FYSC14 compulsory elements (reminder)

Hopefully done:

Tuesday 2/4 (introduction)

Thursday 18/4 (lab-prep)

Thursday 25/4 (lab-prep)

Lab period 2 (Separate 2.5 hp grade)

Two written assignments to be handed in (25% of final 5 hp grade)

To be done:

Oral exam (75% of final 5 hp grade)

All partial elements of the course: written assignment 1+2, lab, oral exam, DESY trip have to be passed for the course to be passed.

A final ECTS grade will be provided.

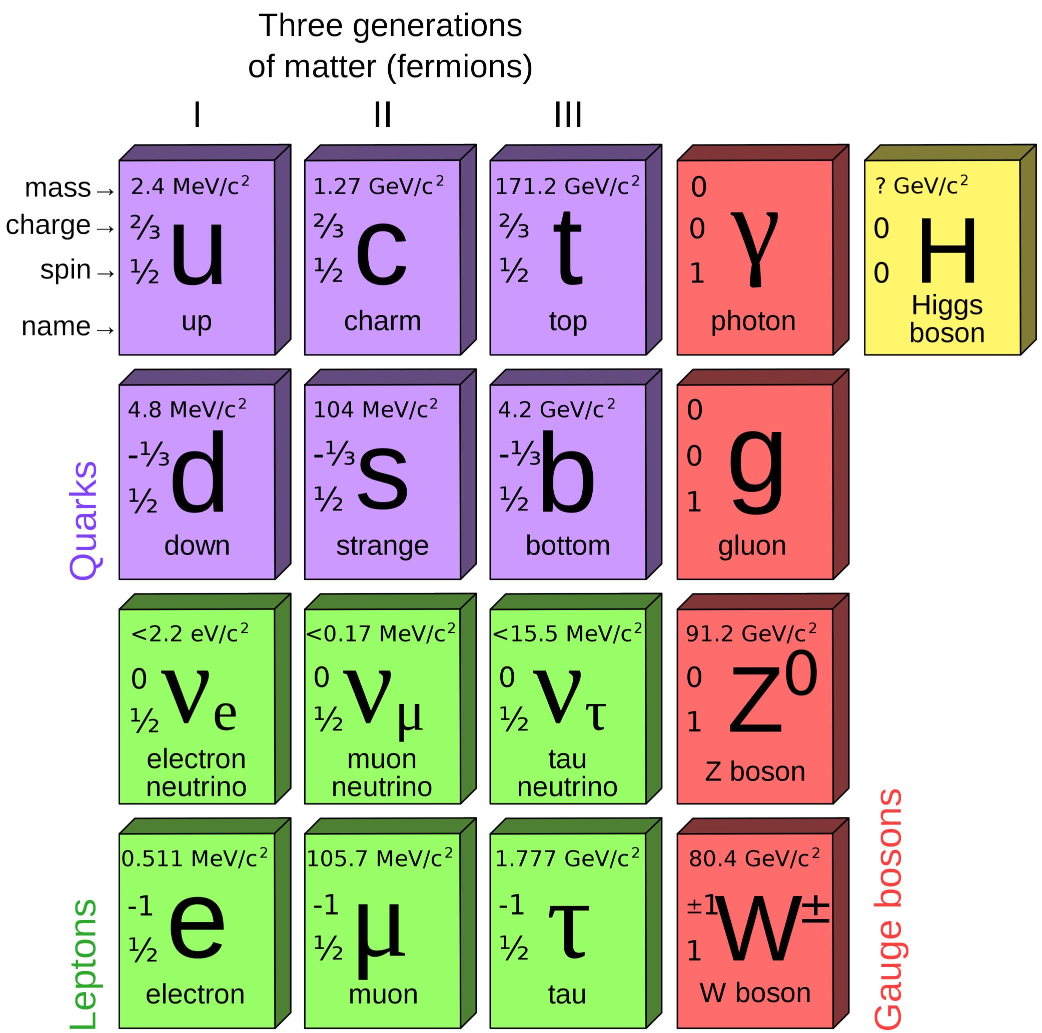
Exam sign up

- Use: http://doodle.com/v2qcw5sa33fb5rc2
- So far: 37/40 slots used
- Dates: 30/5, 31/5, 3/6, 4/6

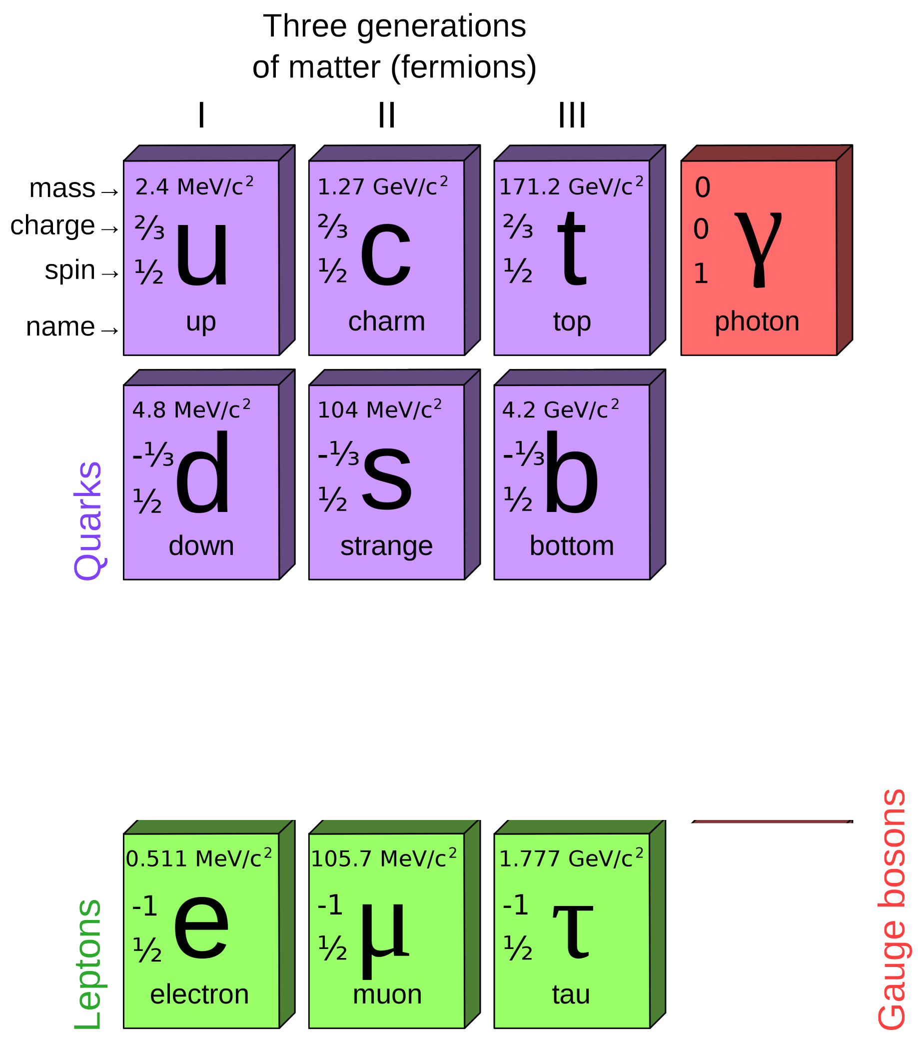
Schedule for the last week

- Monday: Summary of standard model + Higgs talk by Monika Wielers
- Tuesday: Beyond Standard Model and Cosmology
- Wednesday: Exercises are returned + BSM and Cosmology
- Thursday: BSM and Cosmology + Lund string model talk by Torbjörn Sjöstrand
- Friday: questions + test exam

The particle zoo



The EM interaction



Couples to electric charge and is mediated by virtual photons

Feynman diagram

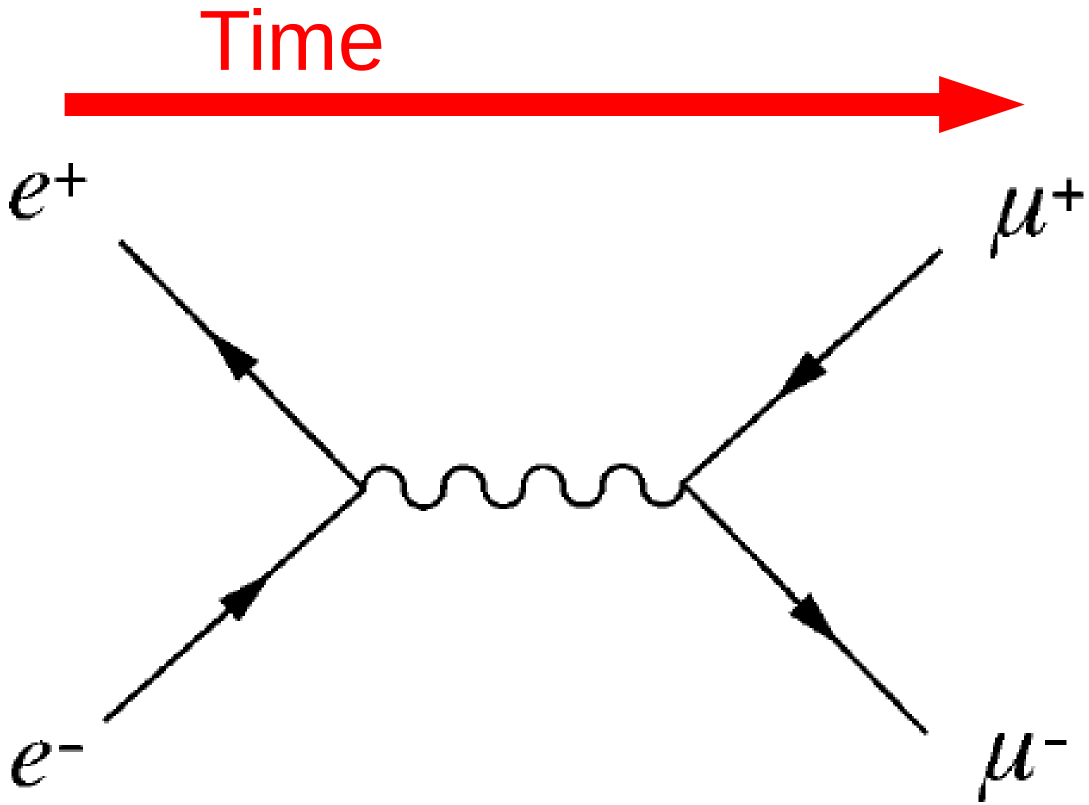


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

Feynman diagram
A calculational tool!

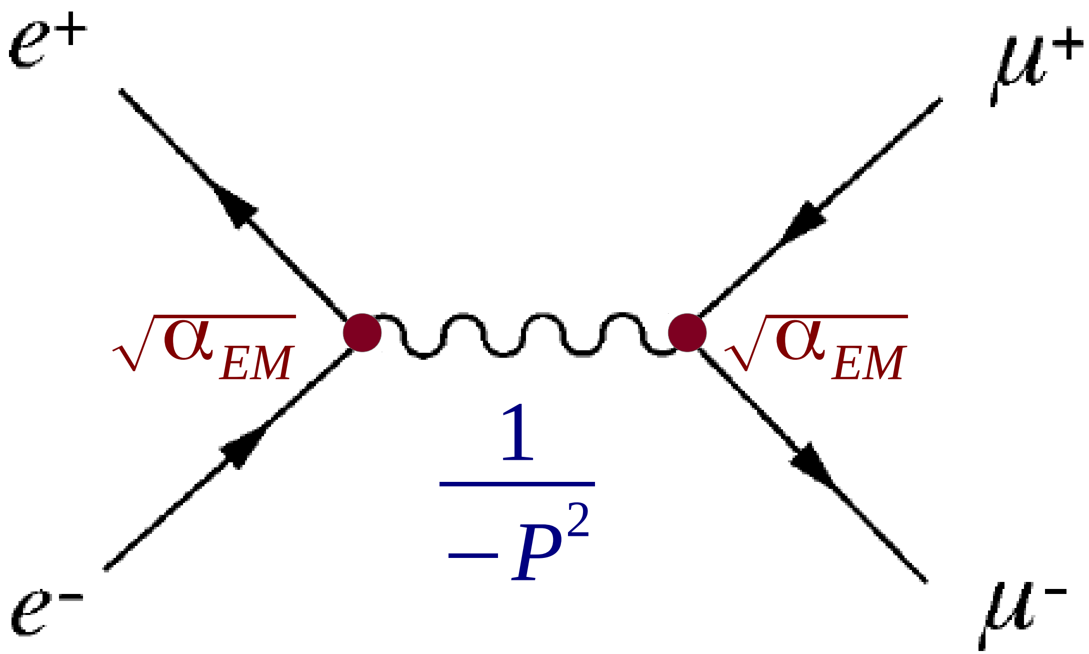


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \to \mu^+ + \mu^-$.

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

What is the microscopic picture of a force/interaction

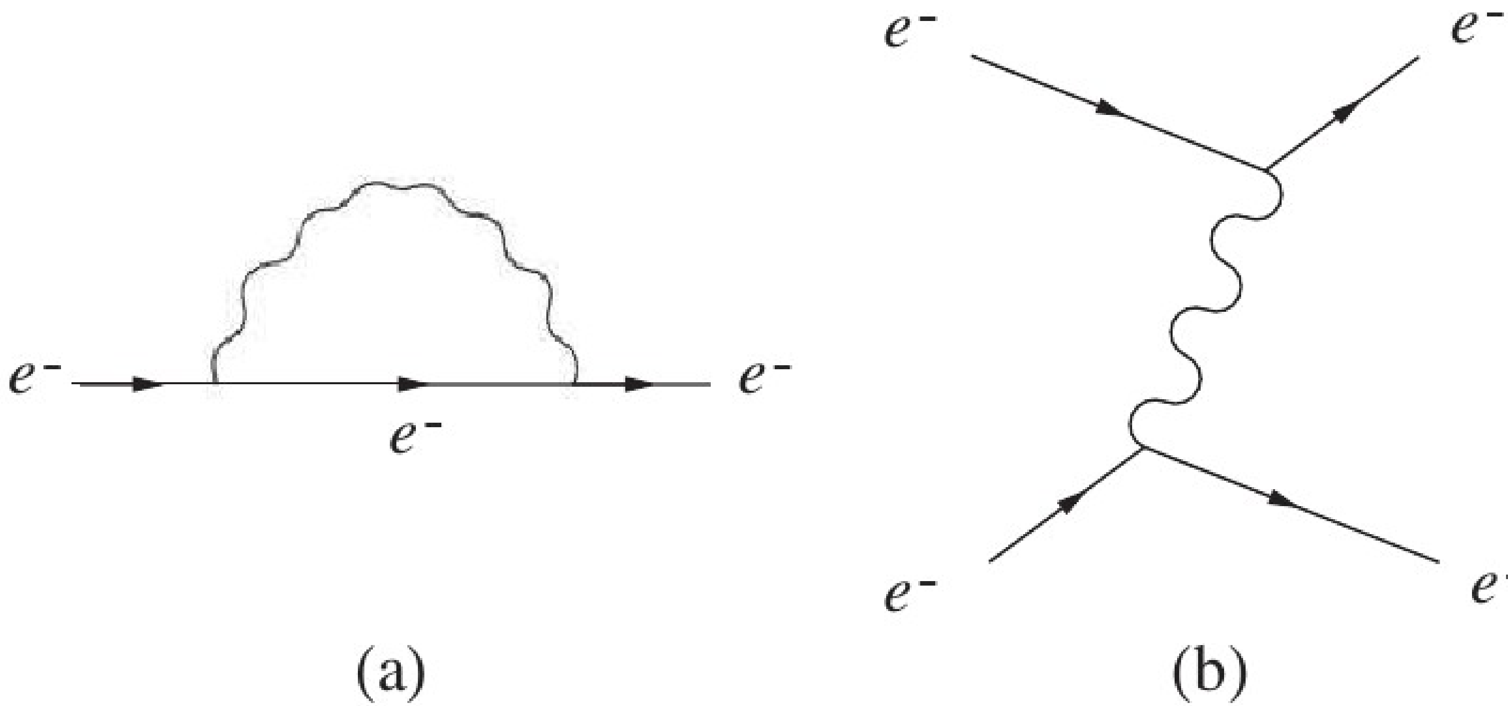


Figure 7.4 The simplest quantum fluctuation of an electron and the associated exchange process.

What is the microscopic picture of a force/interaction

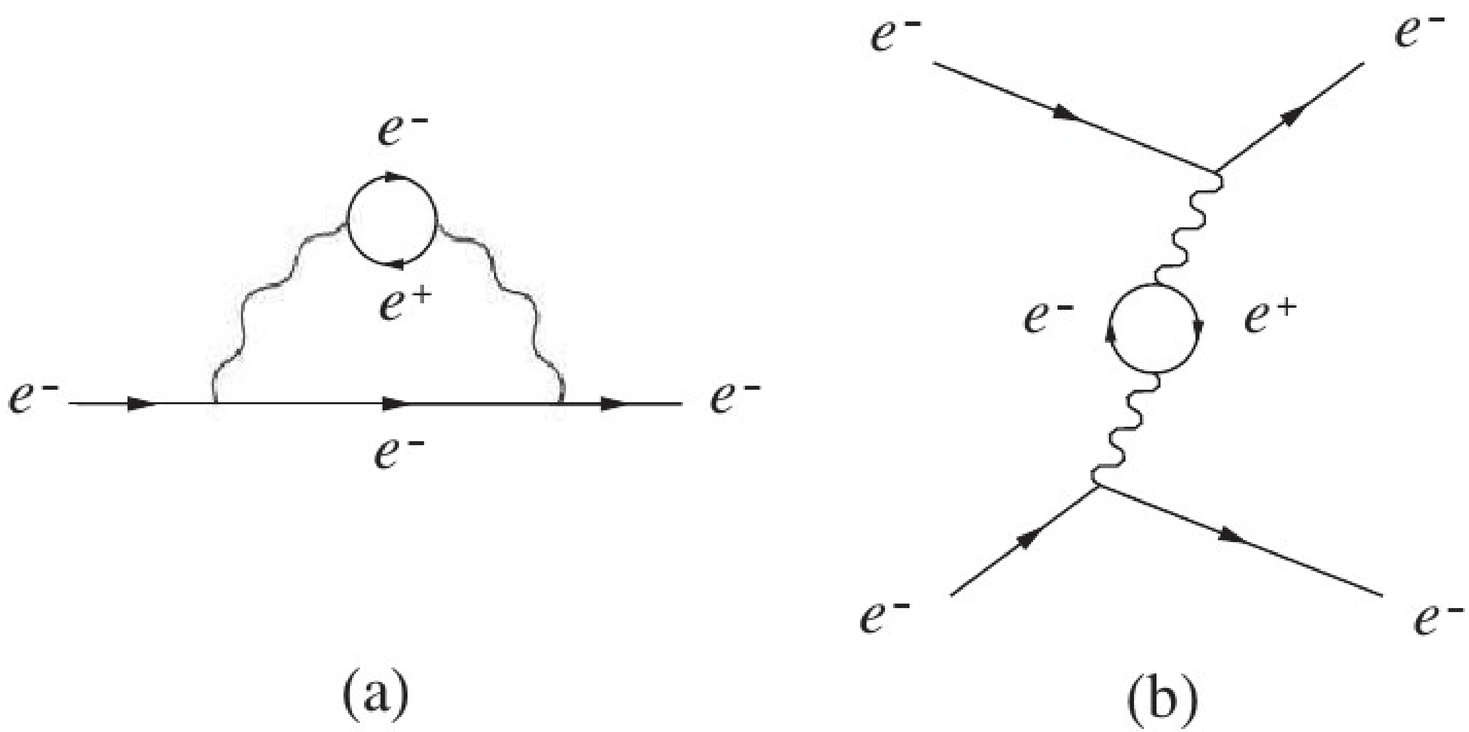


Figure 7.5 A more complicated quantum fluctuation of the electron, together with the associated exchange process.

Question: how important are these higher order diagrams?

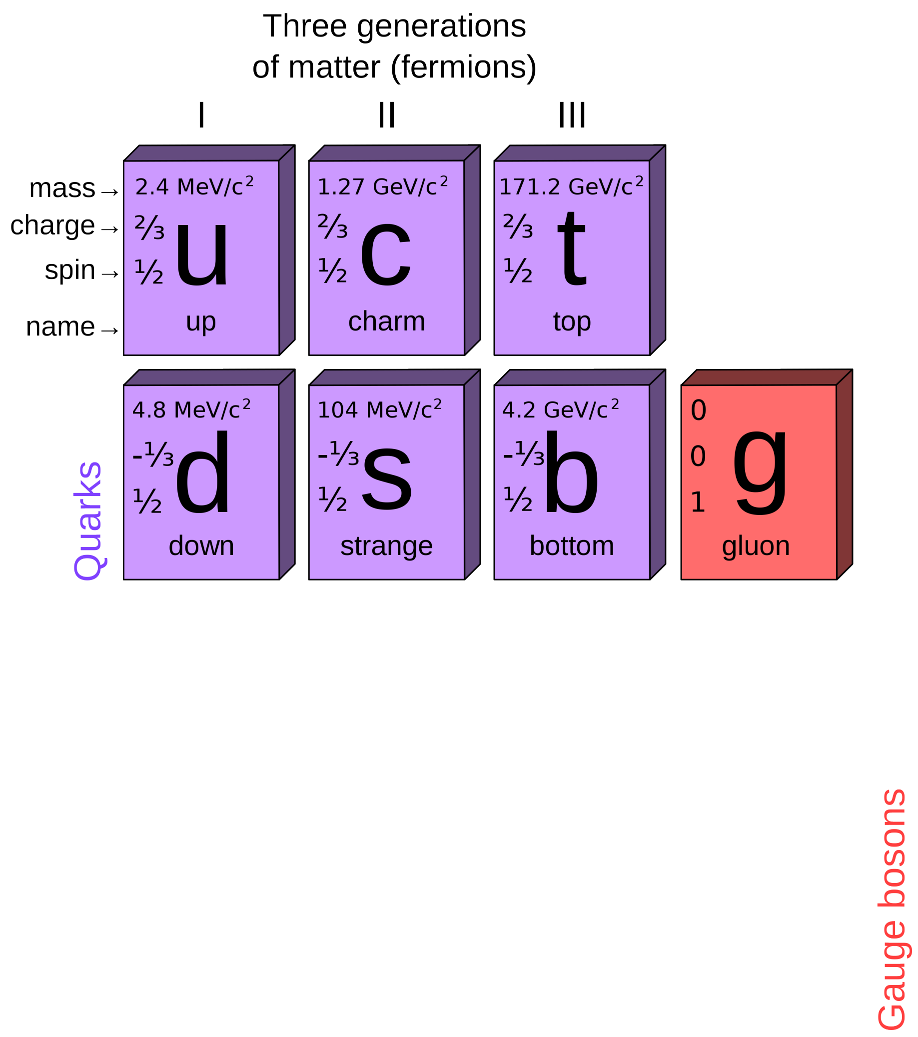
This is the trick of perturbation theory

As $\alpha \sim 1/137$ then higher order diagrams contribute very little to probablities/cross sections

=>

Often it is enough to calculate lowest order diagrams for percent level precision!

The strong interaction



Couples to color charge and is mediated by virtual gluons

Another process: ee → qqbar

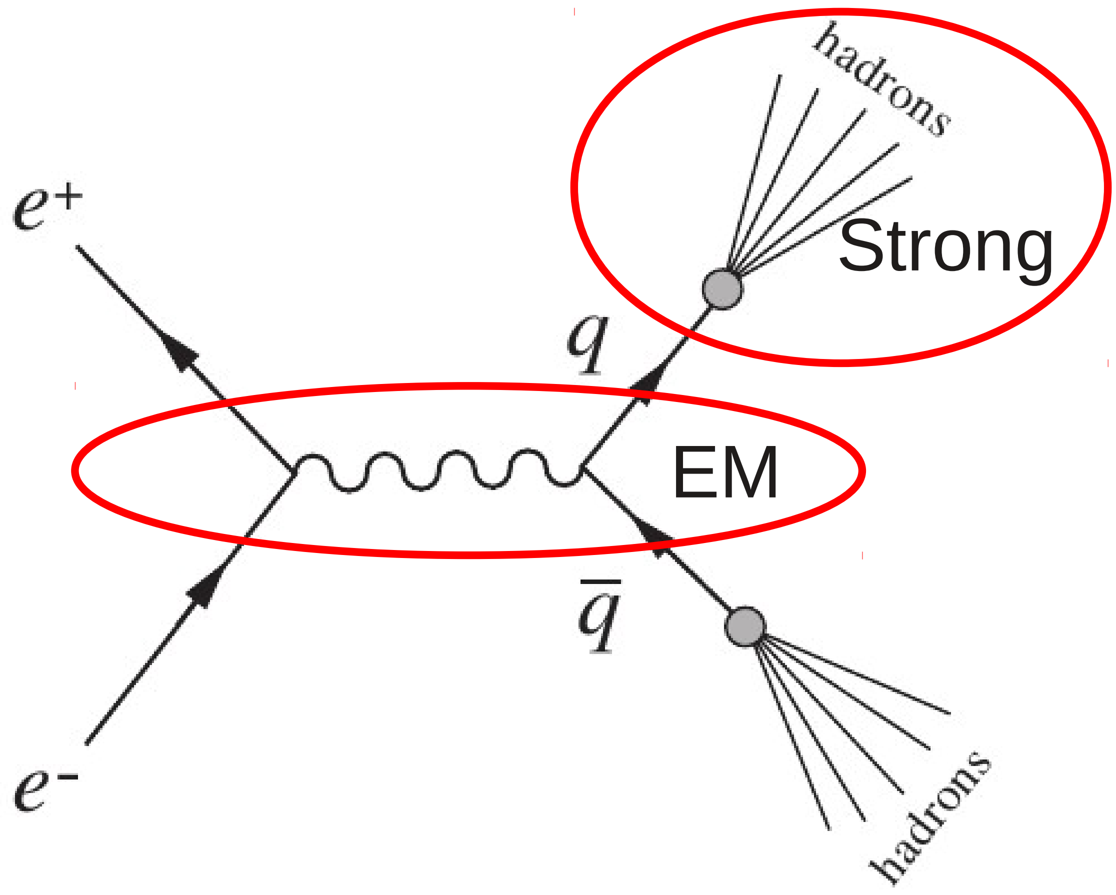


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

What about the ratio?

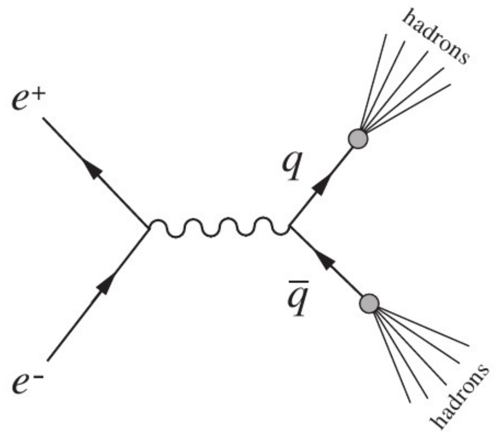


Figure 7.10 Basic mechanism of two-jet production in electron–positron annihilation.

= ?

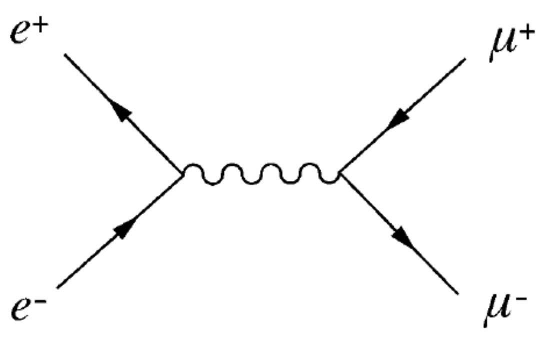
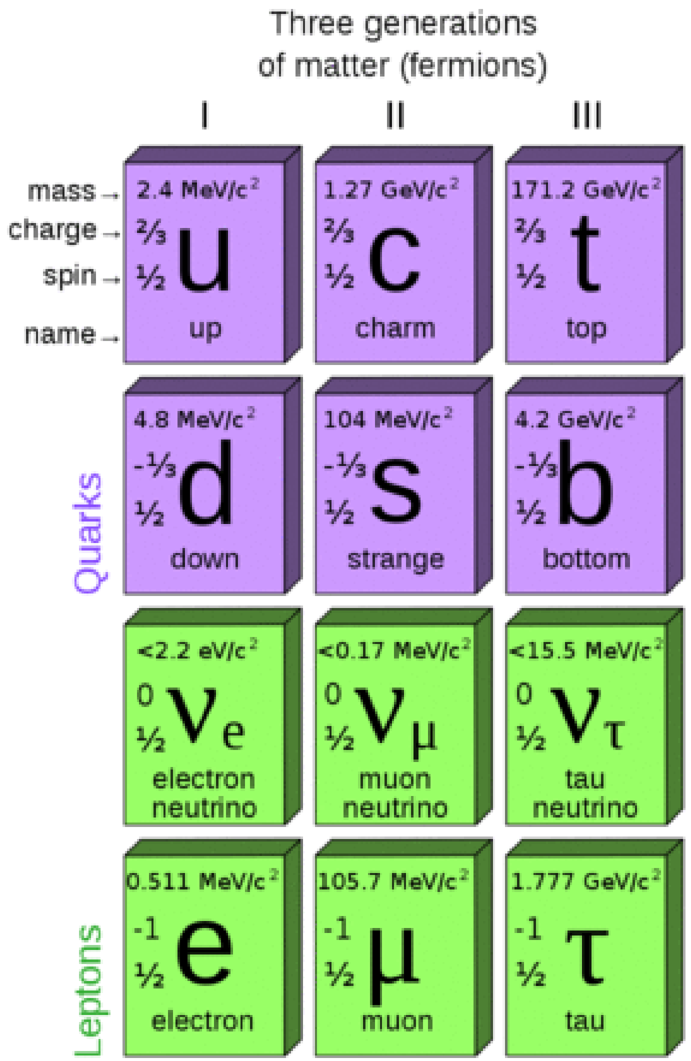


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

The charge difference



q=+2/3

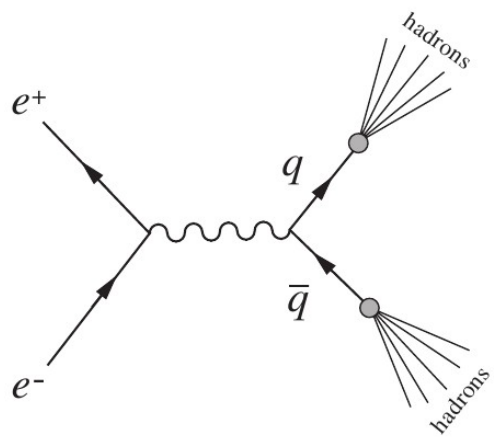
q=-1/3

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?



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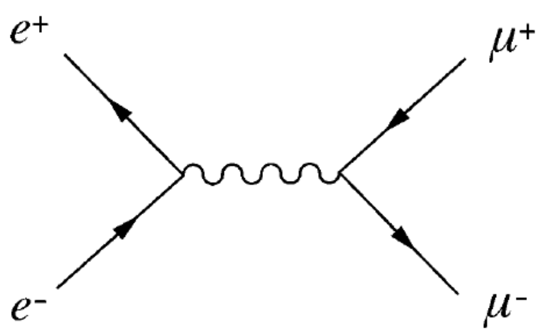


Figure 1.16 Lowest-order Feynman diagram for the process $e^+ + e^- \to \mu^+ + \mu^-$.

=

R ≠11/9

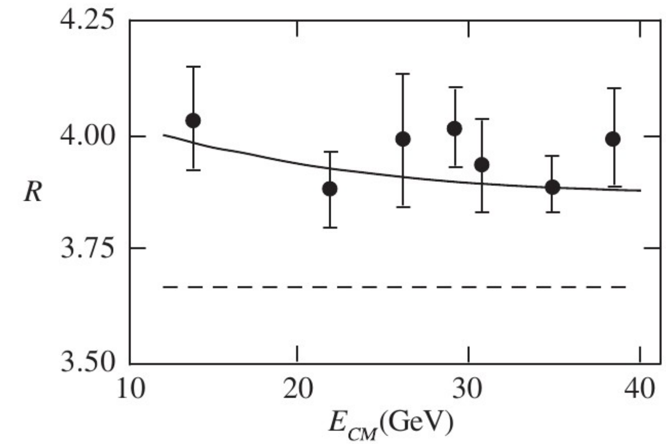


Figure 7.16 Comparison between the measured values of the cross-section ratio R of Equation (7.18) and the theoretical prediction (7.22) for three colours, $N_C = 3$. The dashed line shows the corresponding prediction (7.21) omitting small contributions of order α_s. (Data from the compilations of Wu,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

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

Feynman diagram of quark-quark scattering

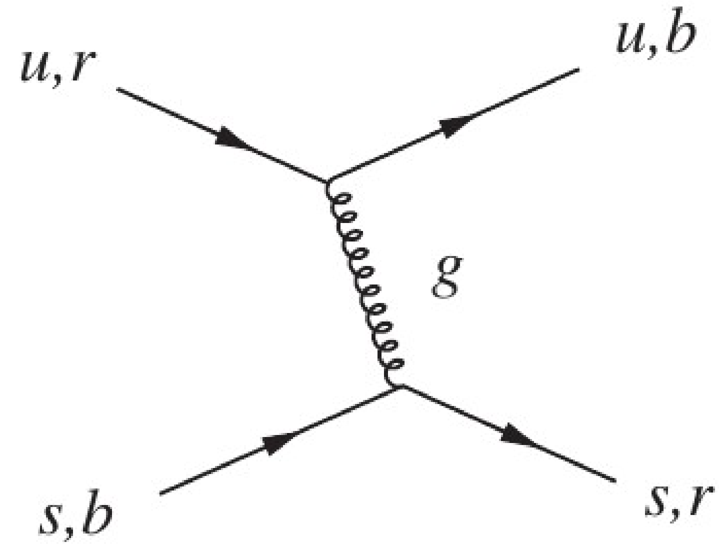


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour u or s is unchanged on gluon emission, but the colour state can change, as shown.

Color flow

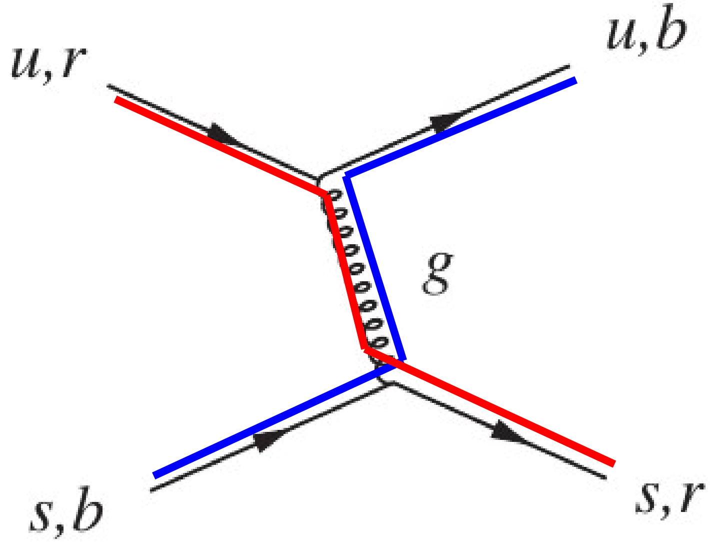


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour u or s is unchanged on gluon emission, but the colour state can change, as shown.

Special QCD processes because gluons are colored!

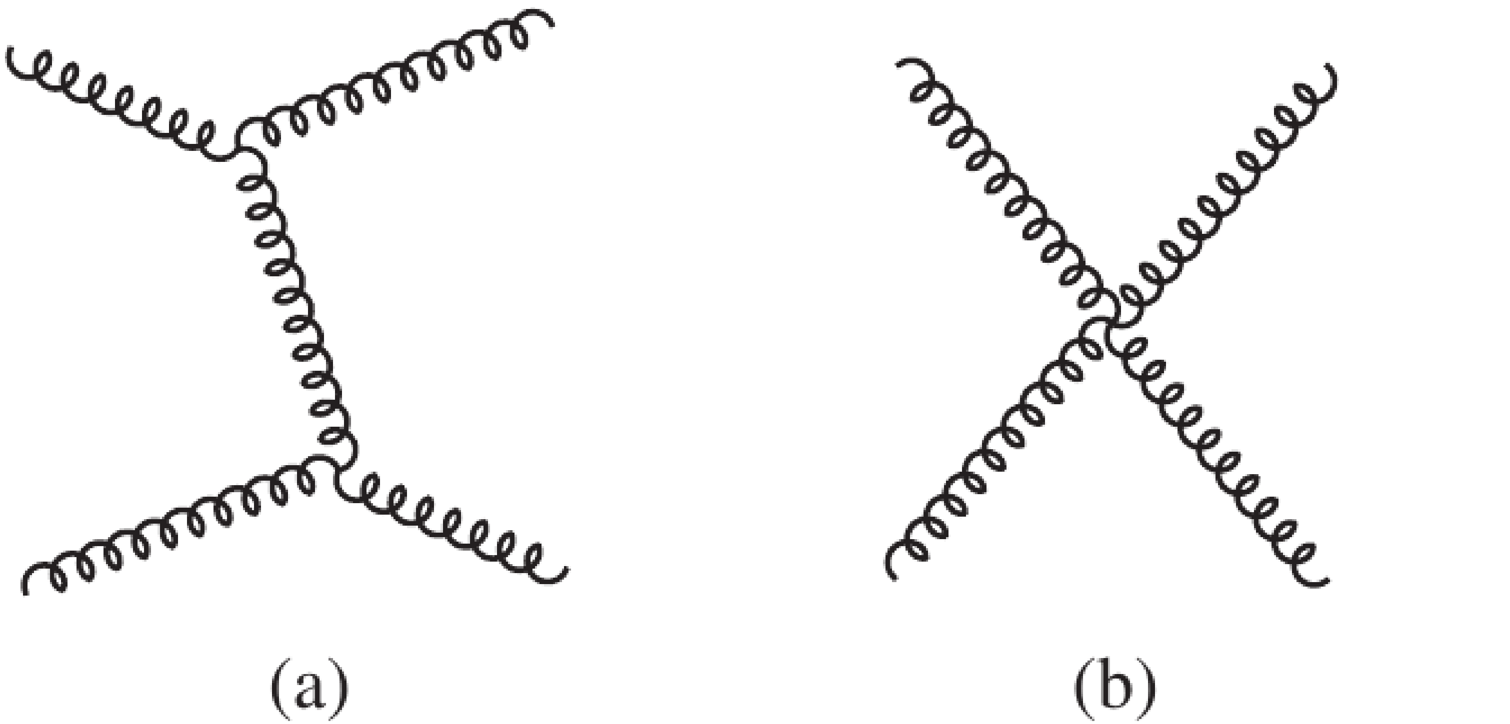


Figure 7.2 The two lowest-order contributions to gluon–gluon scattering in QCD.

The strong coupling

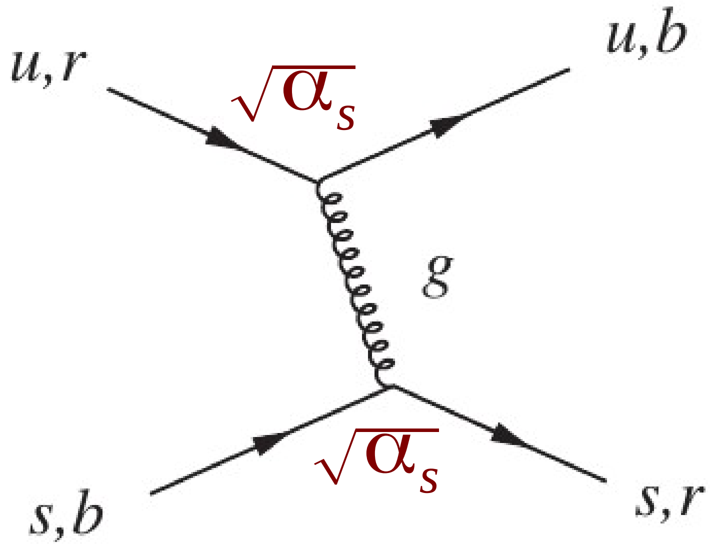
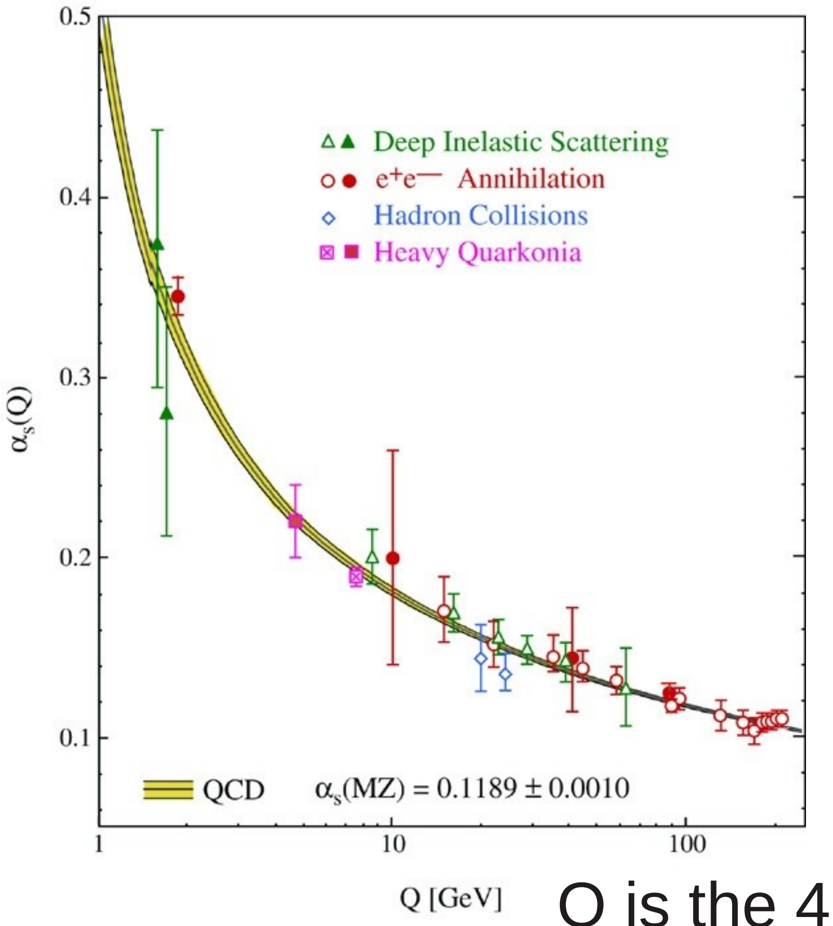


Figure 7.1 Example of quark–quark scattering by gluon exchange, where the gluon is represented by a 'corkscrew' line to distinguish it from a photon. In this diagram the quark flavour *u* or *s* is unchanged on gluon emission, but the colour state can change, as shown.

The coupling is not fixed but runs!

α_s



Q is the 4 momentum transfer

In fact it becomes ~1 at the scale Λ_{QCD}~200 MeV

QCD is strong because the coupling constant is large!

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

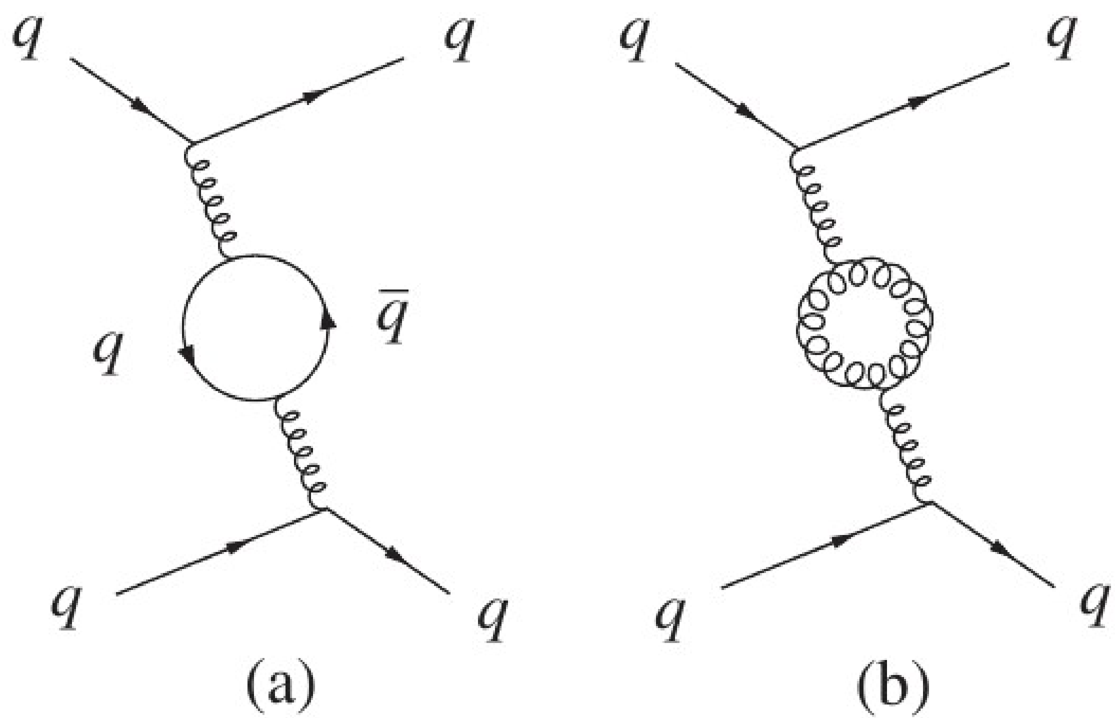
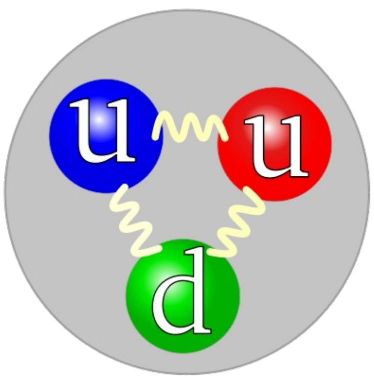
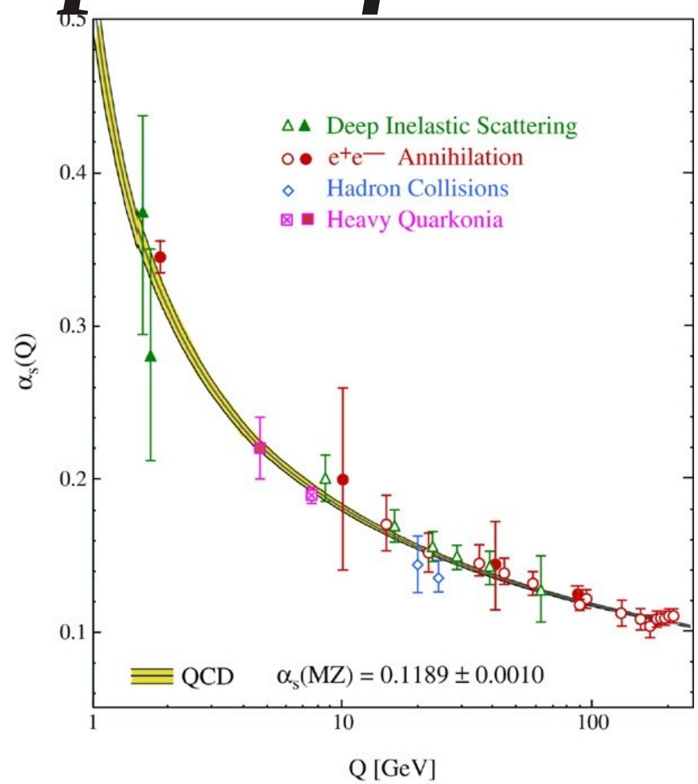
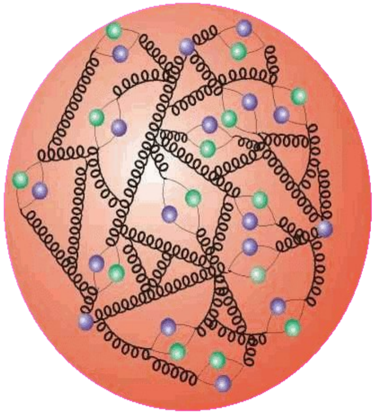


Figure 7.7 The two lowest-order vacuum polarization corrections to one-gluon exchange in quark–quark scattering.

2 limits of QCD:Confinement (soft) and Asymptotic freedom (hard)







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

<u>ASYMPTOTIC FREEDOM</u>
Perturbative physics
(theoretical predictions)
Example: Quark scatterings

CONFINEMENT: Only color neutral particles (hadrons) are observed

3 color charges (red, green, blue)

<u>Not real colors</u> but e.g. qx, qy, qz that can be +qx for quarks (red) and -qx for anti-quarks (anti-red)

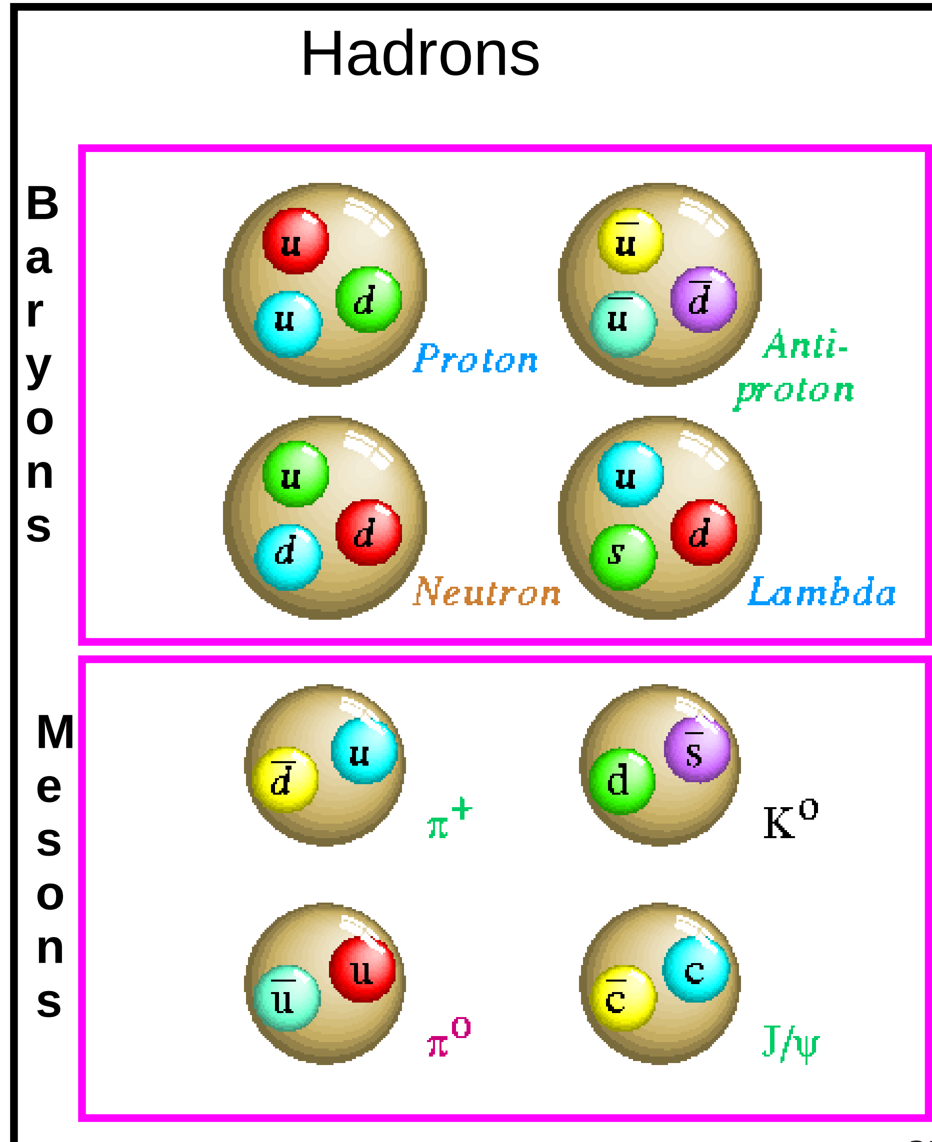
Hadrons have to be colorless

Baryons have all 3 colors

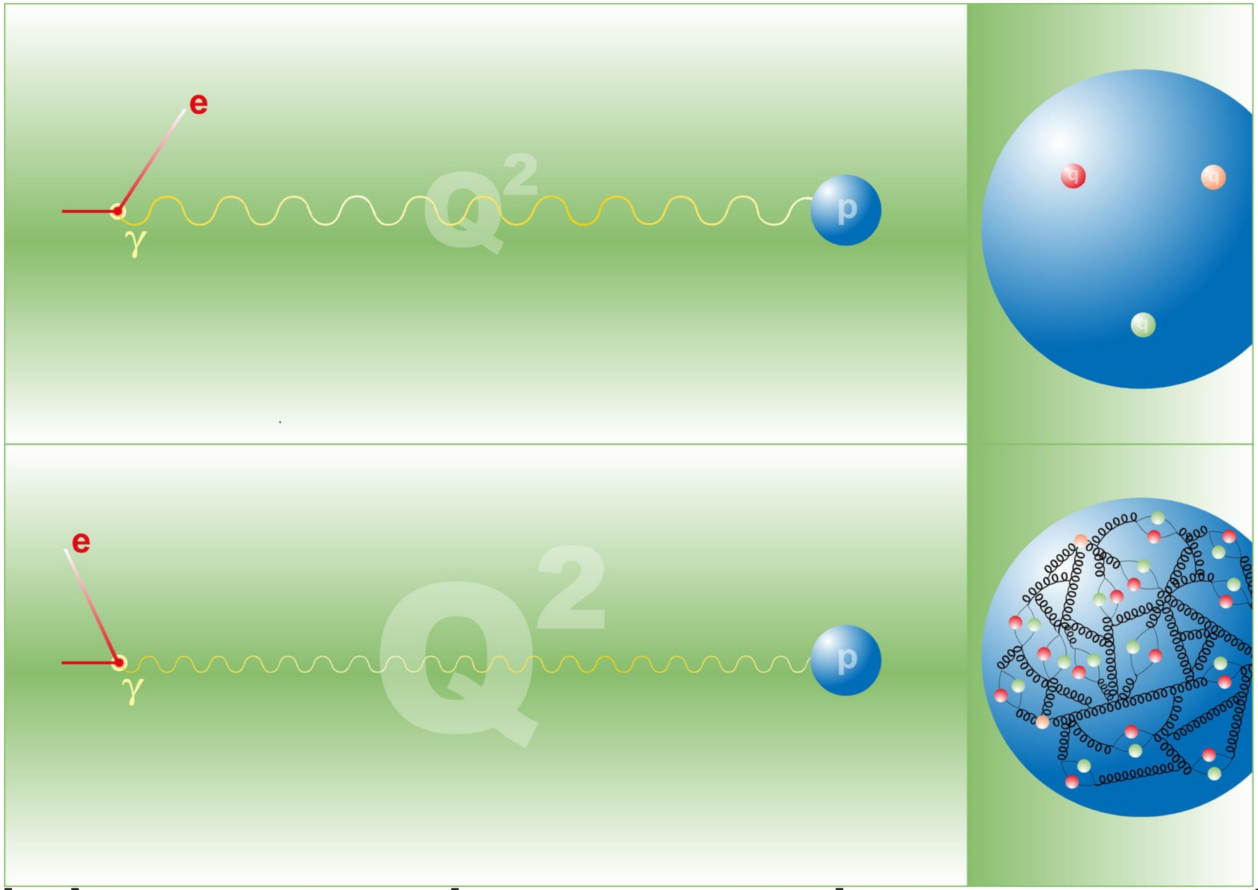
Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!



Deep inelastic scattering: probing asymptotic freedom



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

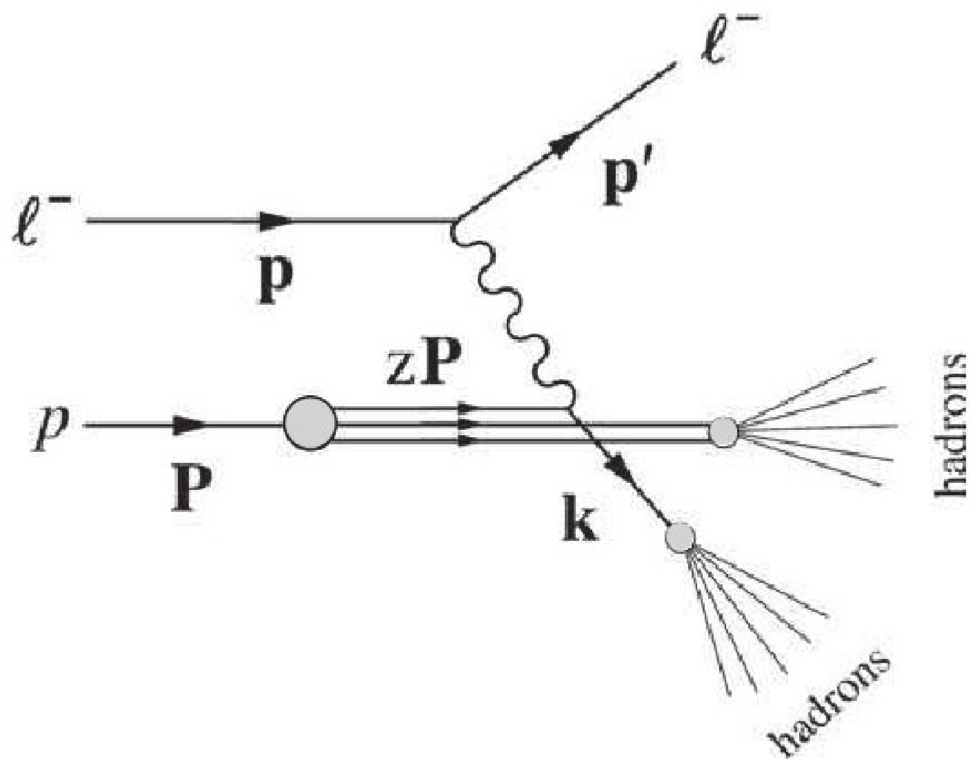


Figure 7.20 Dominant contribution to deep inelastic lepton–proton scattering in the quark model, where $\ell = e$ or μ.

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

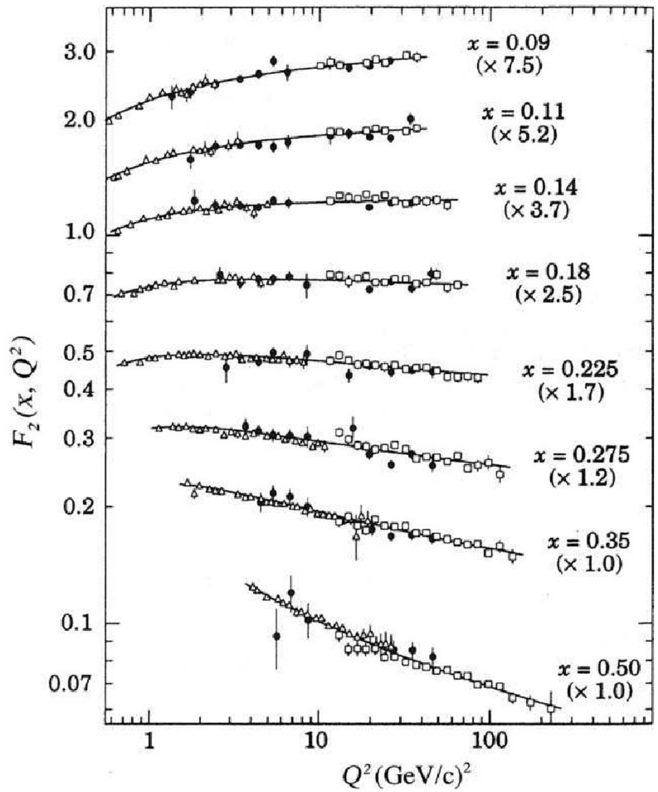
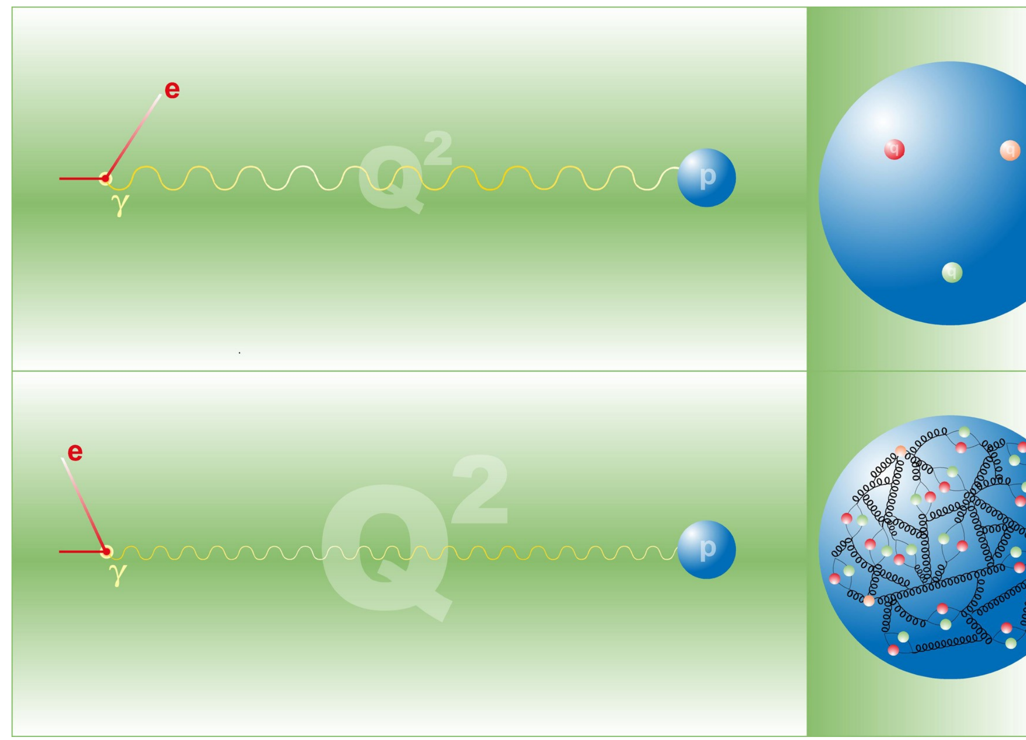


Figure 7.21 Measured values of the structure function $F_2(x, Q^2)$ from a deep inelastic scattering experiment using muons. The data points at the lower x values have been multiplied by the factors in brackets so that they can be displayed on a single diagram. (Reprinted Figure 32 with permission from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



Quarks have no structure

Result: information about the proton structure

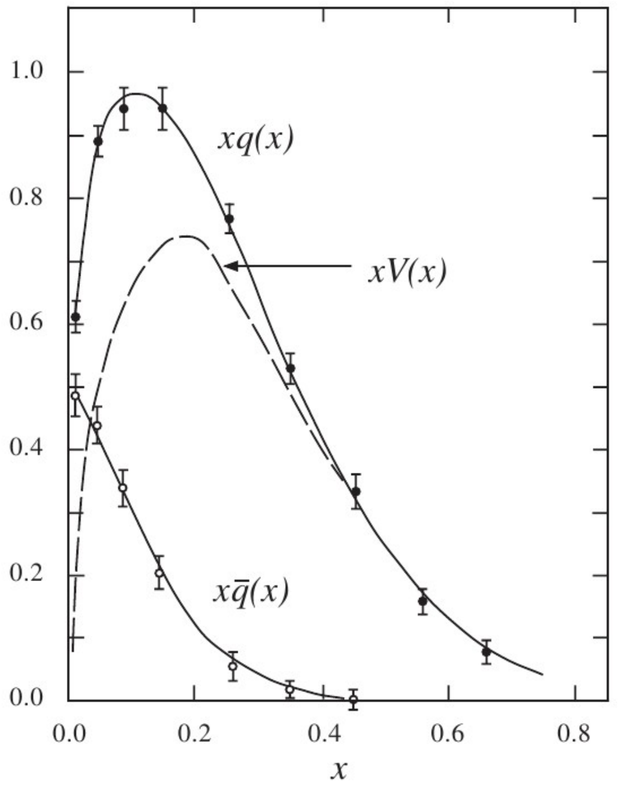
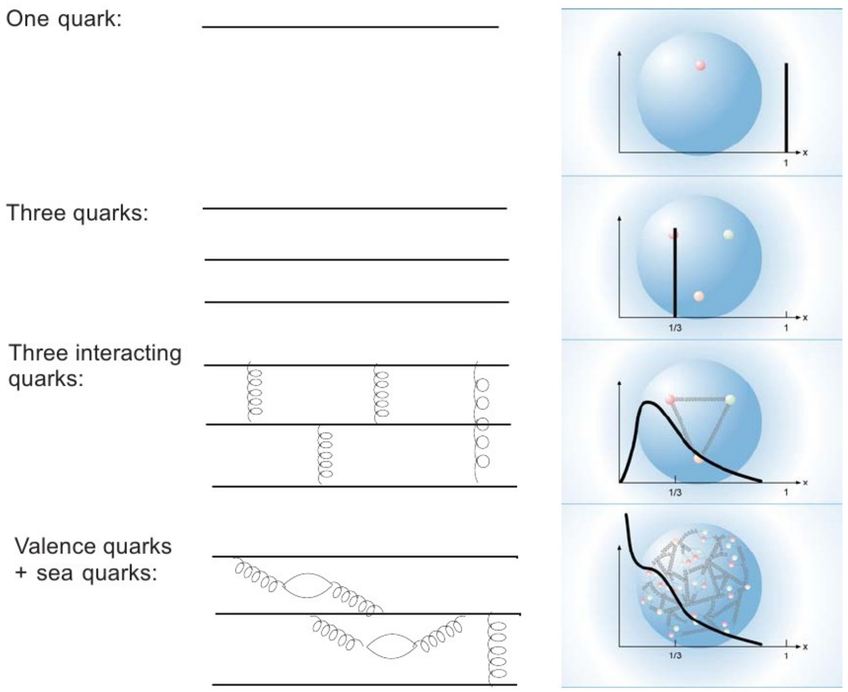
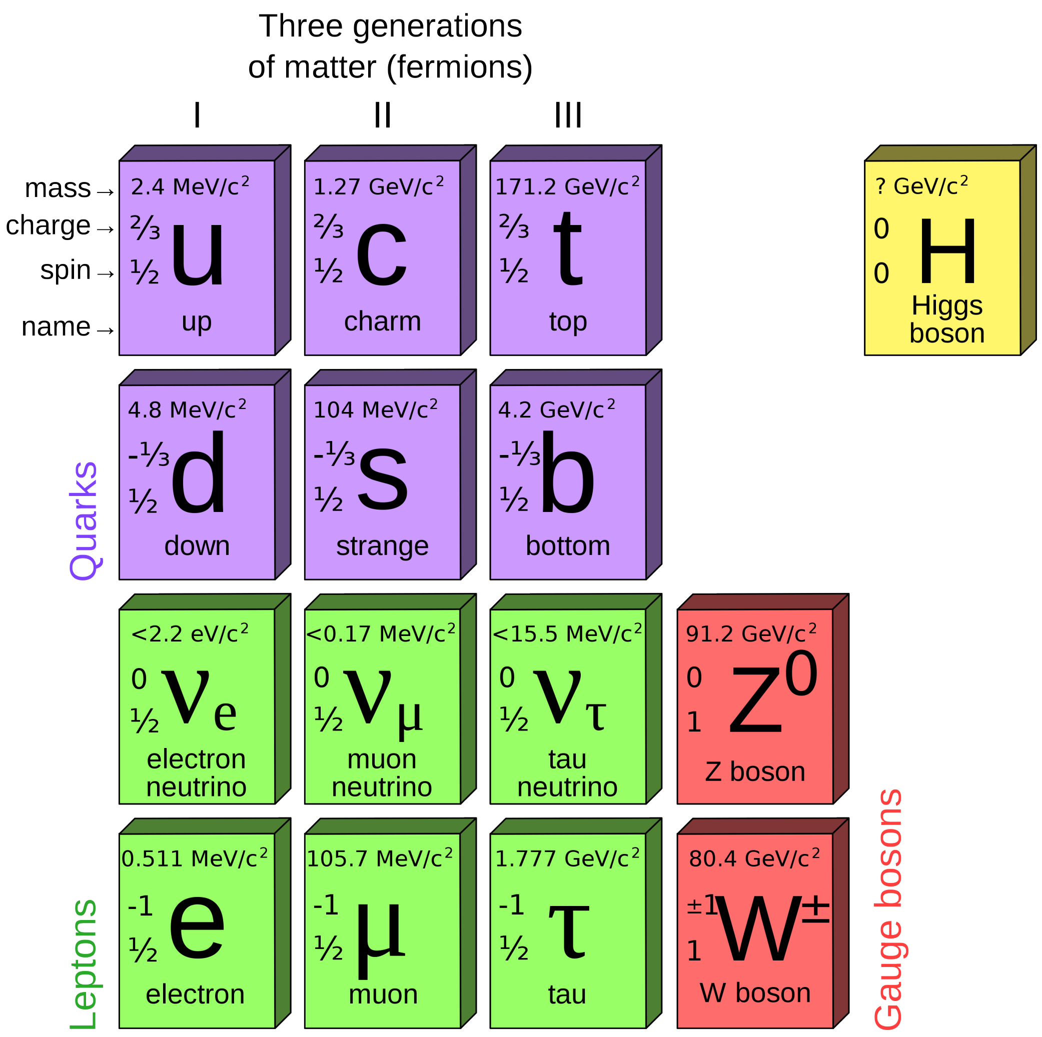


Figure 7.23 Quark and antiquark distributions (7.59a), together with the valence qua distribution (7.59b), measured at a Q^2 value of about 10 GeV^2, from neutrino experimei at CERN and Fermilab.



The weak interaction



Couples to “weak charge” and is mediated by virtual W and Zs

An additional process!

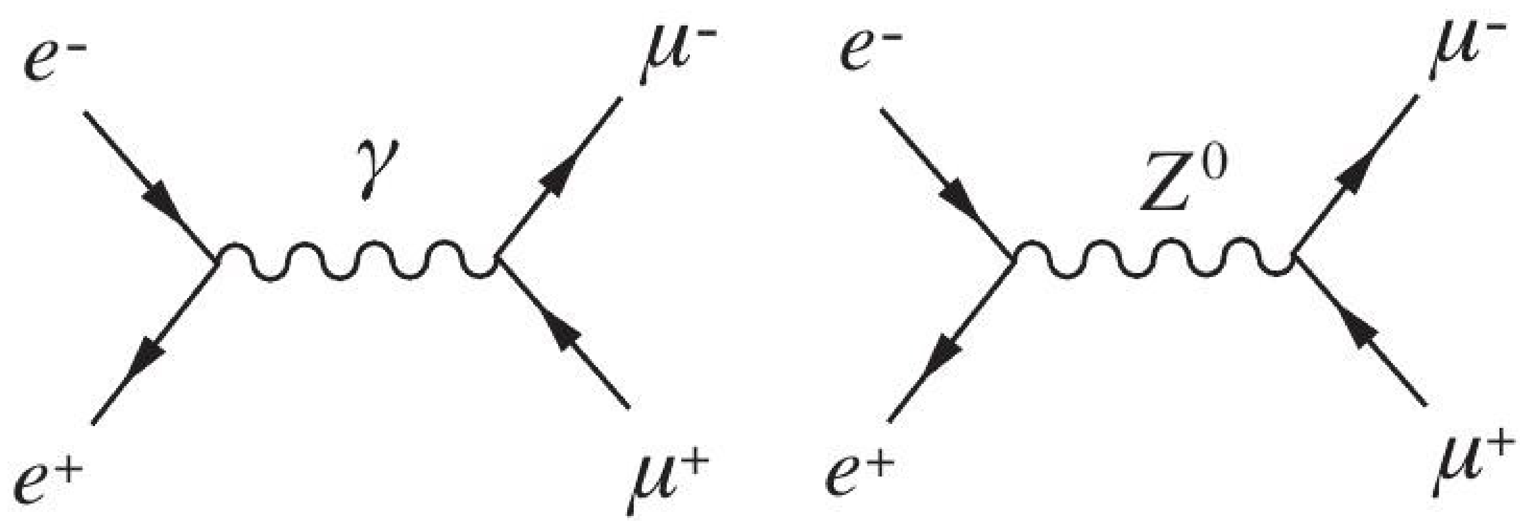


Figure 9.2 The two dominant contributions to the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ in the unified theory.

Where is the difference? (1/2)

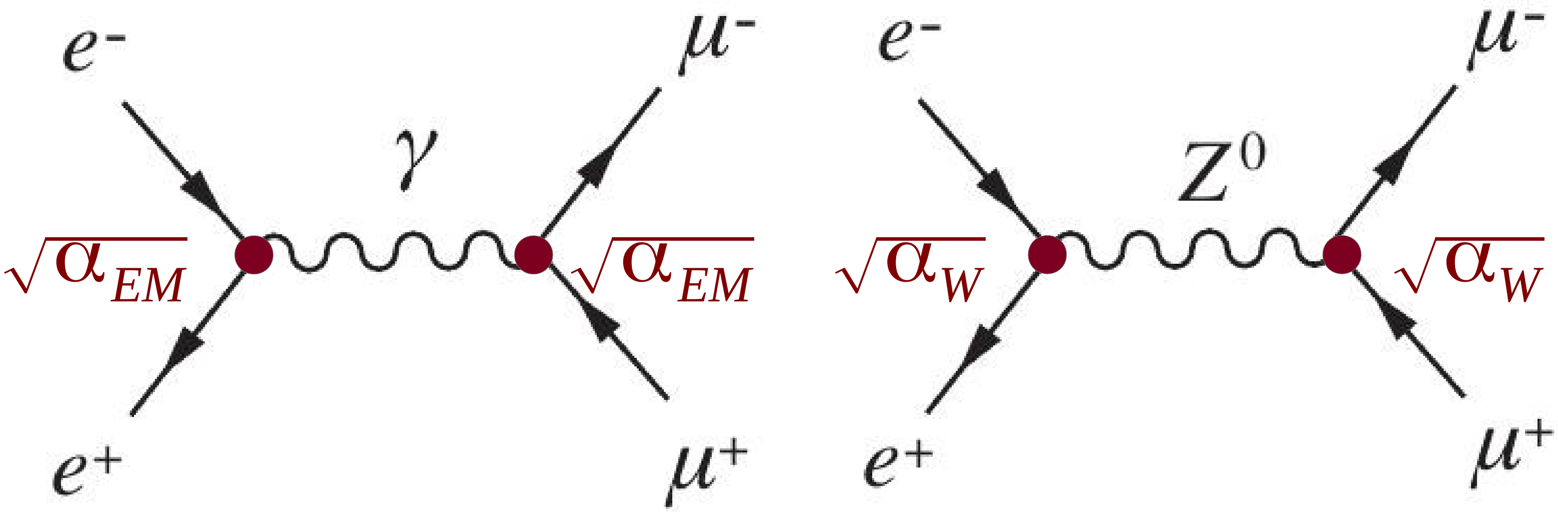


Figure 9.2 The two dominant contributions to the reaction $e^+ + e^- \to \mu^+ + \mu^-$ in the unified theory.

In fact couplings are similar: $\sqrt{\alpha_{EM}} \sim \sqrt{\alpha_W}$

Where is the difference? (2/2)

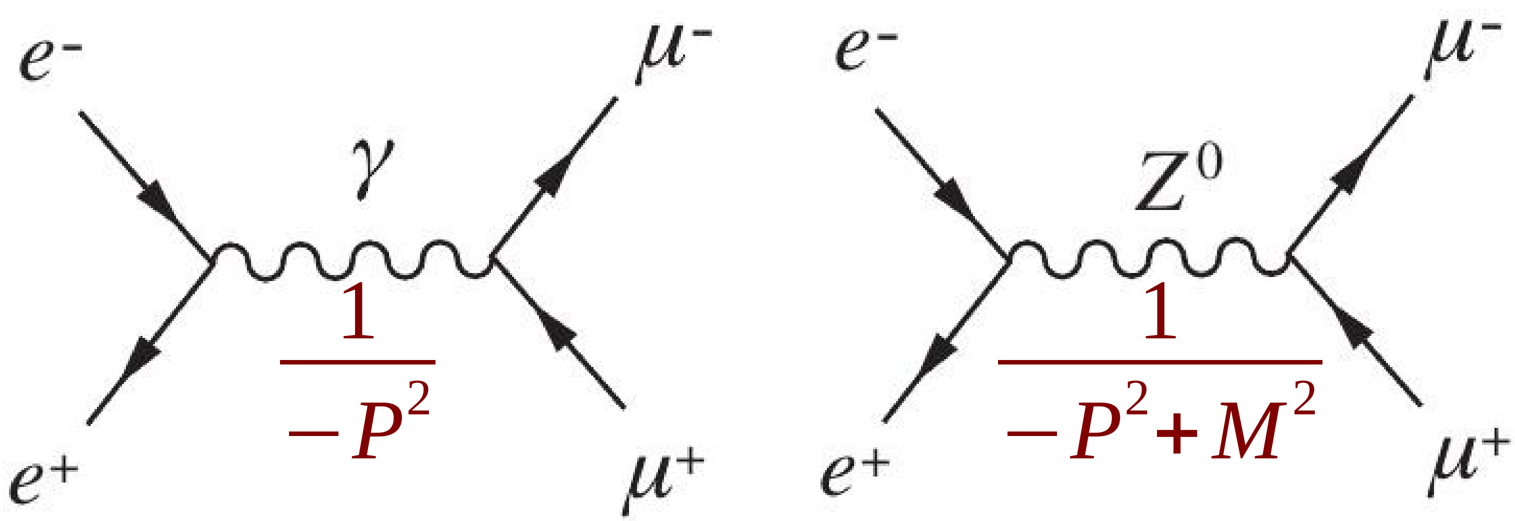


Figure 9.2 The two dominant contributions to the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ in the unified theory.

Huge difference as Mz~90 GeV (~ 90 proton masses!)

What is the effect (1/2) ?

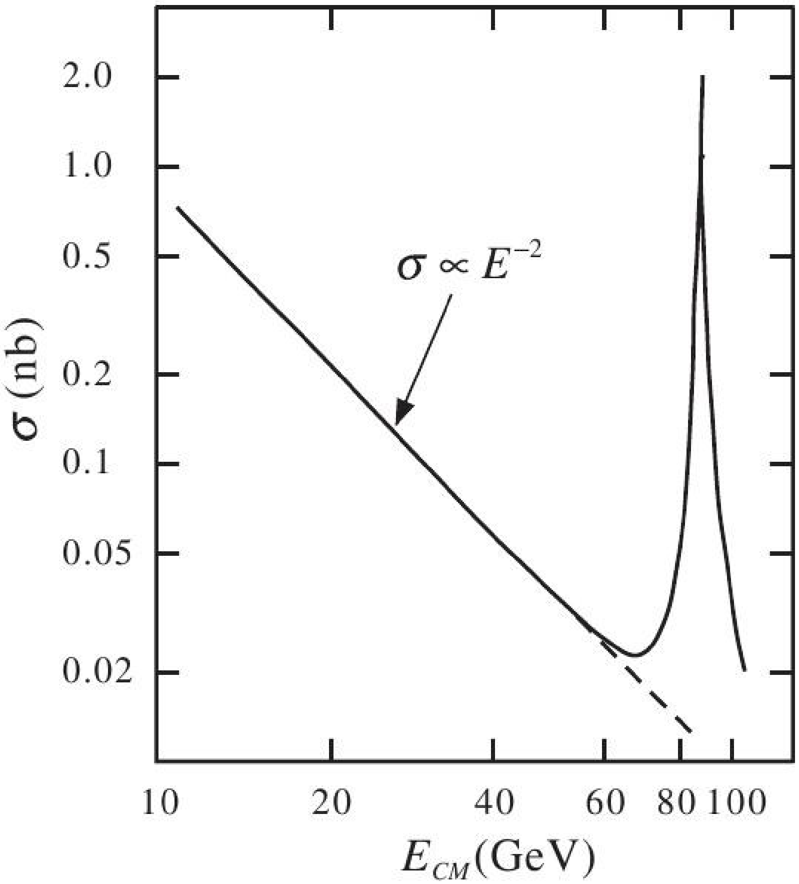


Figure 9.9 Total cross-section for the reaction $e^+ + e^- \to \mu^+ + \mu^-$ as a function of the total centre-of-mass energy (9.20). The dashed line shows the extrapolation of the low-energy behaviour (9.17) in the region of the Z^0 peak.

What is the effect (2/2) ?

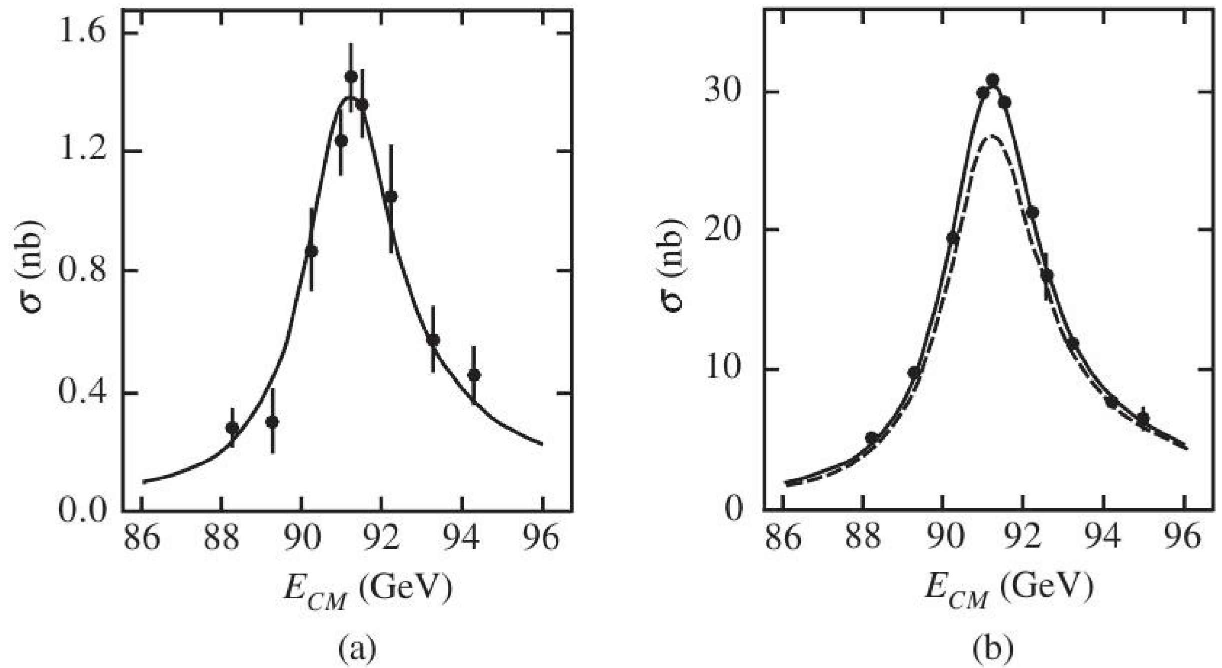
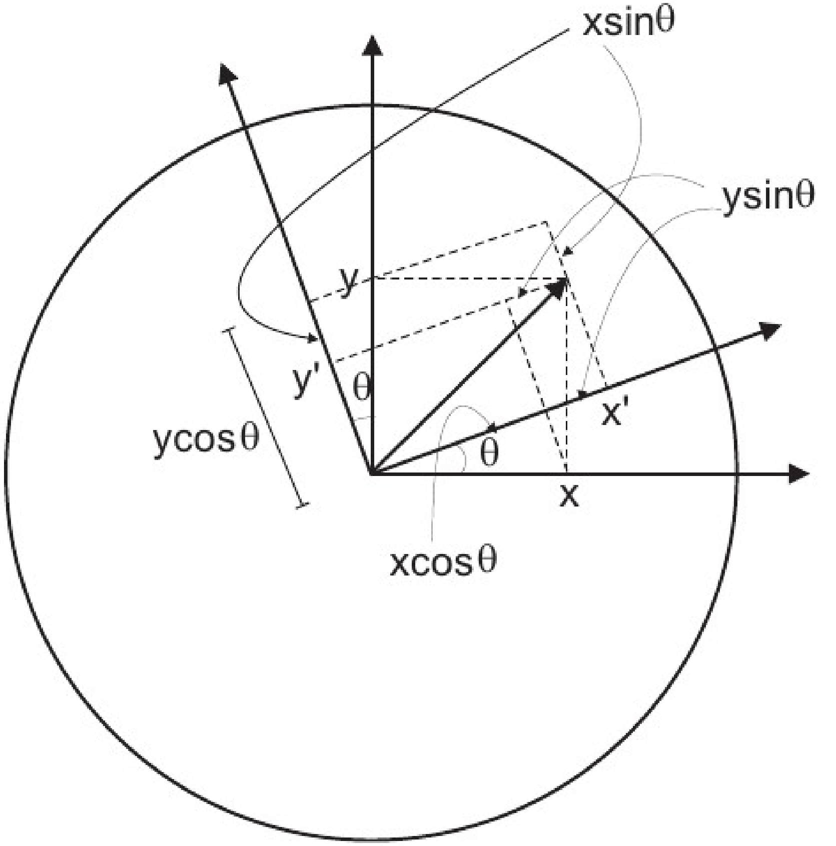


Figure 9.10 Measured cross-sections for (a) $e^+ + e^- \rightarrow \mu^+ + \mu^-$ and (b) $e^+ + e^- \rightarrow$ hadrons, in the region of the Z^0 peak. The solid and dashed lines show the predictions of the standard model on the assumptions that there are three and four types of light neutrinos, respectively. (Reprinted from Akrawy, M. Z., *et al.*, *Physics Letters B*, **240**, 497. Copyright 1990, with permission from Elsevier.)

This is how we know that there are only 3 interacting light neutrinos

Neutrino oscillations



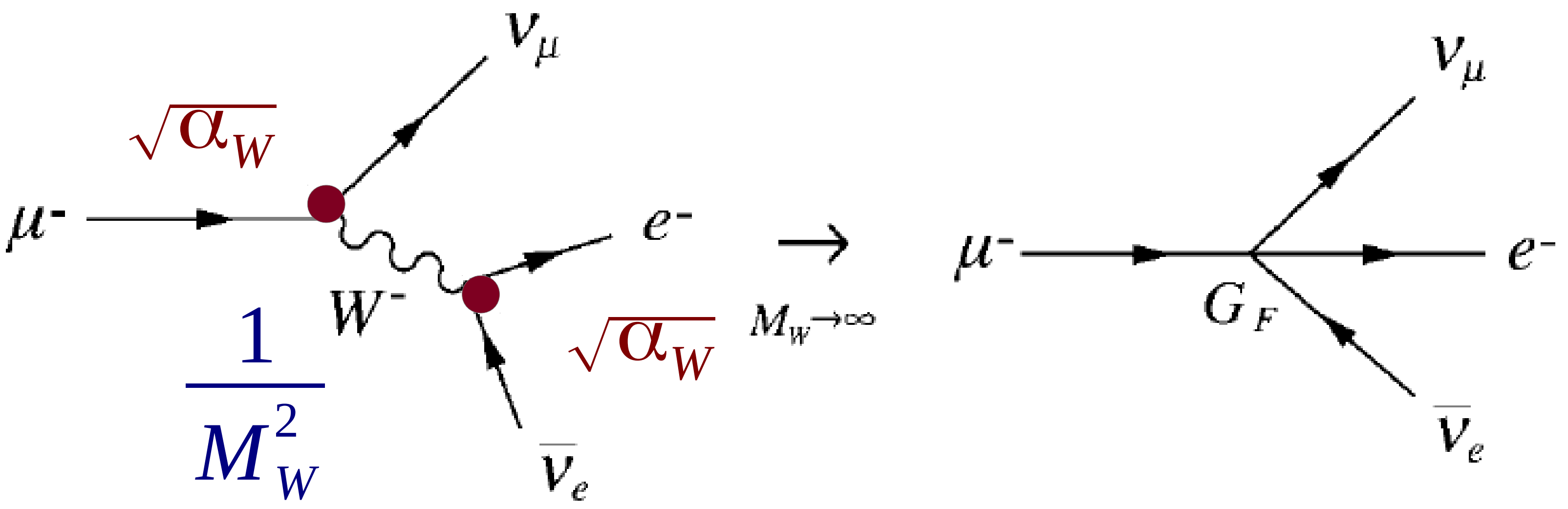
$x' = x \cos\theta + y \sin\theta$

$y' = y \cos\theta - x \sin\theta$

What is neutrino oscillations?

- Neutrino interaction eigenstates: ν_e, ν_μ, ν_τ are not mass eigenstates: ν_1, ν_2, ν_3
- If the mass eigenstates have different masses their phases evolves asynchronous in time
- This gives rise to neutrino oscillations in the interaction states, e.g., $\nu_e \leftrightarrow \nu_\mu$ that have been measured experimentally (indirectly = disappearance)
- There are ideas to also make neutrino experiments at ESS!

What about the W?



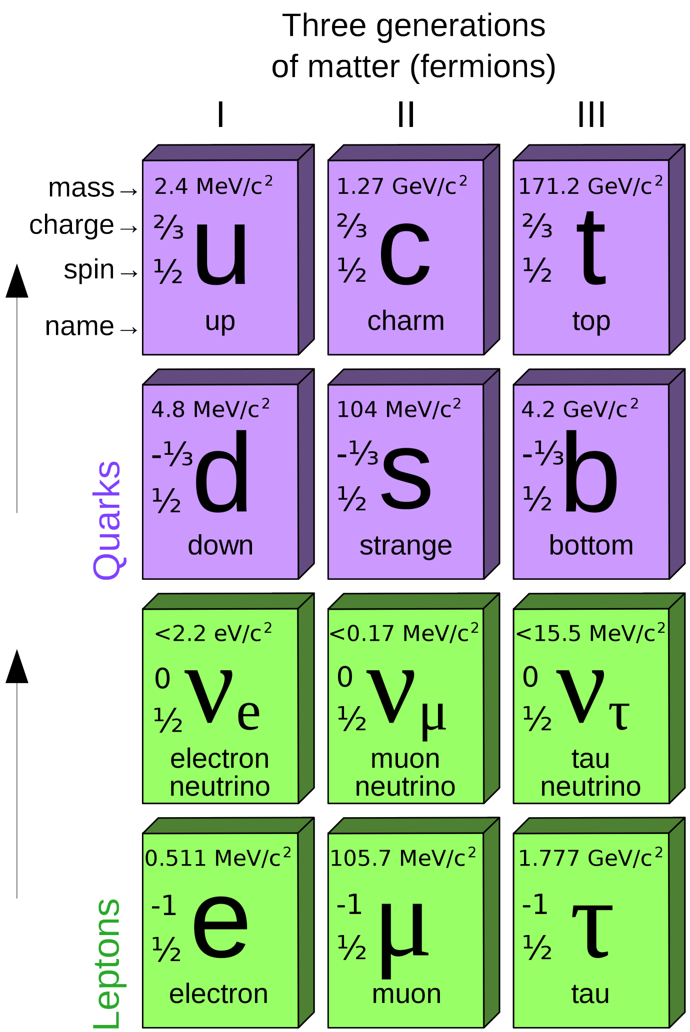
$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{M_W^2} = \frac{4\pi\alpha_W}{M_W^2} \qquad (2.17)$$

- G_F = 1.166 x 10^{-5} GeV^{-2}
- So α_W~ 0.0042, so that α_W ~ 0.58*α

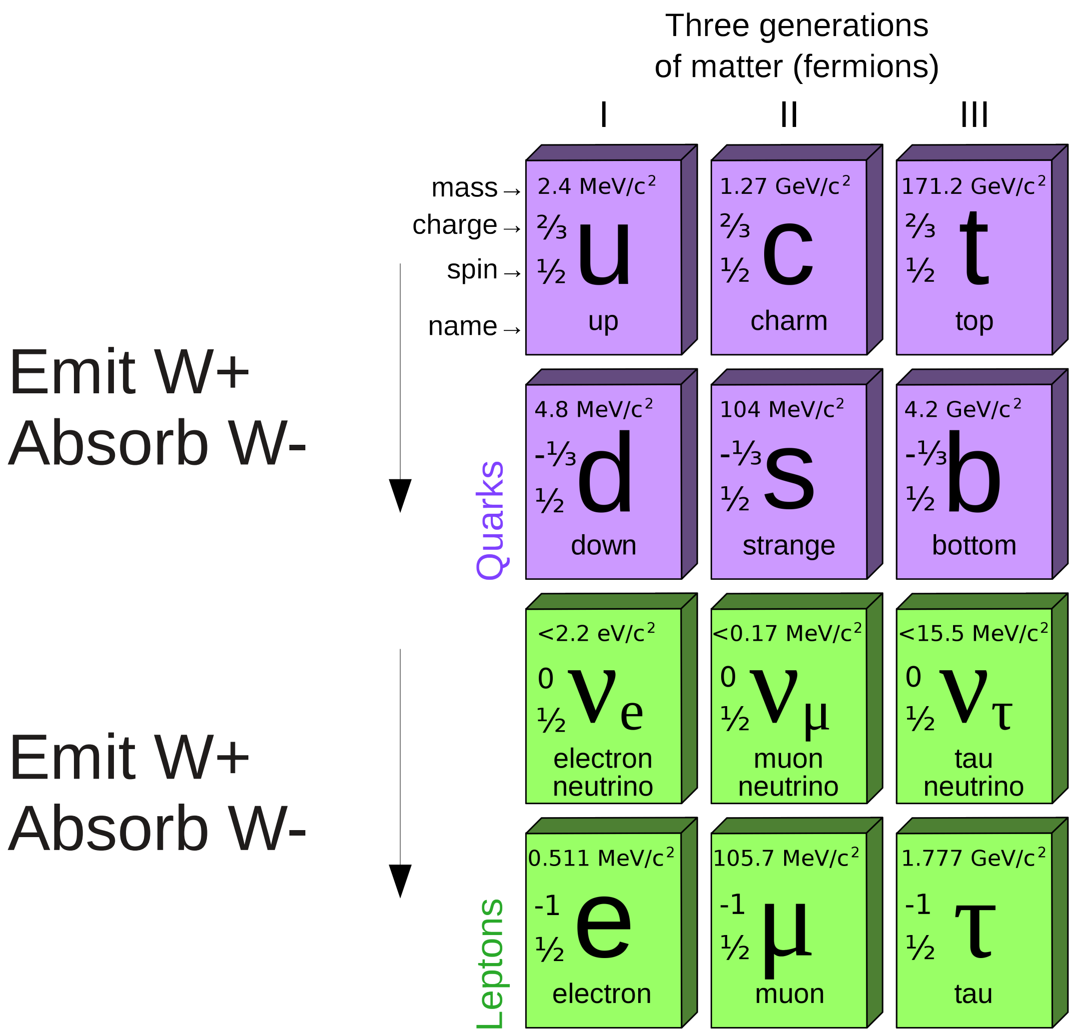
Quark-lepton symmetry
Similar coupling

Emit W-
Absorb W+

Emit W-
Absorb W+

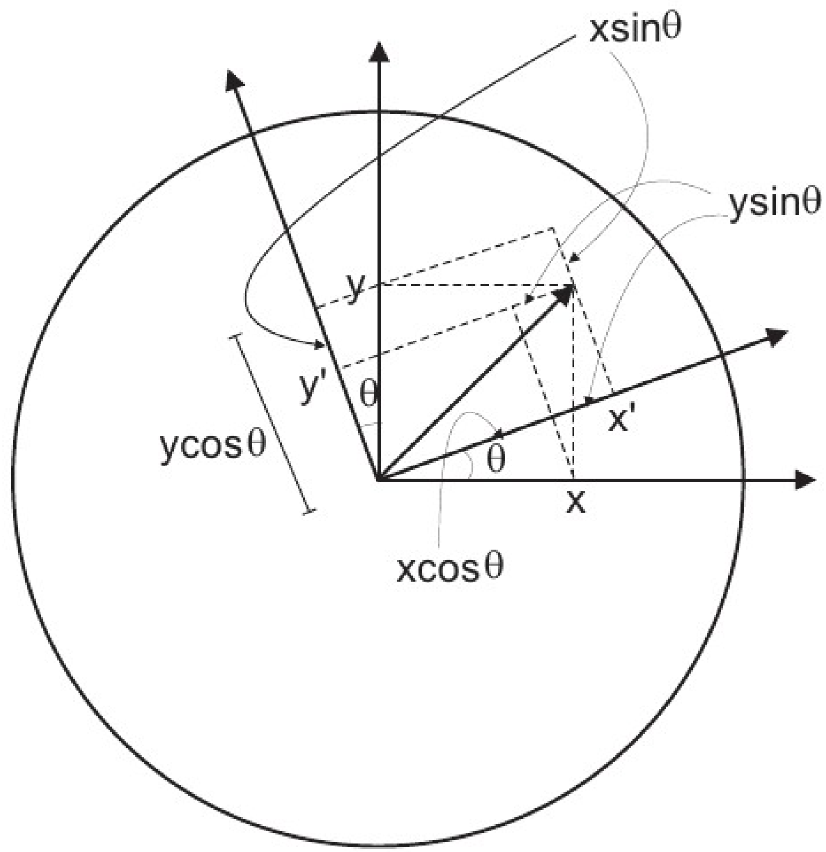


Quark-lepton symmetry
Similar coupling



That is why one draws the neutrino above the electron!

~~Neutrino oscillations~~
Quark mixing



$x' = x \cos\theta + y \sin\theta$

$y' = y \cos\theta - x \sin\theta$

Important conclusion

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad (8.43)$$

- This is a very good approximation of nature!
- The mixing between b and d and s is very small
  - But this is as mentioned very important for c decays

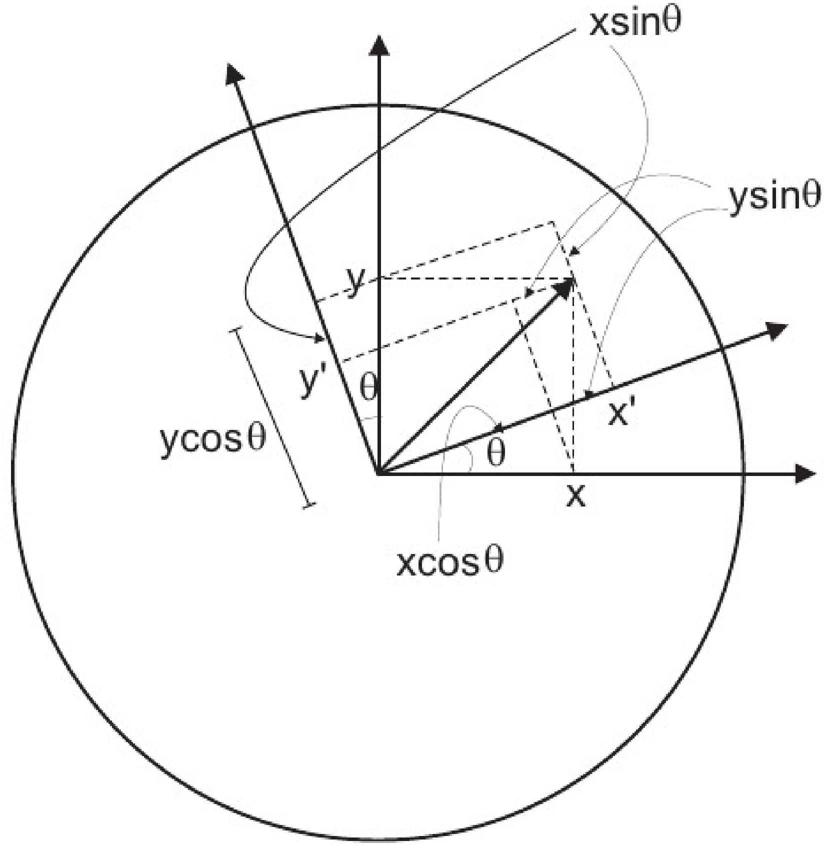
Best values for the Cabibbo–Kobayashi–Maskawa matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}, \qquad (11.27)$$

and the Jarlskog invariant is $J = (3.05^{+0.19}_{-0.20}) \times 10^{-5}$.

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-ckm-matrix.pdf

~~Neutrino oscillations~~
~~Quark mixing~~
Gauge boson mixing!



$$x' = x \cos\theta + y \sin\theta$$

$$y' = y \cos\theta - x \sin\theta$$

The gauge bosons are mixed

- The weak interaction couples to “rotated” states:

  $|\gamma> = |B> * \cos \theta w + |W0> * \sin \theta w$

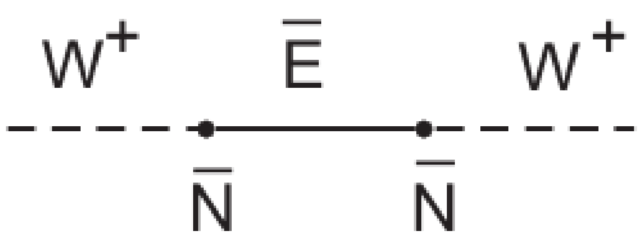
  $|Z0> = - |B> * \sin \theta w + |W0> * \cos \theta w$

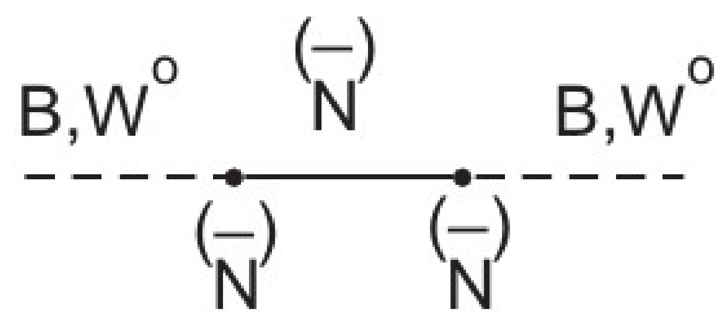
- The angle θw~30 degrees is called the weak mixing angle (or the Weinberg angle)
- We follow Leif's notes here

From Leif's notes

Basic idea:

Interactions with vacuum particles N and N-bar:





N ($\bar{N}$) is neutrino like and E ($\bar{E}$) are electron like.
In particular the couplings are exactly the same.
This guarantees that the photon remains massless.

Important Higgs result

- The weak mixing angle can be related to the ratio between the masses:

$$\cos\theta_W = \frac{M_W}{M_Z}$$

So what is the Higgs

- The Higgs mechanism (E, E-bar, N, N-bar) provides mass to the Z and W
  - And it is assumed that in fact all free masses (NOT the proton mass) of quarks and leptons are generated in a similar way
- The remaining field is the Higgs particle
- It couples to mass (not EM charge, weak charge or color)!
  - (That is also how/why it gives mass)