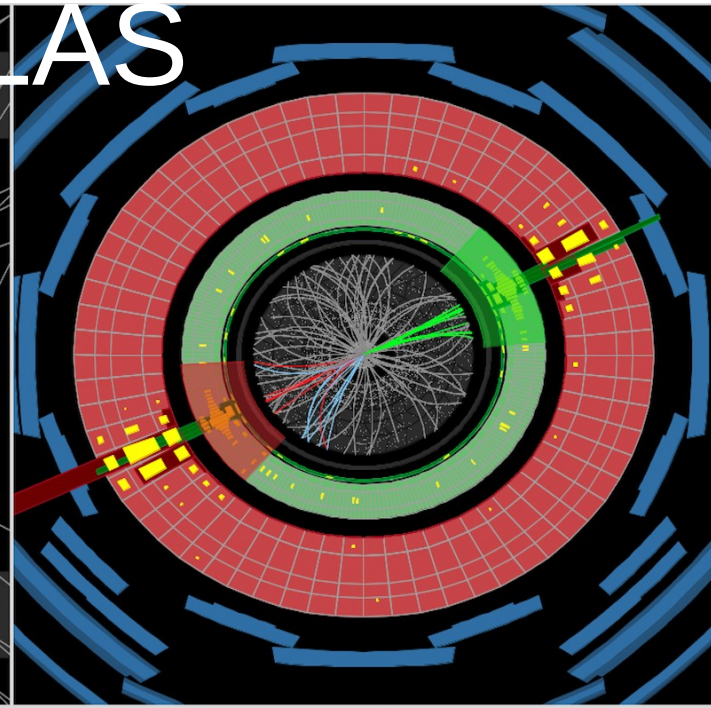
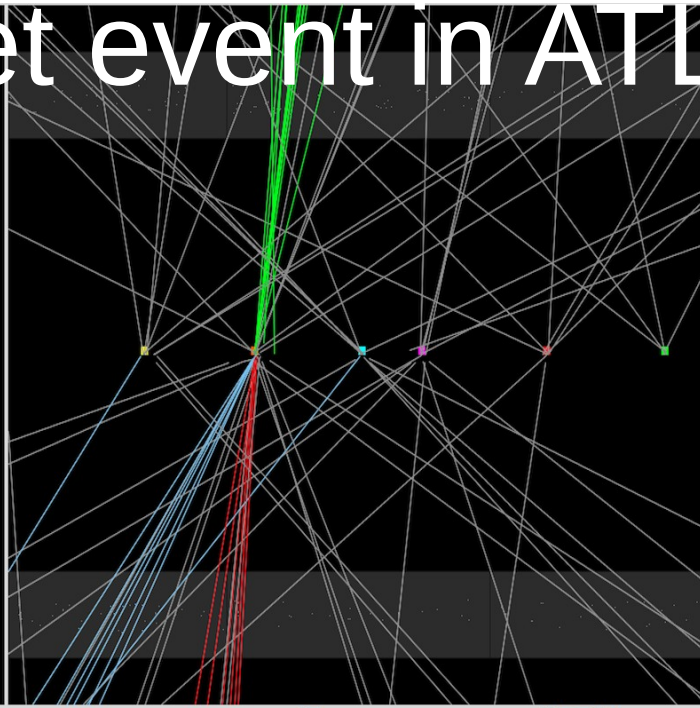
2 jet event in ATLAS



ATLAS EXPERIMENT

Run Number: 201006, Event Number: 55422459

Date: 2012-04-09 14:07:47 UTC



3 jet event: hard gluon

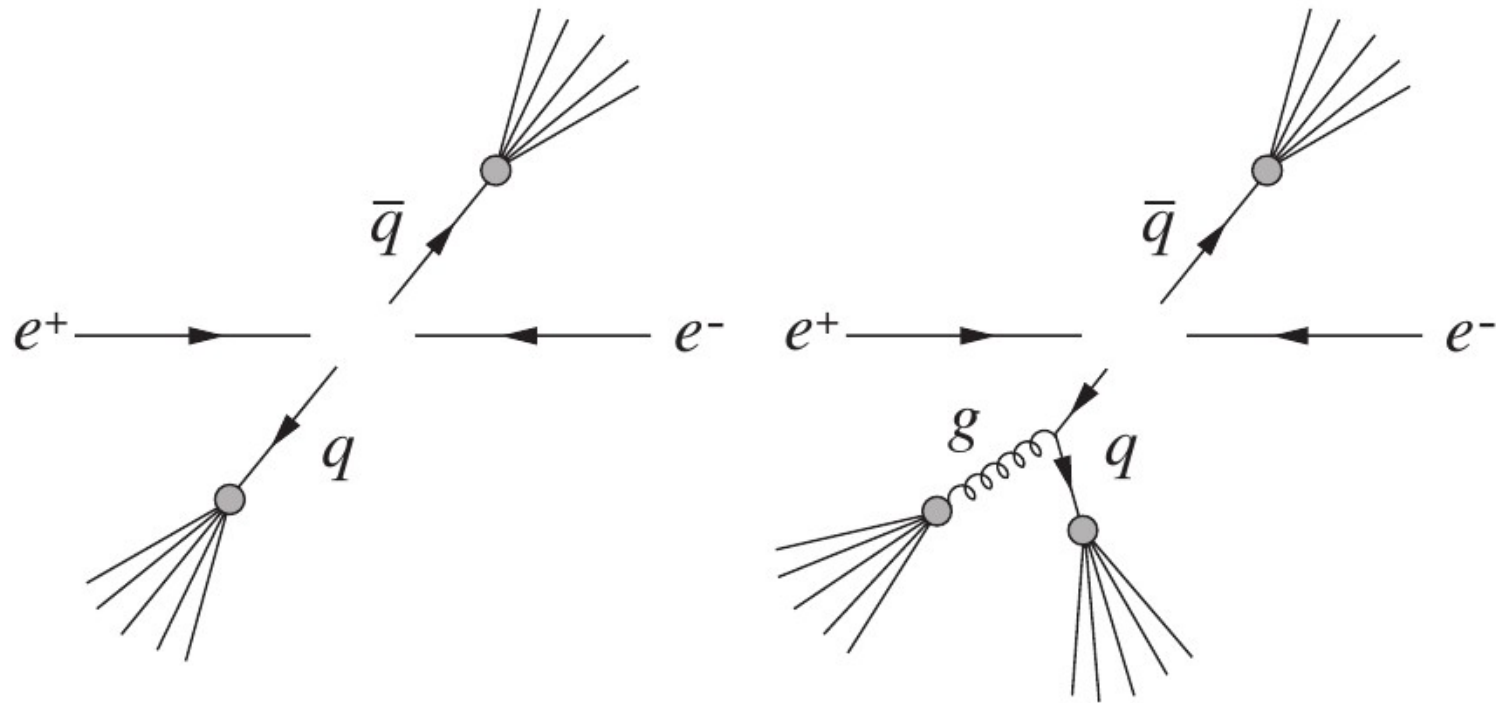
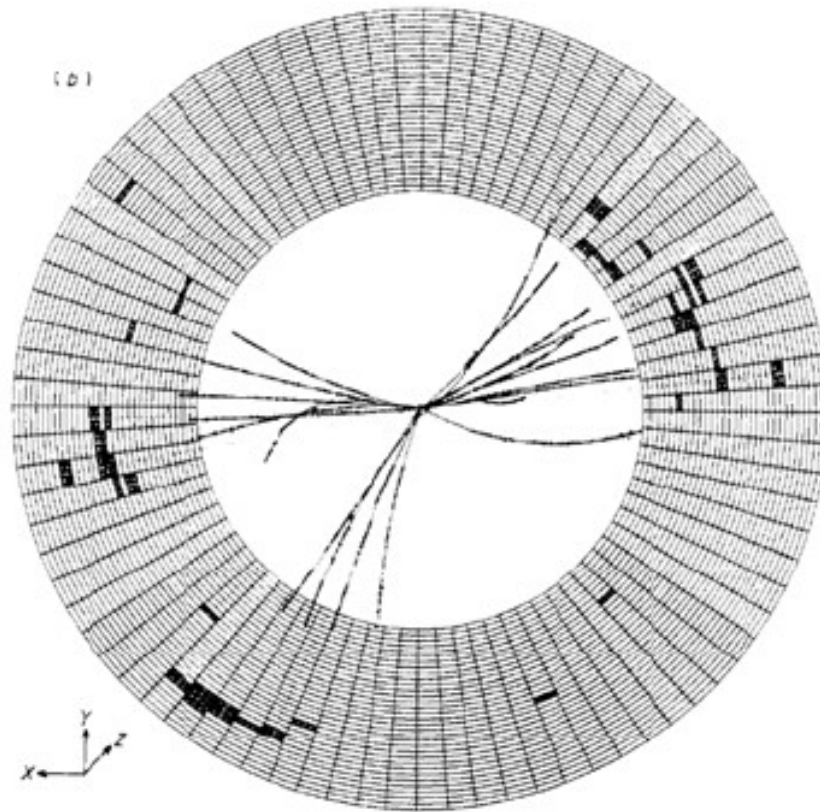


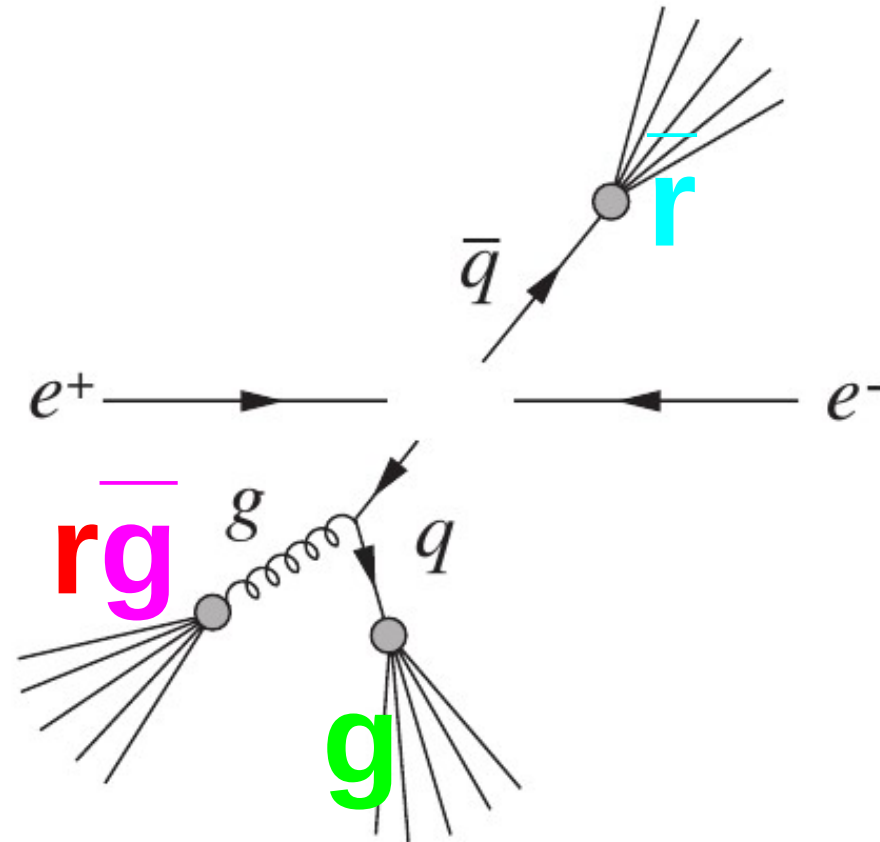
Figure 7.13 Schematic diagrams representing (a) two-jet and (b) three-jet formation in electron-positron annihilation in the centre-of-mass frame.

3 jet event in e^+e^-

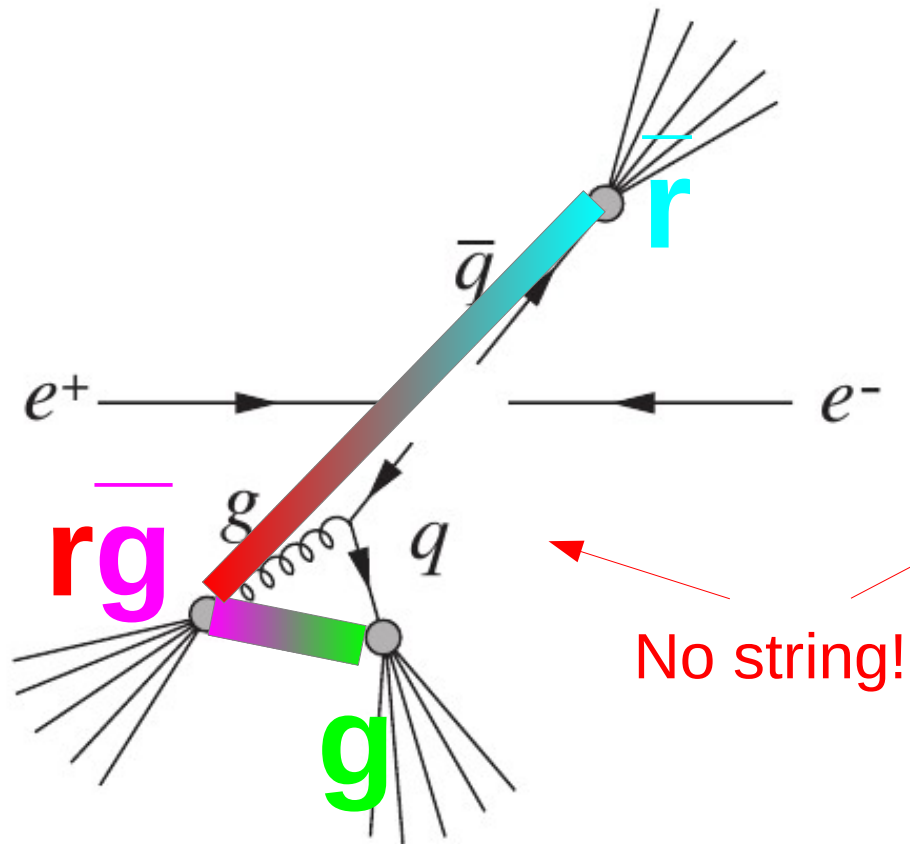


A simple look at fragmentation

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



What happens when you have a 3 jet event!



No string!

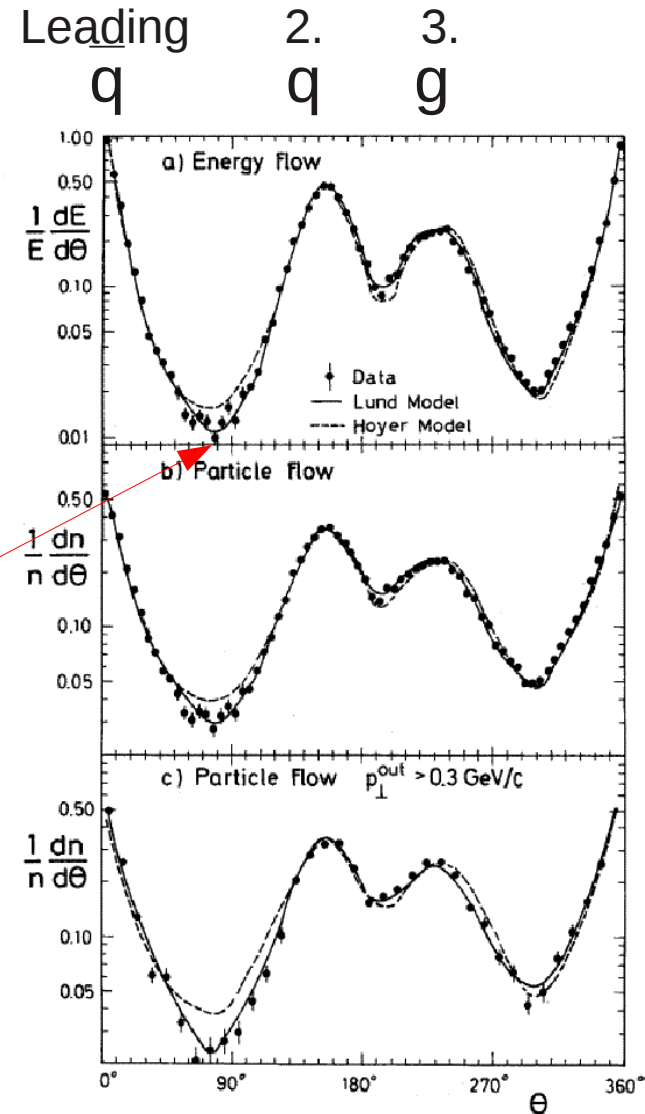
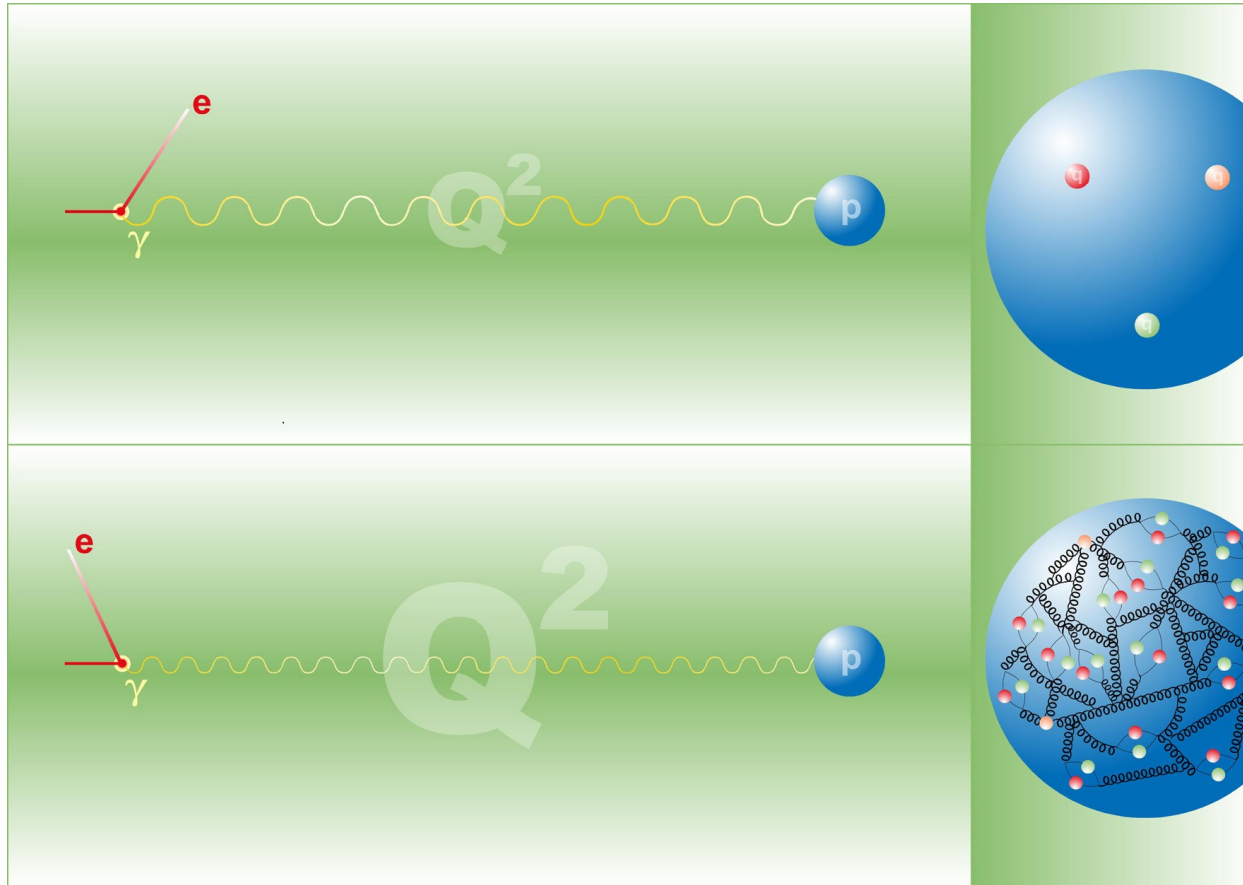


Figure from Leif's notes

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

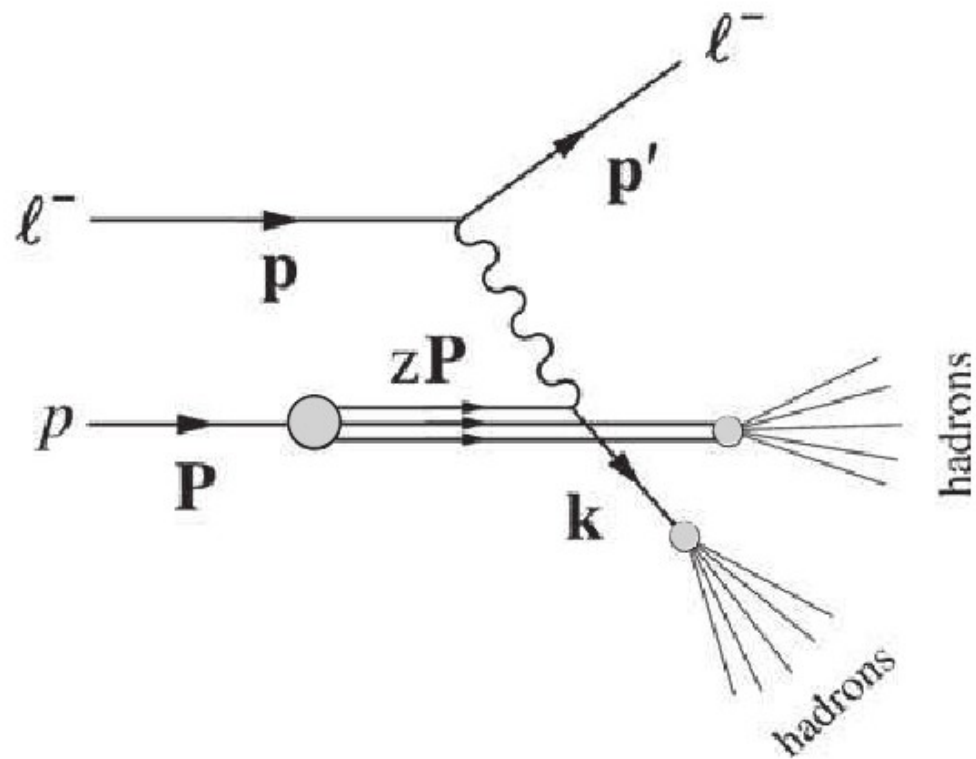


Figure 7.20 Dominant contribution to deep inelastic lepton–proton scattering in the quark model, where $\ell = e$ or μ .

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

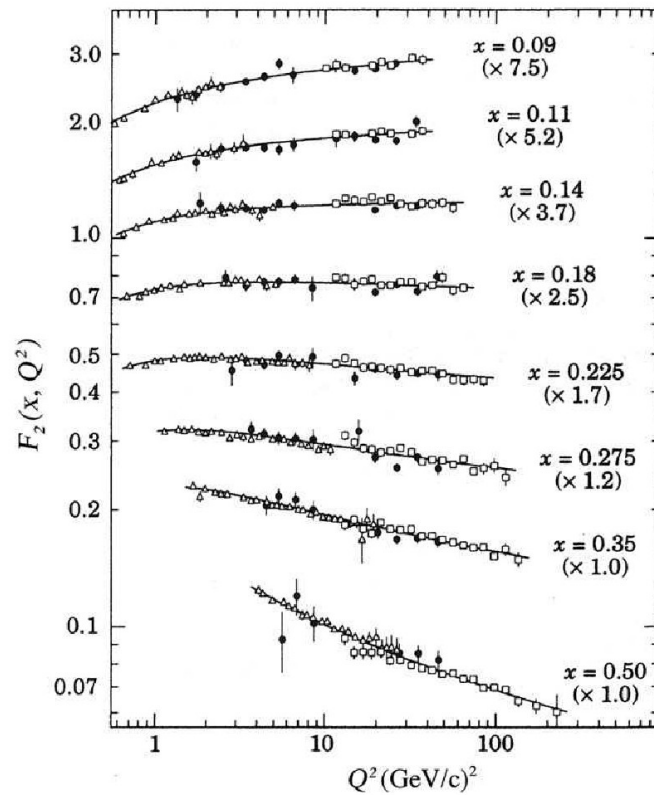
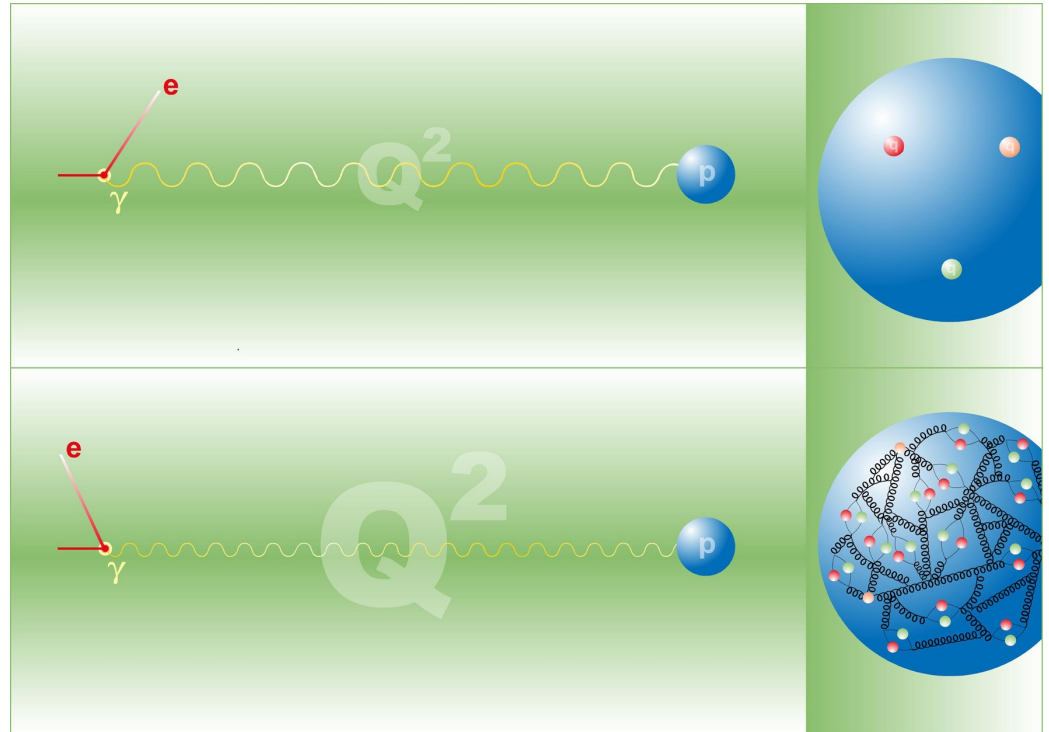


Figure 7.21 Measured values of the structure function $F_2(x, Q^2)$ from a deep inelastic scattering experiment using muons. The data points at the lower x values have been multiplied by the factors in brackets so that they can be displayed on a single diagram. (Reprinted Figure 32 with permission from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



What do we learn?

No Q dependence \rightarrow Quarks have no structure

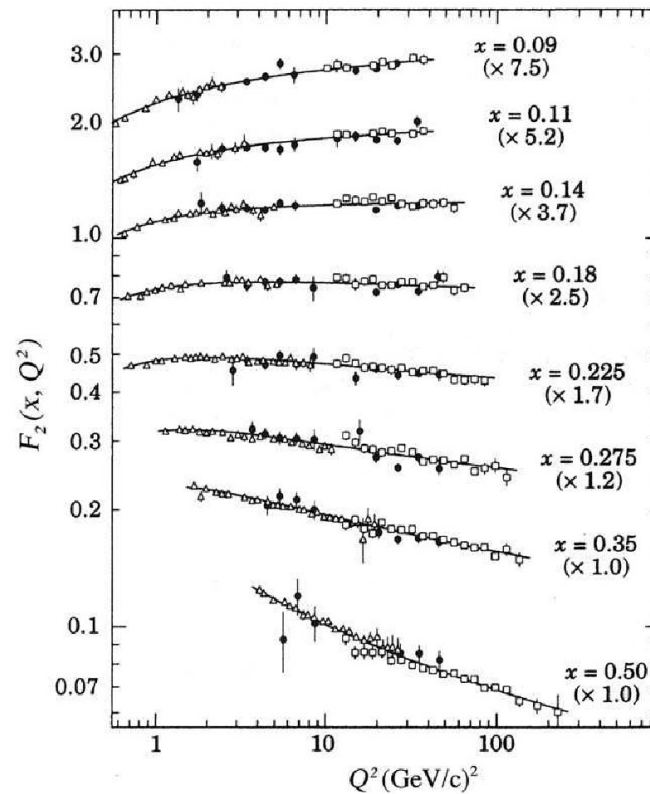


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The small Q dependence is due to gluons

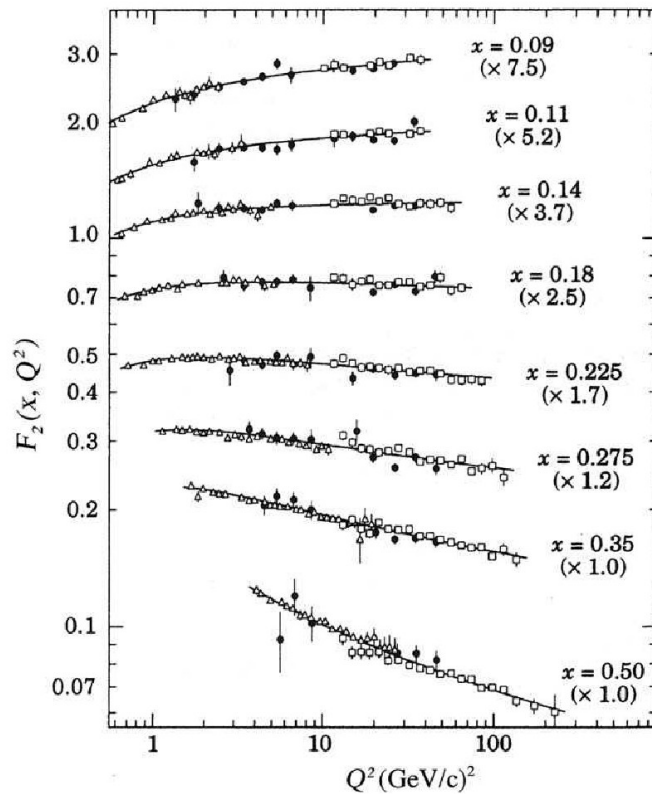


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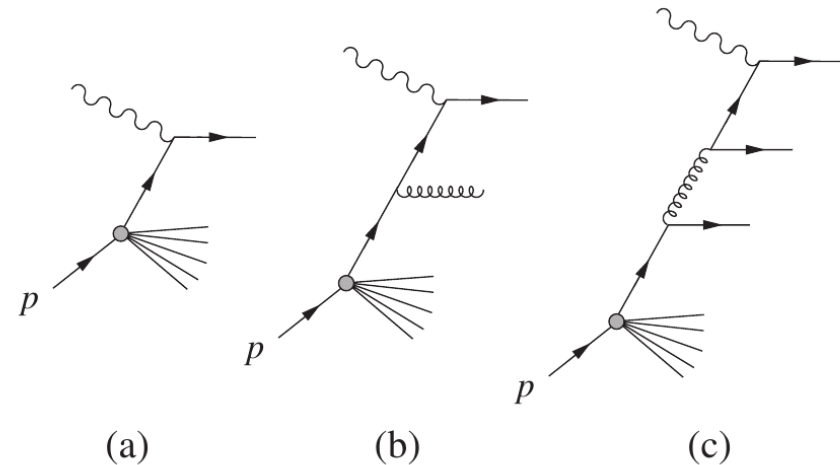


Figure 7.22 (a) The interaction of the exchanged photon with the struck quark in the parton model, together with (b, c) two of the additional processes that occur when quark–gluon interactions are taken into account.



Number of quarks grows at small x

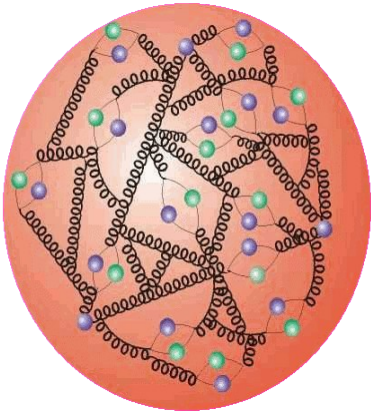
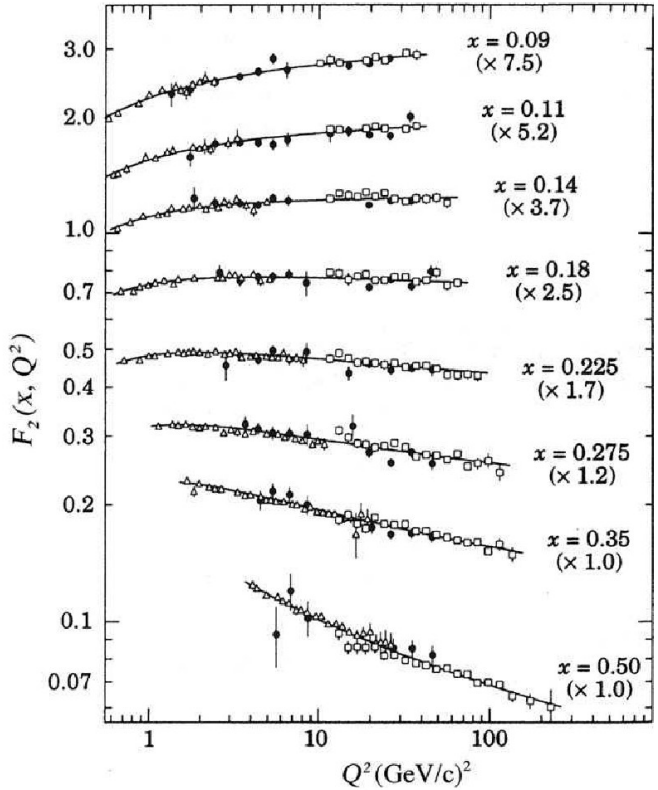
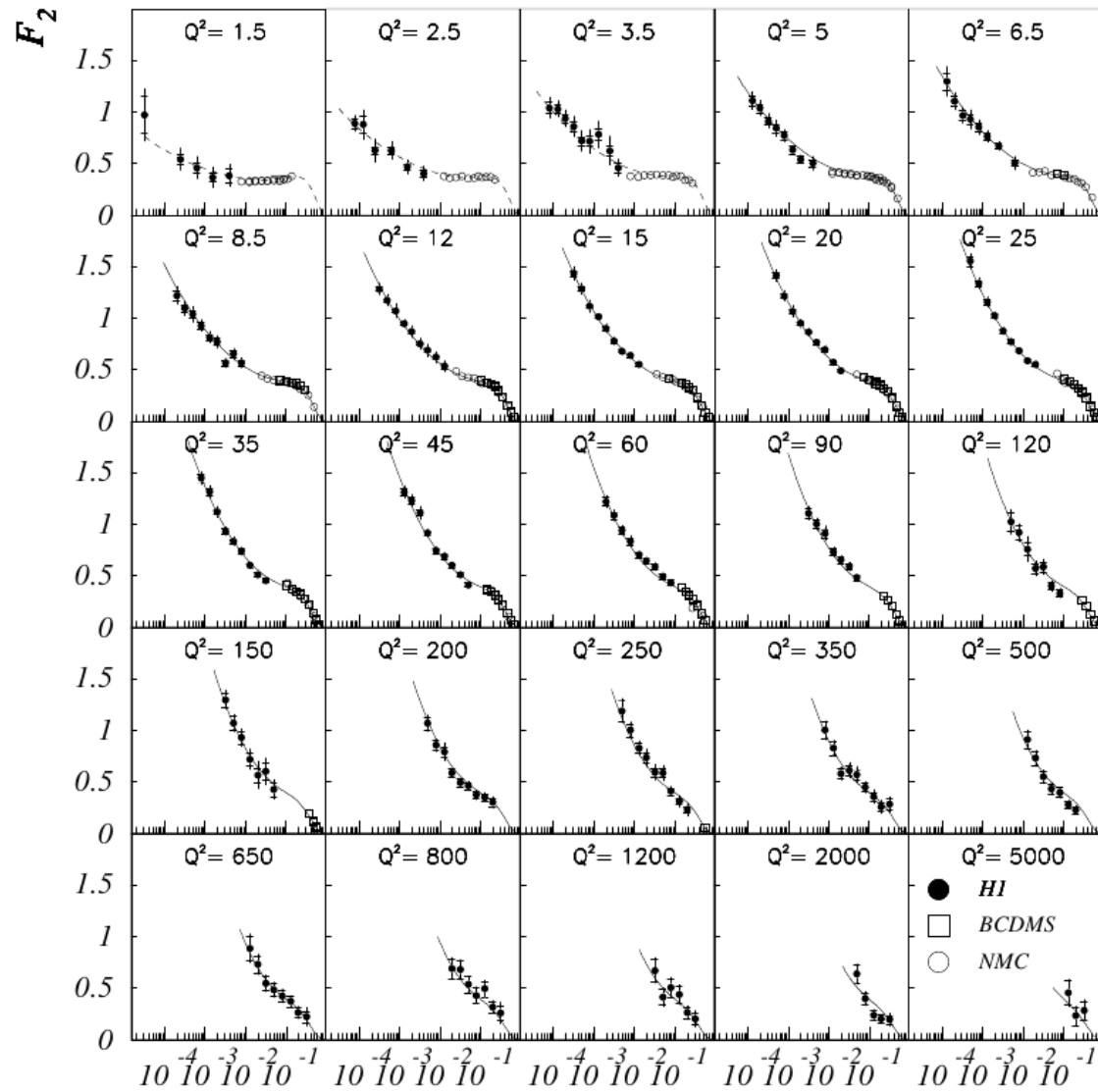
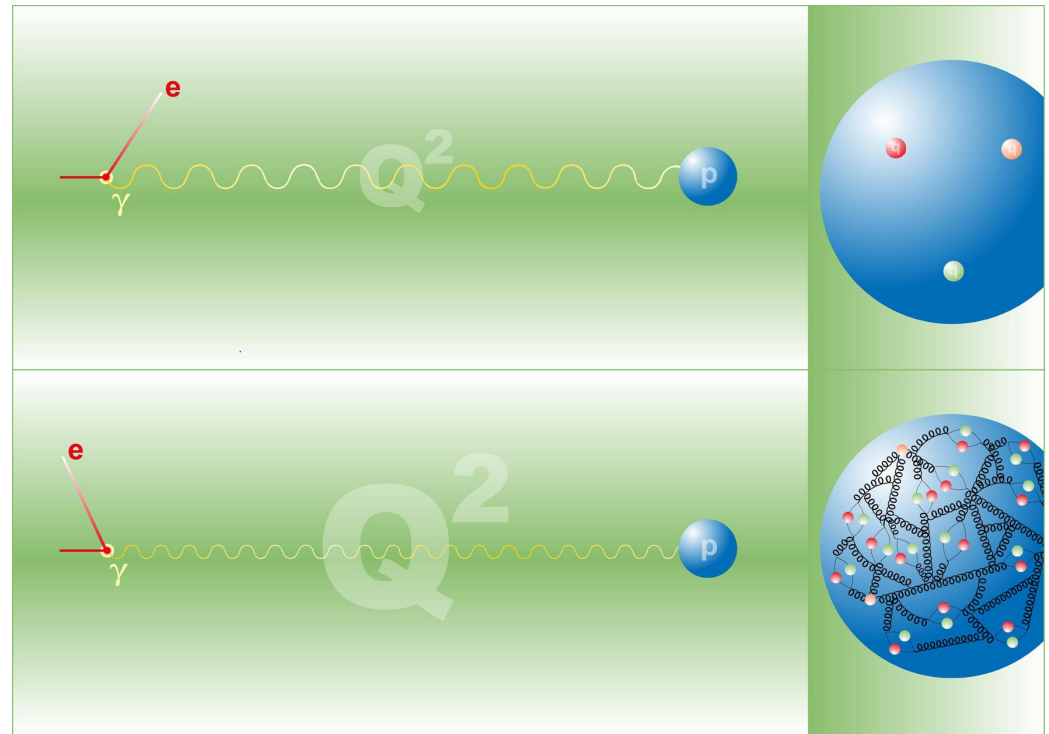
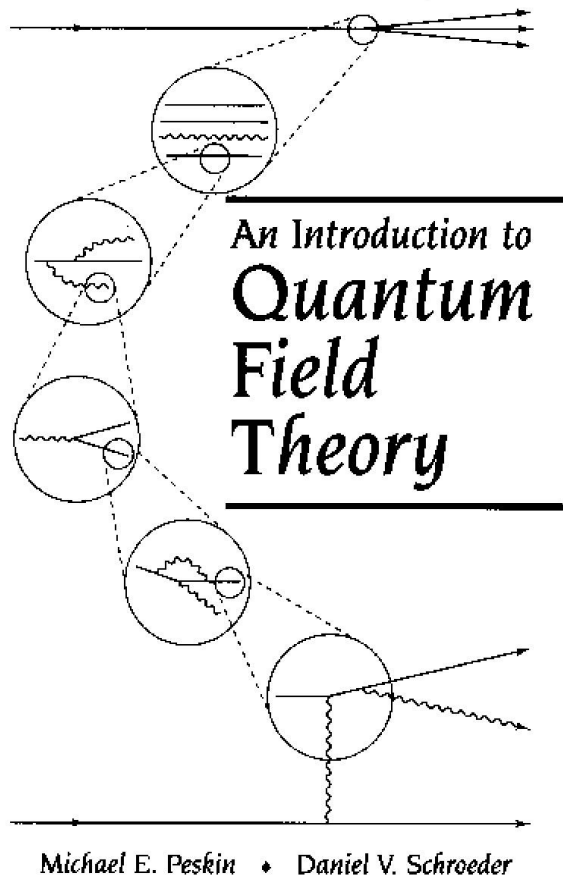


Figure 7.21 Measured values of the structure function $F_2(x, Q^2)$ from a deep inelastic scattering experiment using muons. The data points at the lower x values have been multiplied by the factors in brackets so that they can be displayed on a single diagram. (Reprinted Figure 32 with permission from 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

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

$$F_2(x, Q^2) = \sum_a e_a^2 x f_a(x), \quad (7.56)$$

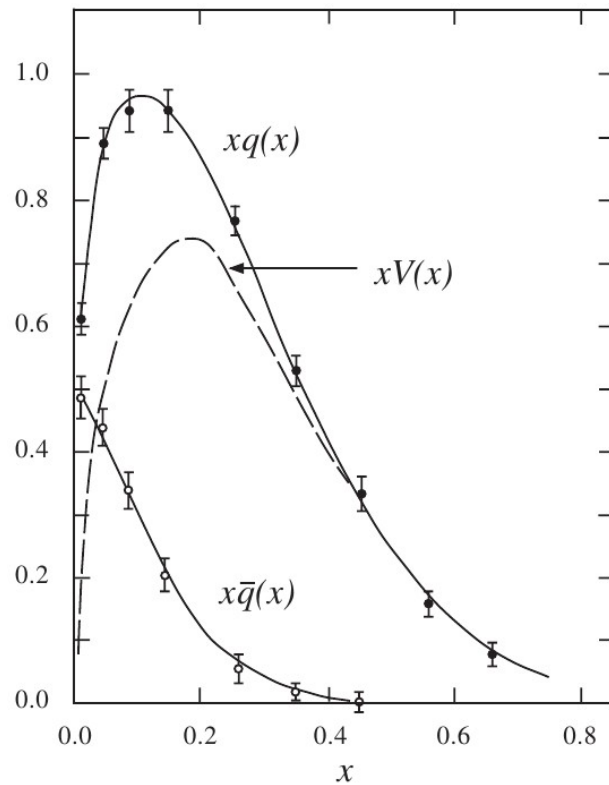
~~$$F_1(x, Q^2) = 0 \quad (\text{spin} - 0) \quad (7.57a)$$~~

and

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

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

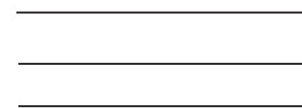
Result: information about the proton structure



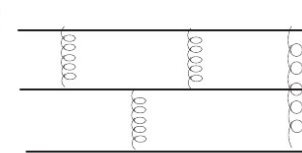
One quark:



Three quarks:



Three interacting quarks:



Valence quarks + sea quarks:

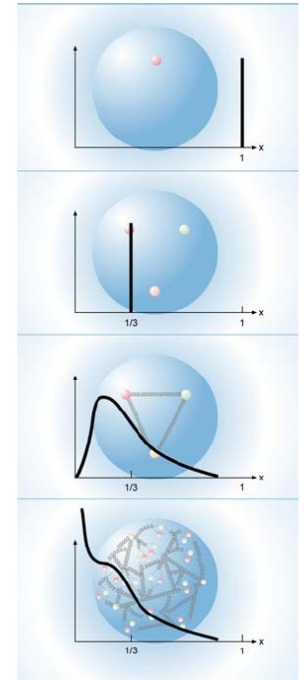
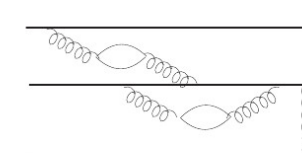


Figure 7.23 Quark and antiquark distributions (7.59a), together with the valence quark distribution (7.59b), measured at a Q^2 value of about 10GeV^2 , from neutrino experiments at CERN and Fermilab.

Result: 50% of energy carried by valence quarks

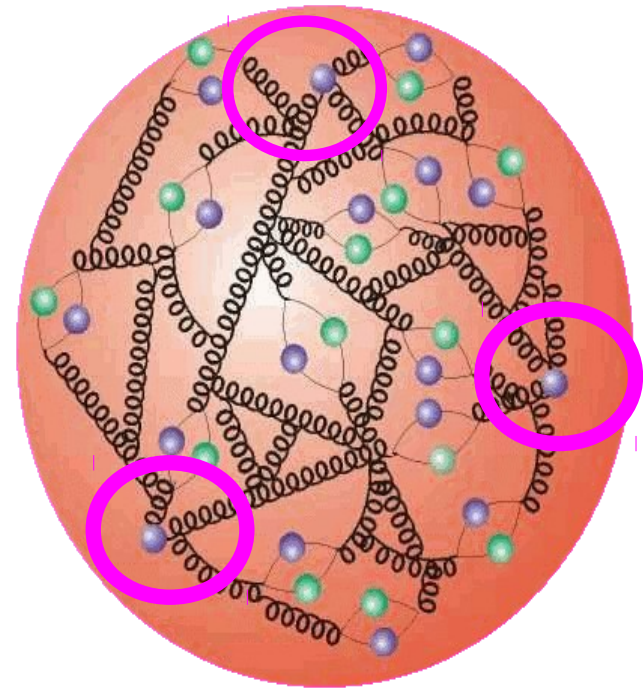
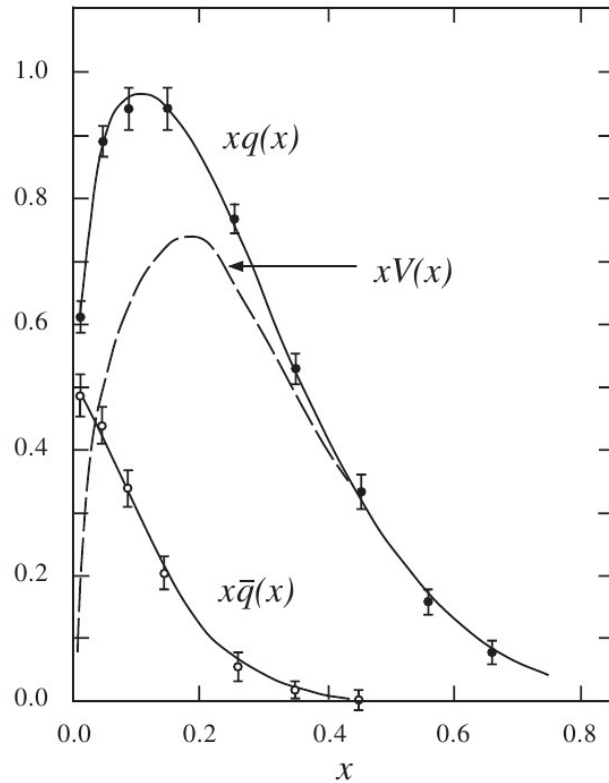


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