The four forces

Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z
Gravitational	10^{-42}	Geometrodynamics	Graviton

The strength of a force is a quite ambiguous concept.

There is no quantum theory of gravity

QED by Tomonaga Feynman and Schwinger in the '40s

GWS model following Fermi, Lee, Yang et many other in the '60s

QCD pioneering work of Yukawa and real theory only in '70s

They describe every known phenomenon. The elements at play are quarks and leptons. Complexity is a challenge…

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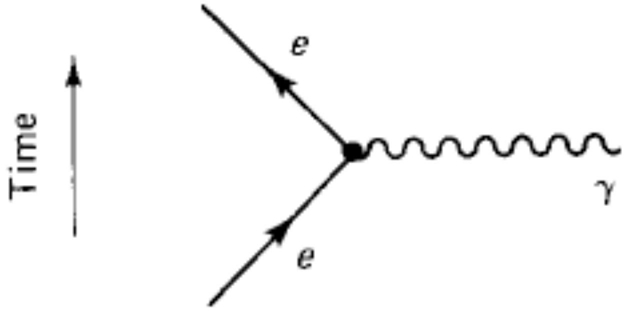
QED (1)

The oldest and the simples of these theories:

All QED phenomena are ultimately reducible to this elementary process:



The charged particle could be any charged particle, muon, quark, W,

Is this a REAL process ?

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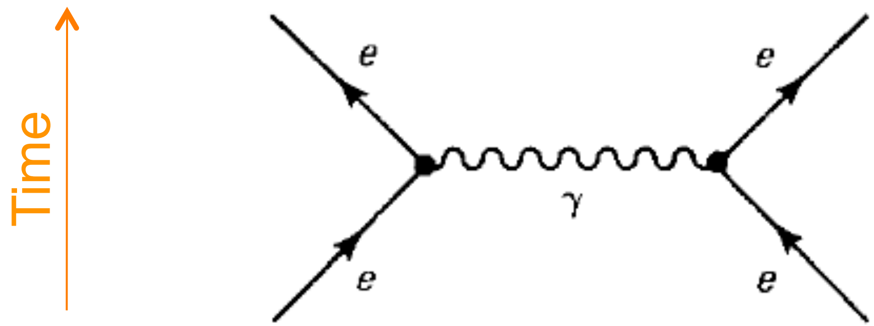
QED(2)

Moeller scattering $e^-e^- \rightarrow e^-e^-$ is described patching twice the previous graph.



Two electrons enter, two electrons come out

Feyman rules tell you how to convert this diagram into a number representing the amplitude for the process

Is this a REAL process ?

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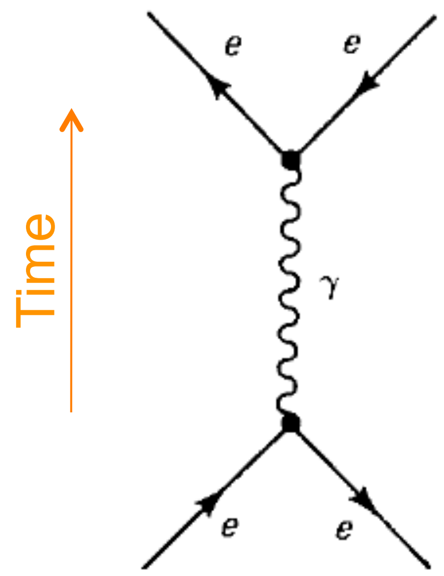
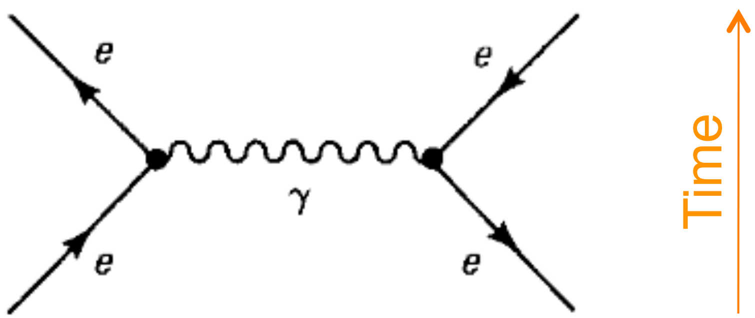
QED(3)

One can rotate these graph. The rule of the game is that a particle “running back in time” is interpreted as the corresponding antiparticle running in time direction



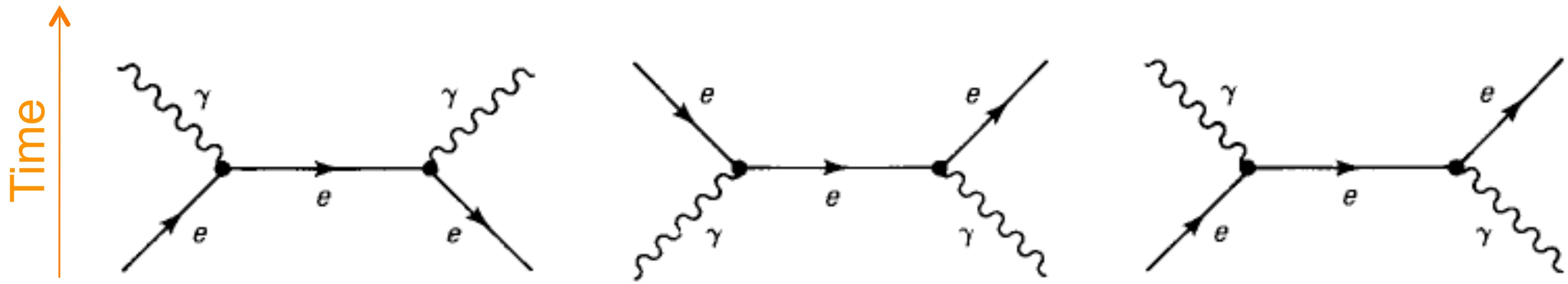
In this case there is also another diagram that contributes



Bhabha scattering

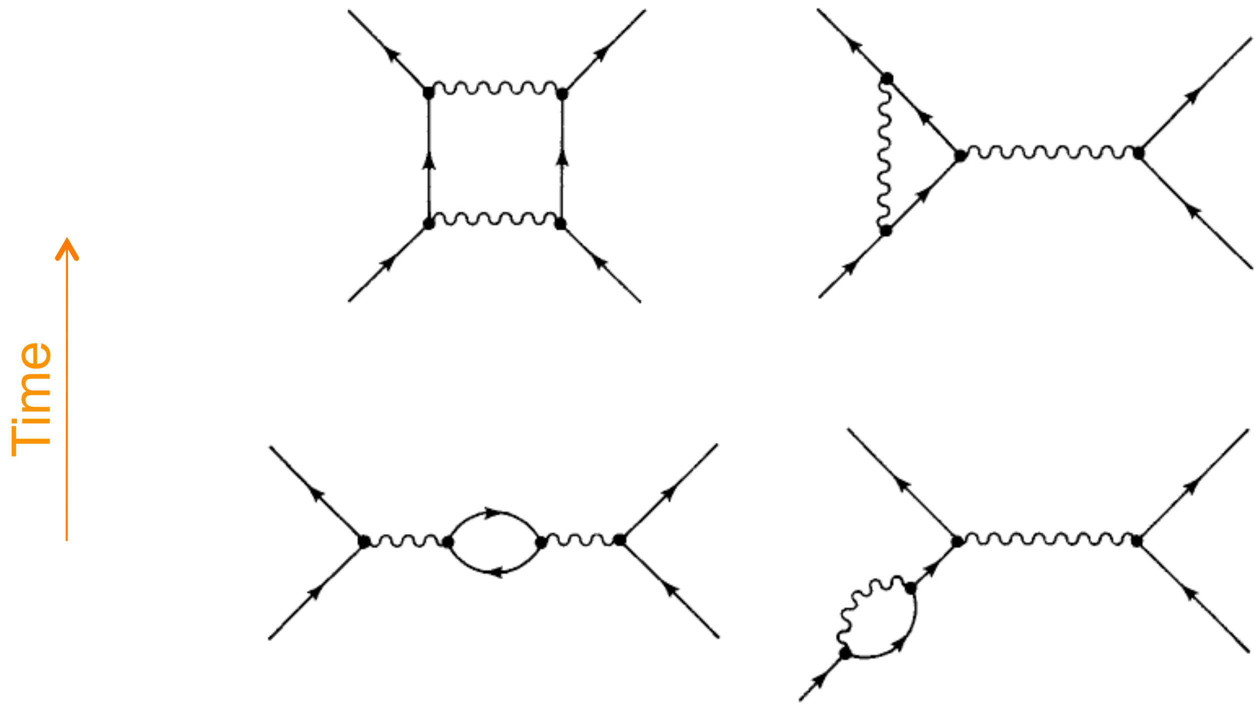
Crossing symmetry and graphs: rotate and twist

QED(4)



Which are the processes? What is the relation with crossing symmetry ?

QED, Higher Orders

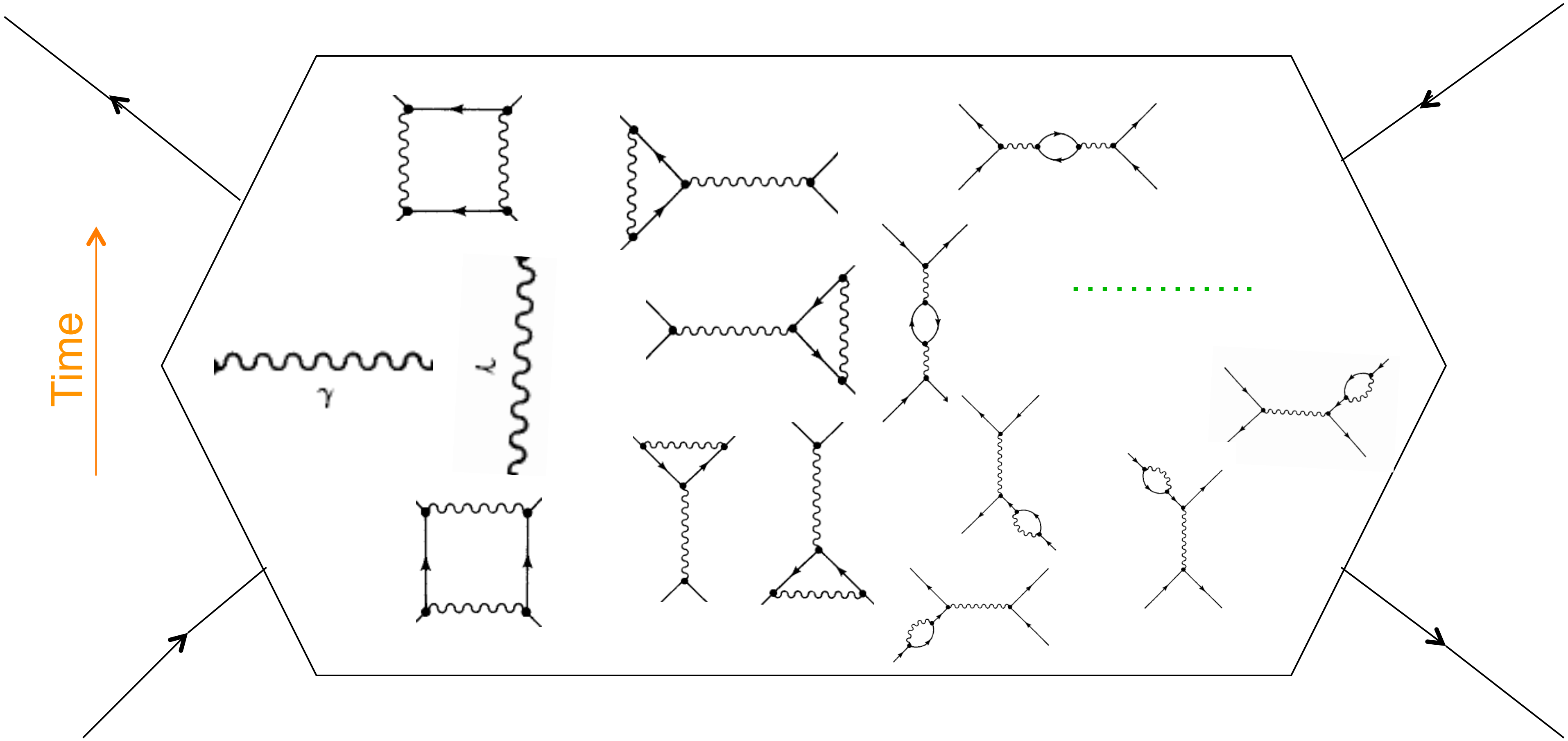


All what happens inside cannot be observed, only the external lines…

Feynman graph are a convention , they DO NOT represent trajectories !

How do we converge ?

Inside the box



How do we converge ?

a special case g-2

PHYSICAL REVIEW D 73, 053007 (2006)

Tenth-order QED contribution to the lepton $g-2$: Evaluation of dominant α^5 terms of muon $g-2$

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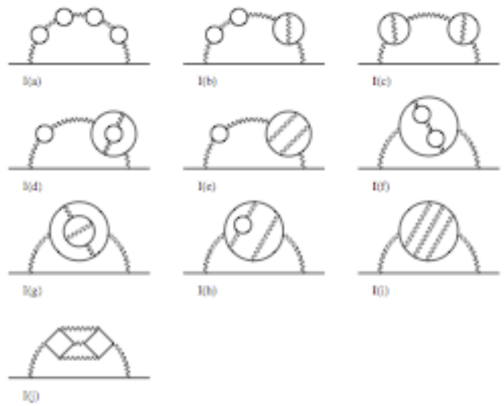

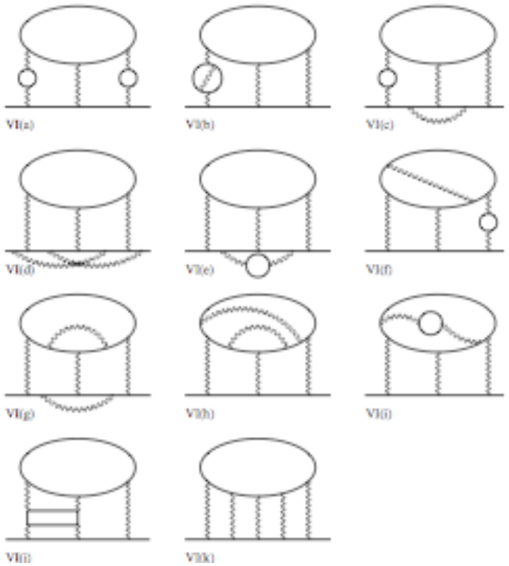

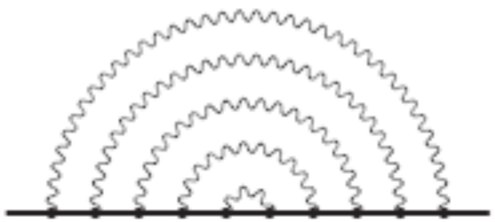

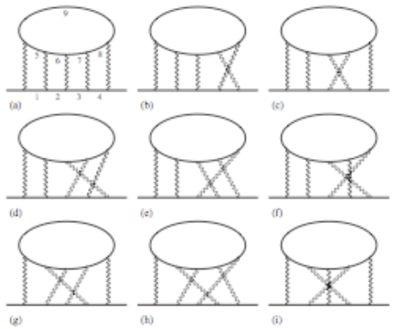

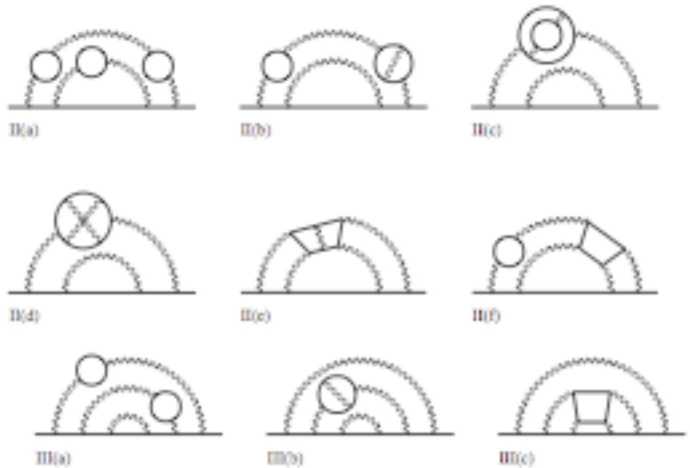

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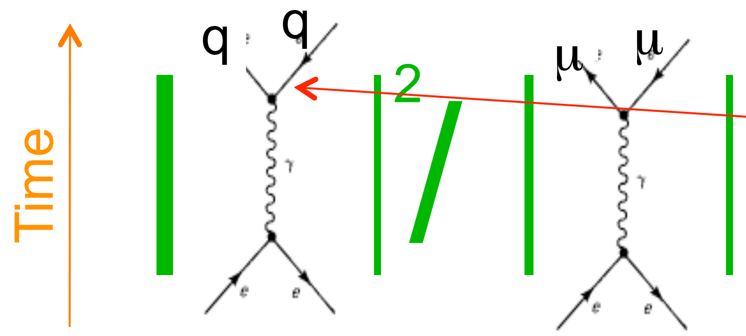
Ratio R

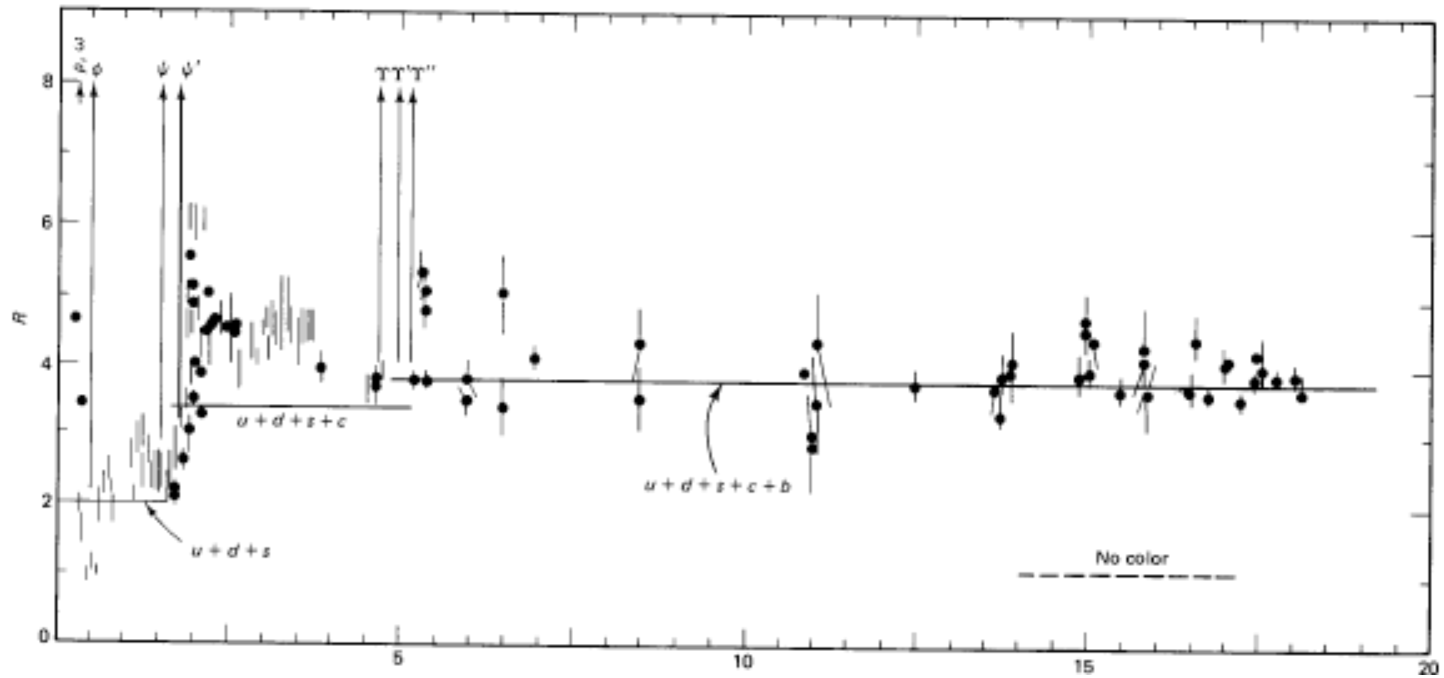


$= 3 * \Sigma q_q^2$ for ($2 m_q < \sqrt{s}$)

colors

$3*((2/3)^2+(1/3)^2+(1/3)^2 \quad +(2/3)^2 \quad +(1/3)^2)$

2 …….. 3.33 …. 3.66



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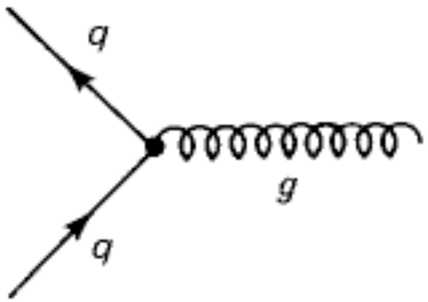
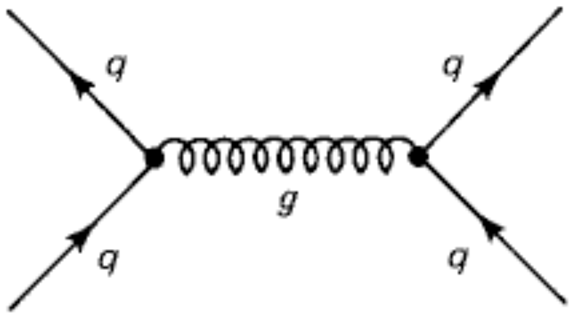
QCD(1)

In Quantum Cromo Dynamics the color plays the role of the electric charge The fundamental process is:

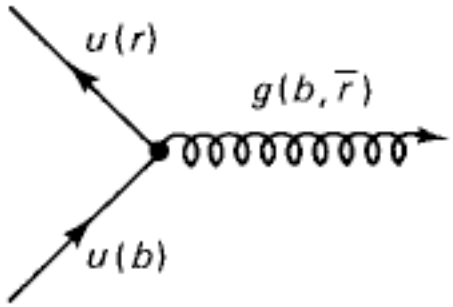


And the force between two quarks is described by



QCD(2)

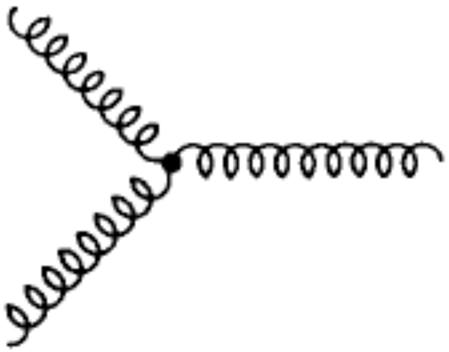
However differently from QED, the color of the quark may change , and so gluons must units of color:

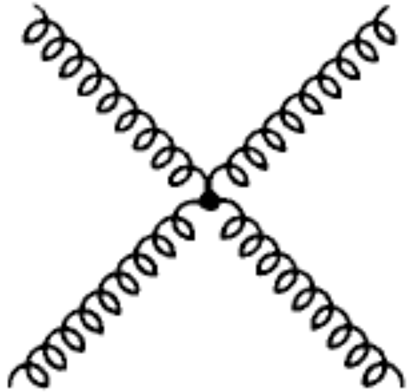


How many different gluons ? One may think ~ 9 … however this is not the case. There are 8 gluons !

QCD(3)

Gluons carry color --> gluons interact !





And the situation, already complicate becomes even more complicate since the coupling constant is large ! This means that more and more graph contribute…. no converging series

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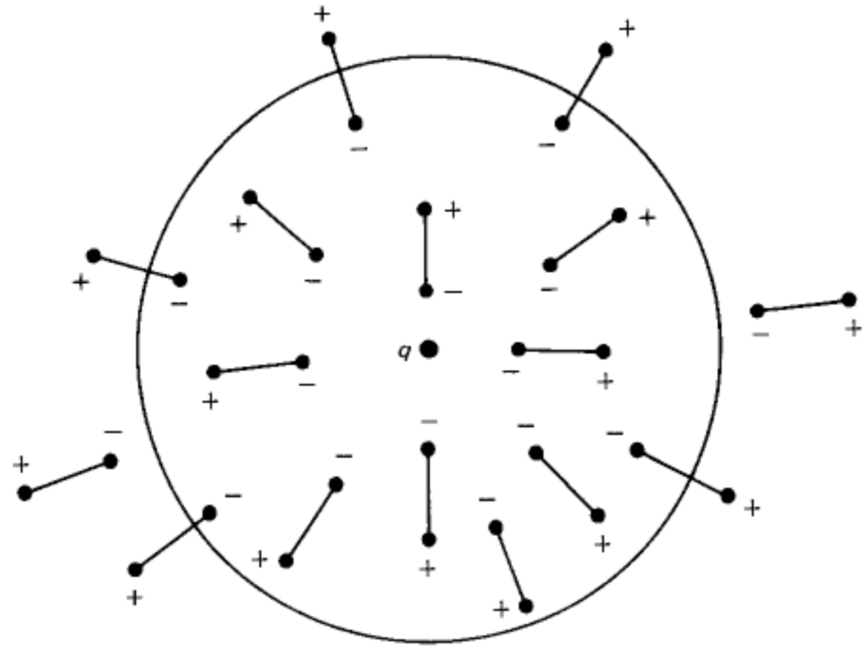
Screening

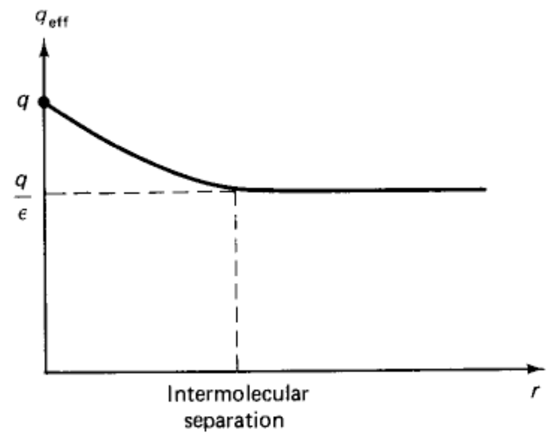


Electric charge in a medium

$q_{eff} = q/\varepsilon$

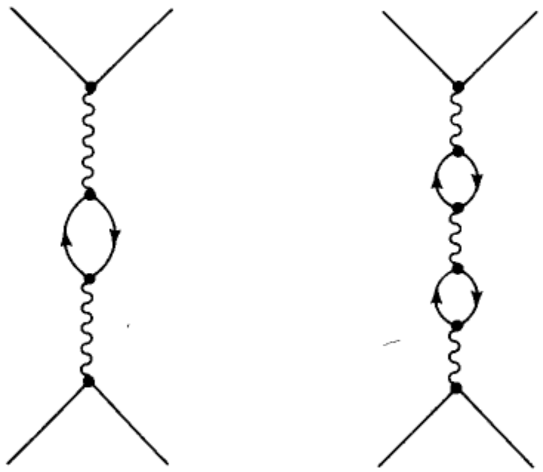
However , when we go very close the change increases:

How close ?



QED and Vacuum polarization

The Vacuum is NOT vacuum , it can sprout electron positron pairs in diagrams like:



Depending how close you are to the charge you see more charge….

What is the scale ? The only scale we have is the mass of the particle and so the relevant length scale is

λ_c=h/mc = 2.4 10^{-10} cm

$\alpha_{qed}(0) = 1/137$

$\alpha_{qed}(100\ \text{GeV}) = 1/128$

In QED the coupling constant INCREASES at decreasing distances i.e. high Q^2

What we have always called "the charge of the electron" is actually the fully screened effective charge.

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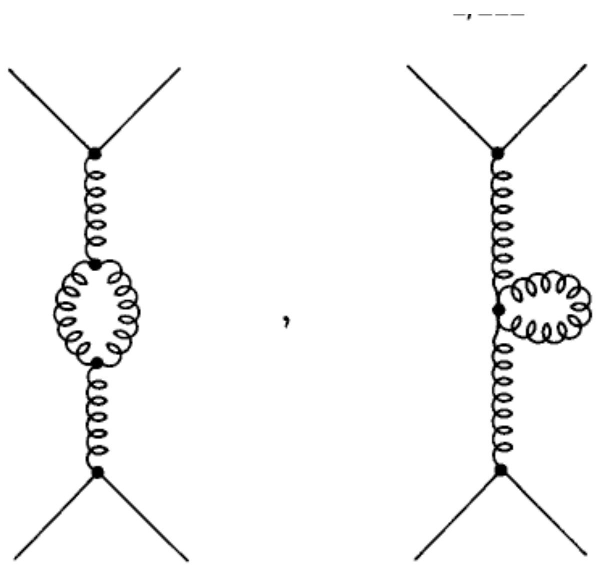
QCD and Vacuum Polarization

In QCD we have a similar effect, however there are two kinds of colored objects, quarks and gluons. And in addition to diagrams similar to QED (but involving now quarks) we have also diagrams for vacuum polarization by gluons:



The net effect of these diagrams is OPPOSITE to those of the quarks

The critical parameter of the theory is

a= 2*n_flavors-11*n_colors

In the nature n_flavors=6 and n_colors=3

a=-21 , negative --->The coupling strength DECREASES at short distances.

ASYMPTOTIC FREEDOM !

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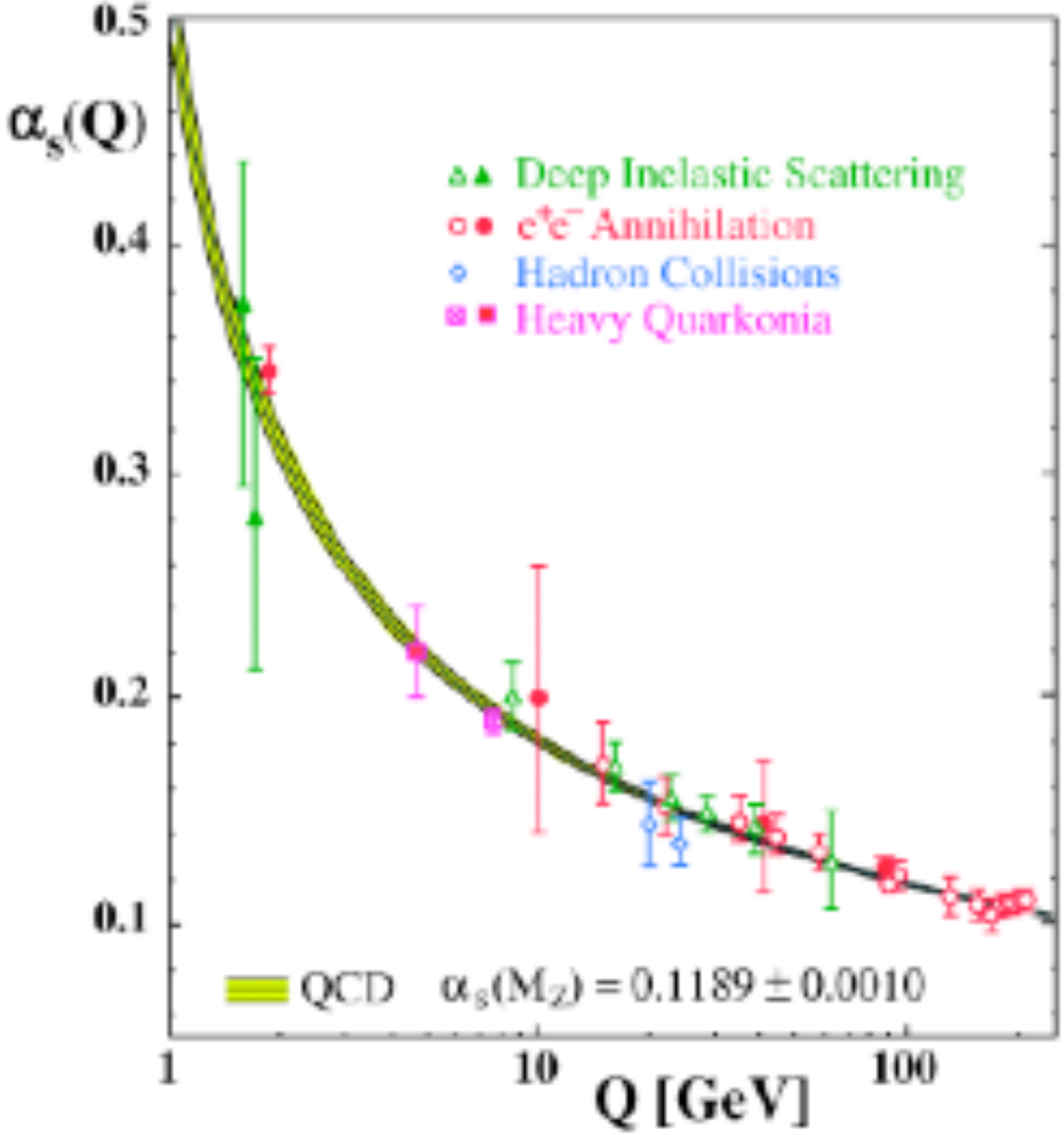
Running of alpha_strong



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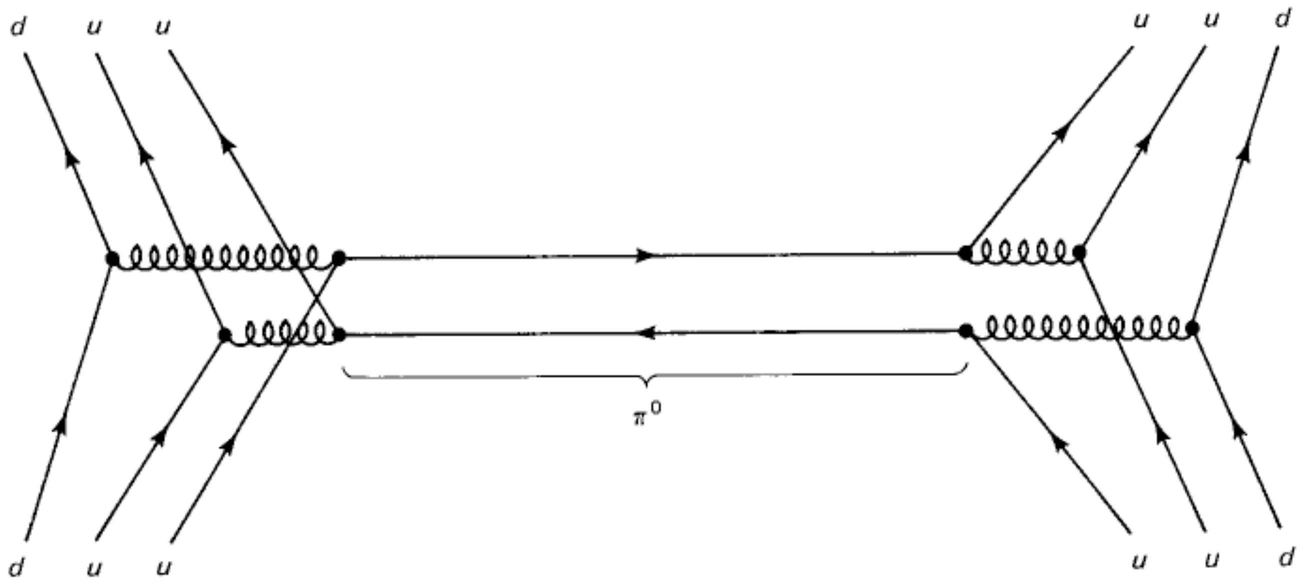
Strong interaction and confinement

Another important difference between QED and QCD is that whereas many free particle carry charge, there is no evidence of free particle carrying color.



This makes calculation difficult. Above is one among many diagrams describing the interaction among two protons.

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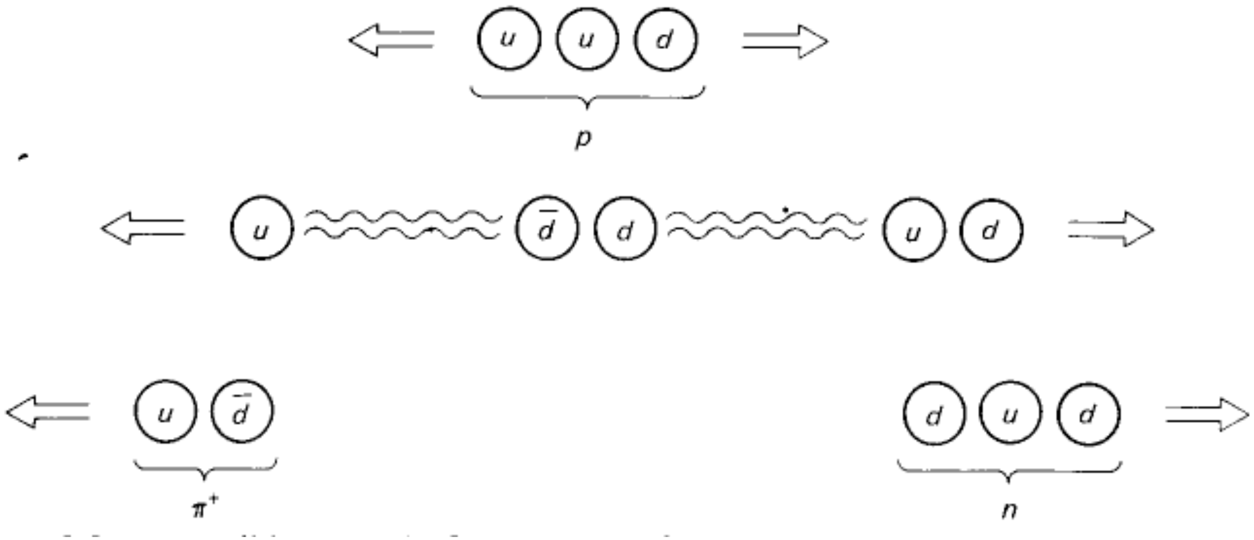
Running of alpha and quark confinement

The confinement has not been proven yet in QCD. However one can imagine that the potential energy increases enormously when quarks are pulled further and further apart. This has inspired the “string” models that are the basis of any QCD Montecarlo:



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Screening in QCD and QED

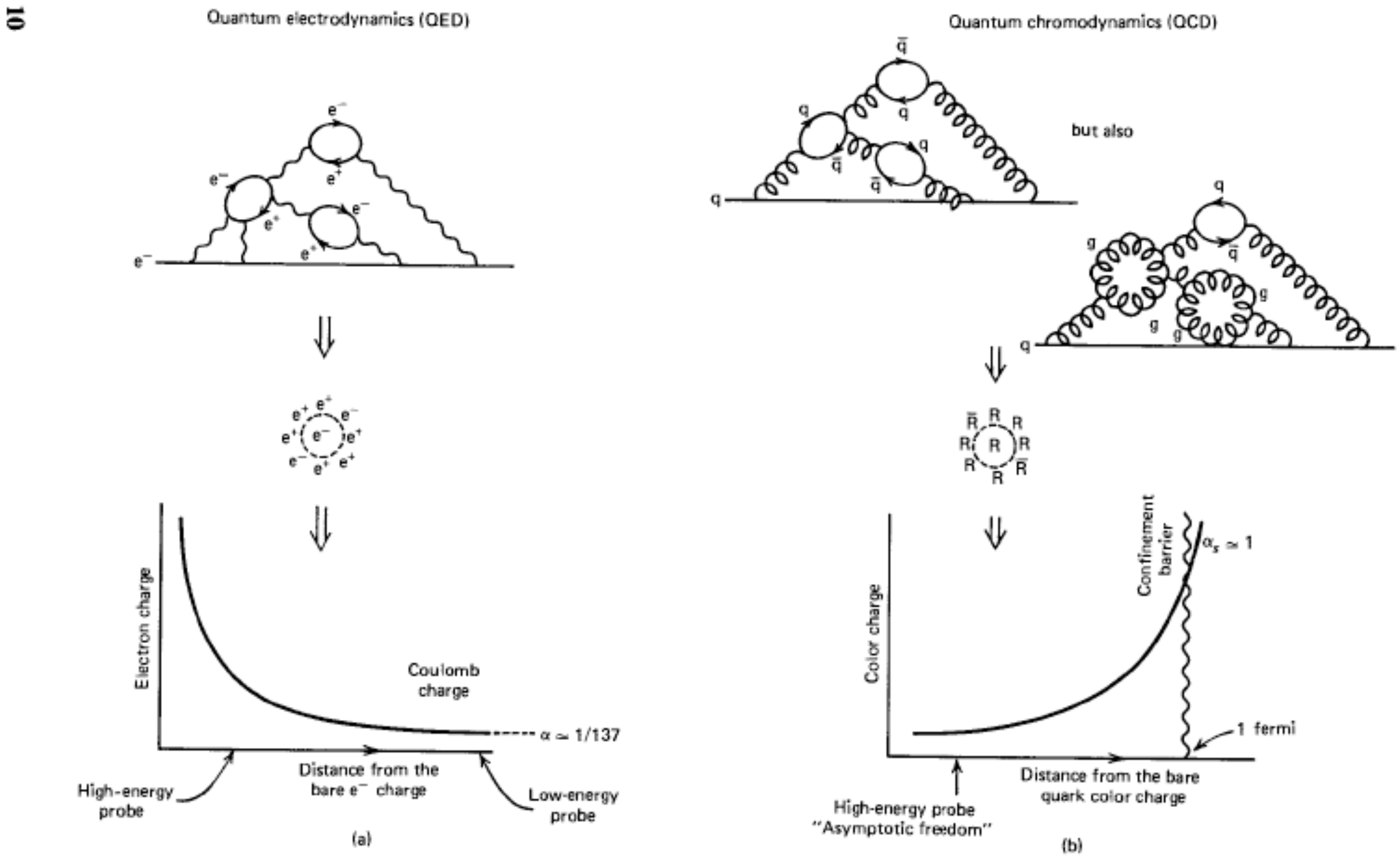
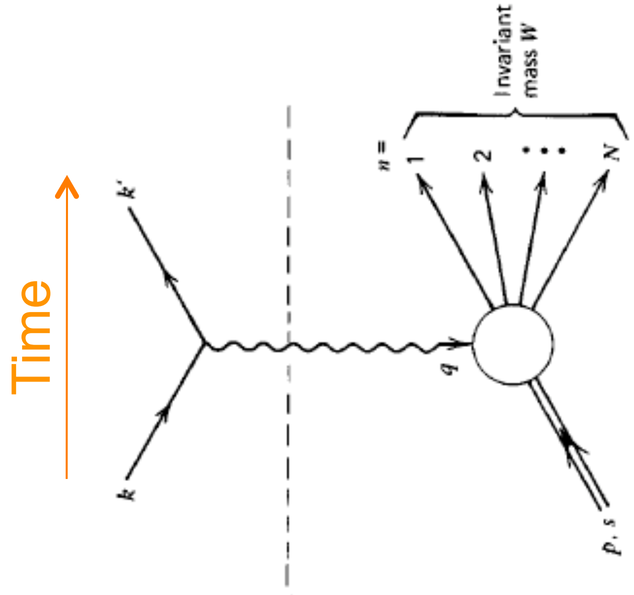


Fig. 1.5 Screening of the (a) electric and (b) color charge in quantum field theory.

Electron proton scattering



At high Q^2 probes the quarks INSIDE the proton. Only quarks and NOT gluons that are electrically neutral

Fraction of momentum carried by the quarks

$$\frac{1}{2}\int_0^1 [F_2^p(x)+F_2^n(x)]dx = \frac{Q_u^2+Q_d^2}{2}\int_0^1 x[u_p(x)+\bar{u}_p(x)+d_p(x)+\bar{d}_p(x)]dx$$

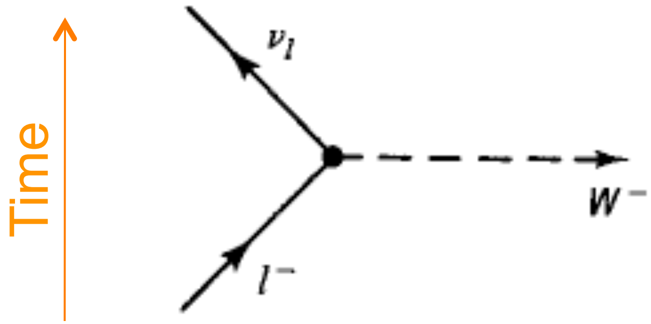
= 0.140±0.005 0.28

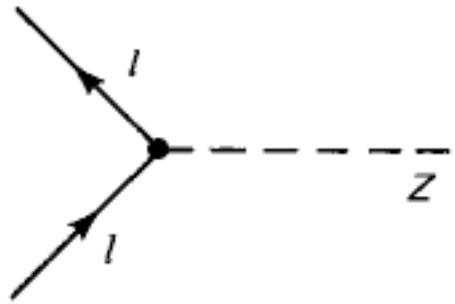
measured

There are electrically neutral objects in the proton that carry ~ 50% of its momentum !

Weak Interaction

There is no definition of “charge” for the weak interaction: all particles experience the weak interaction. There are two types of weak interactions: charge current and neutral current:





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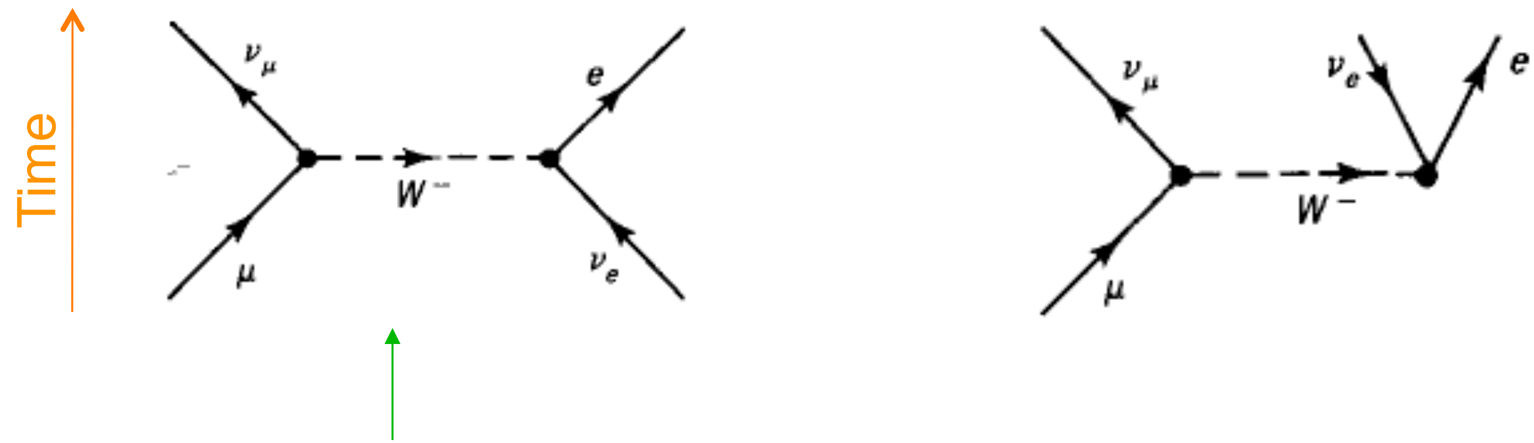
Example of cc Muon scattering and decay



Why is this very difficult experimentally ?

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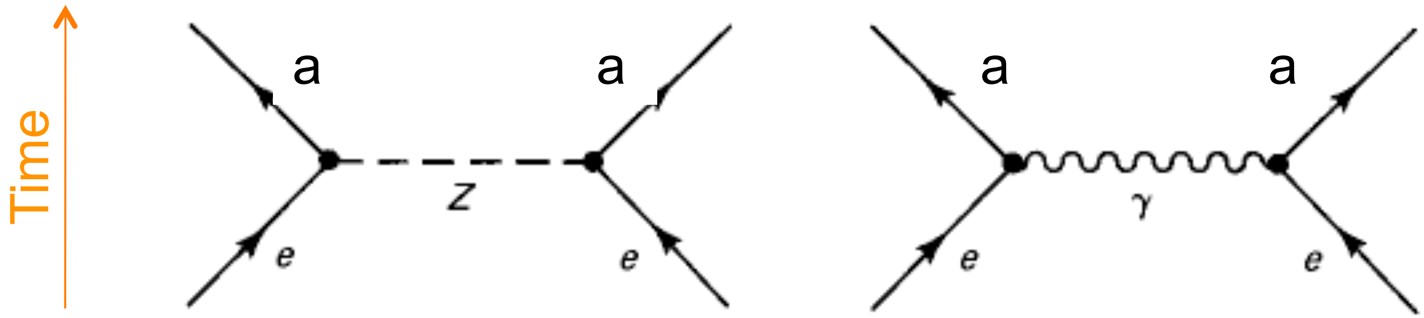
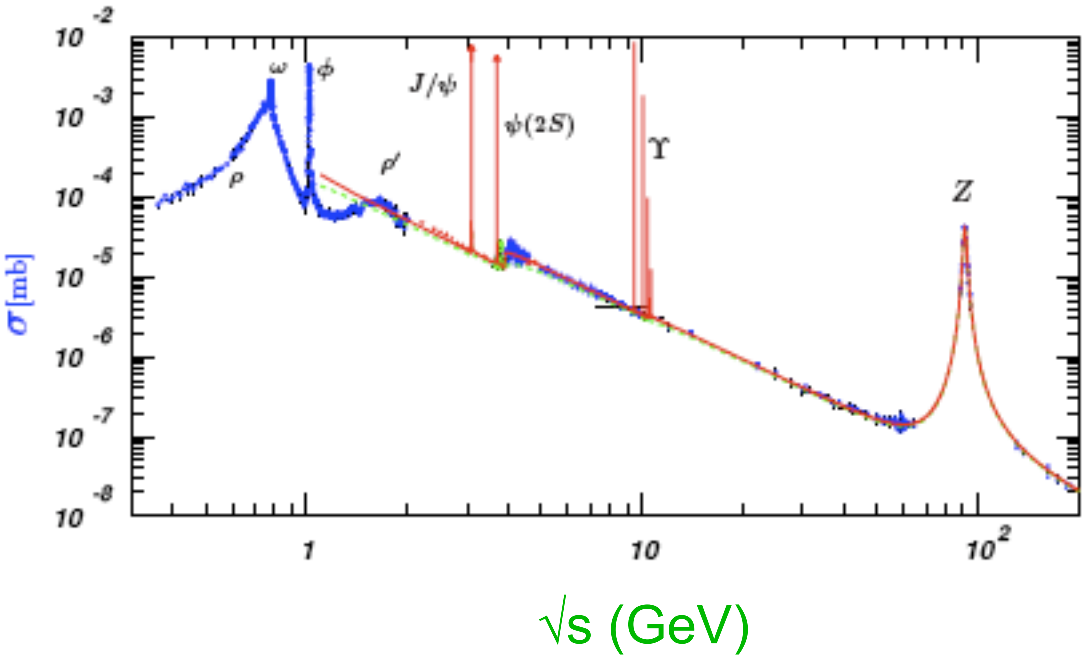
Example of nc : e+e- annihilation

At low Q2 the weak processes are masked by the electromagnetic ones





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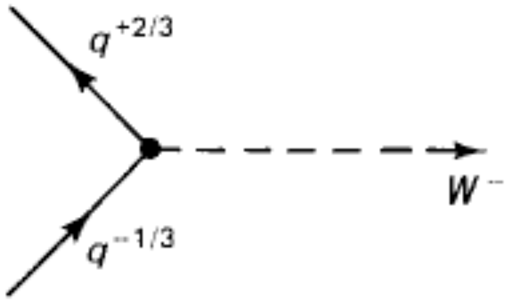
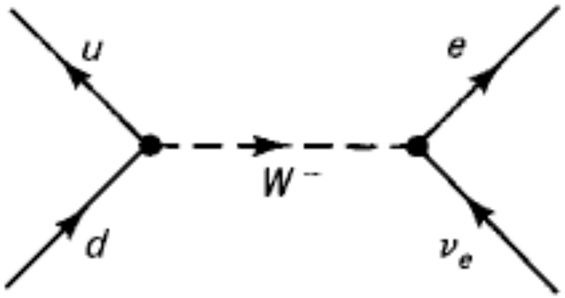
Weak interactions of quarks

In the weak interaction of leptons the vertex connect always members of the same generation. This enforces the conservation of the Leptonics numbers (e, mu and tau separately).





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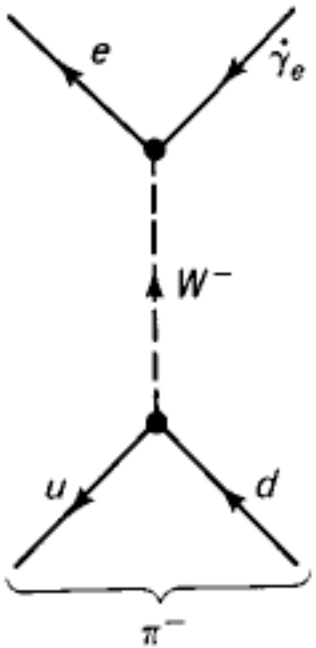
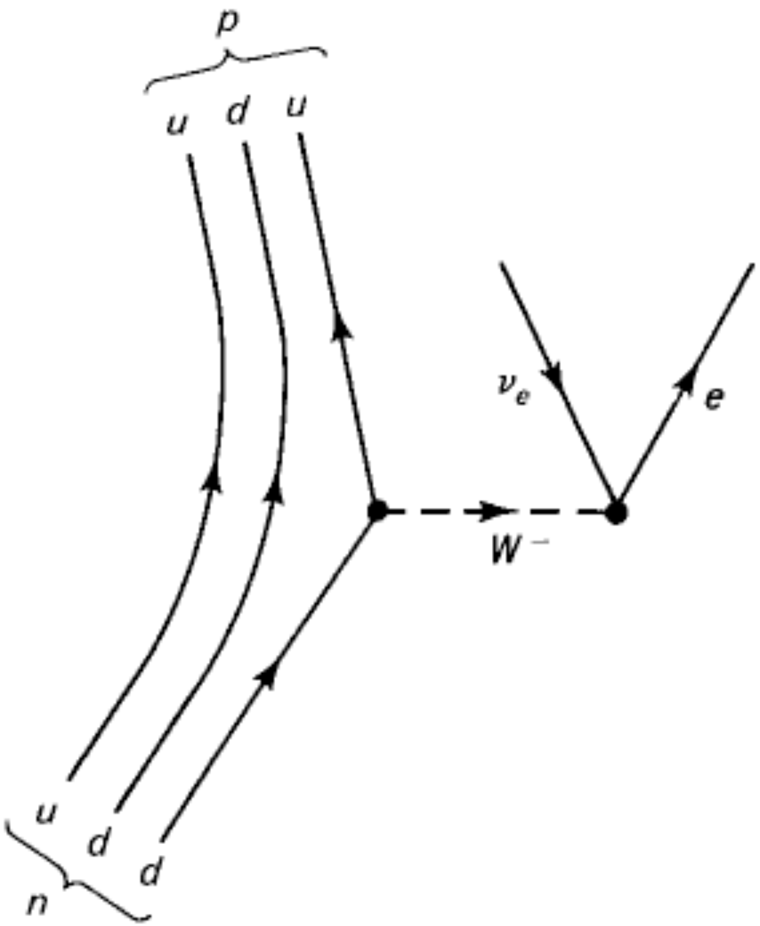
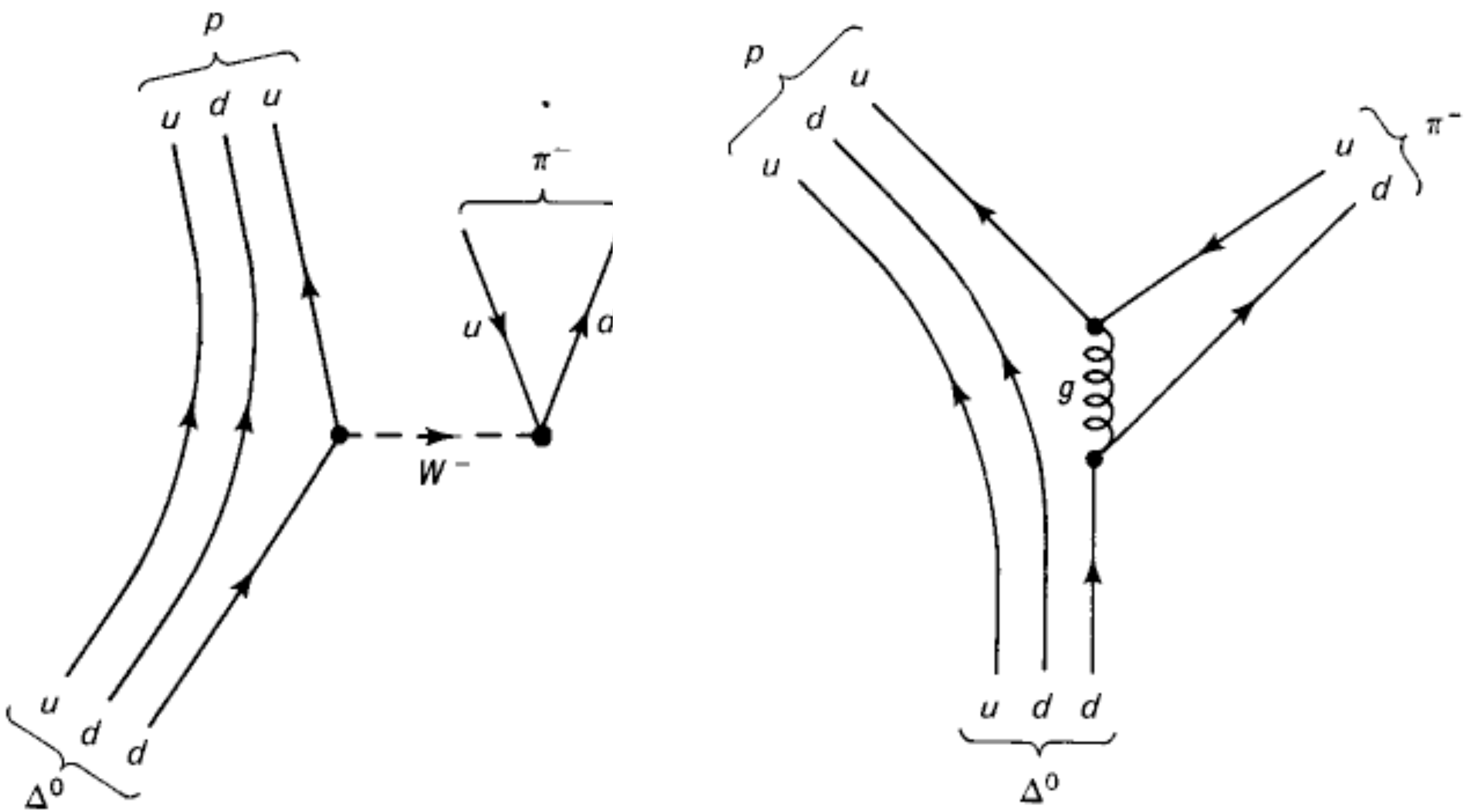
Pion decay - Neutron decay





However most common decay is into muons…

Delta weak and strong decay



why this does not held for the neutron ?

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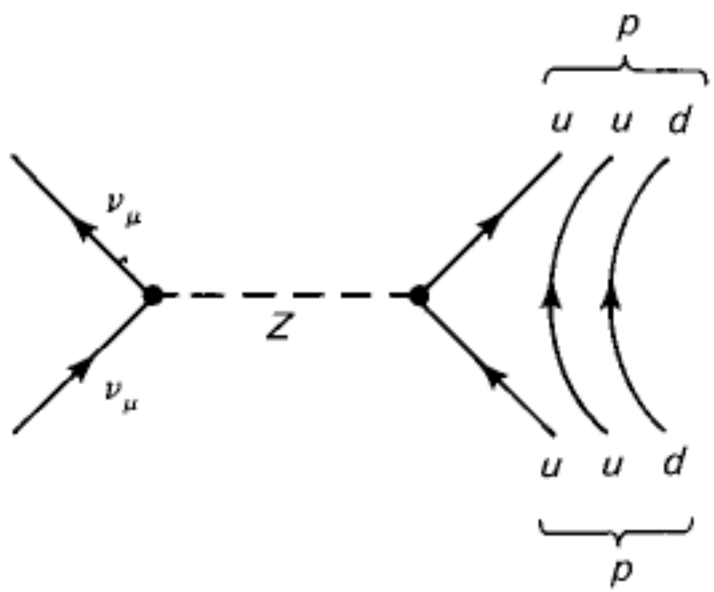
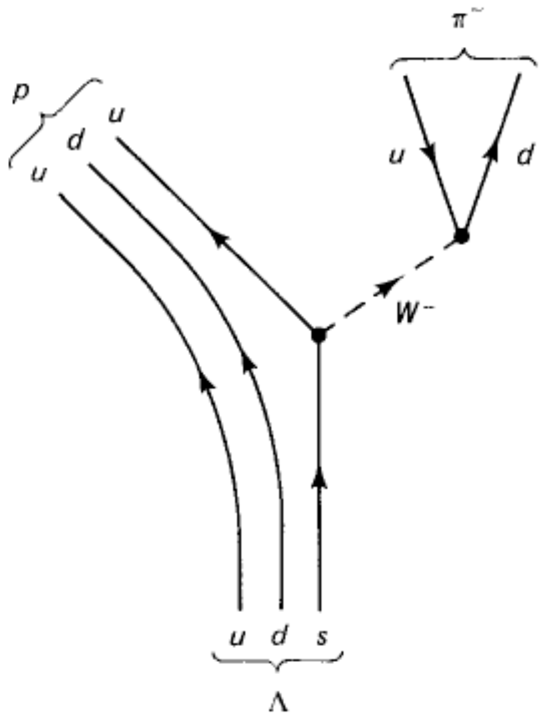
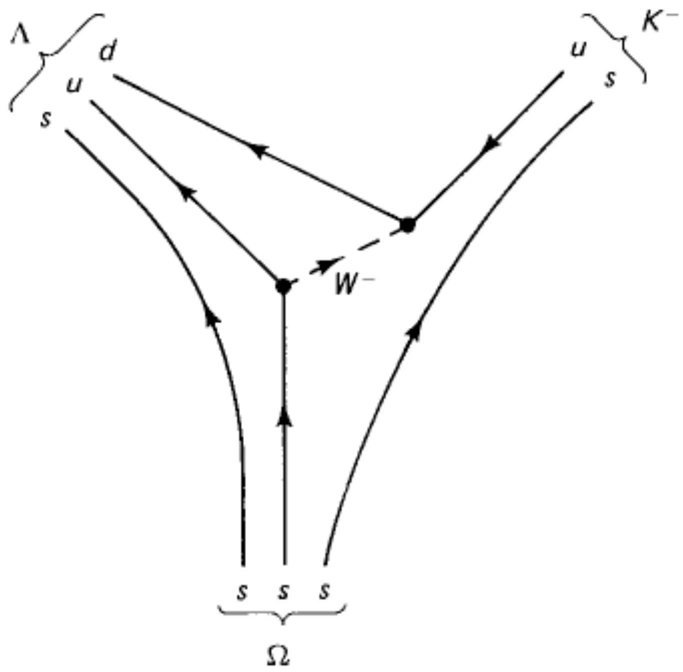
Neutrino-Neutrino Scattering



Strangeness change

This picture is ok, but is too simple. If we can operate in a single generation we cannot explain the processes with change of strangeness





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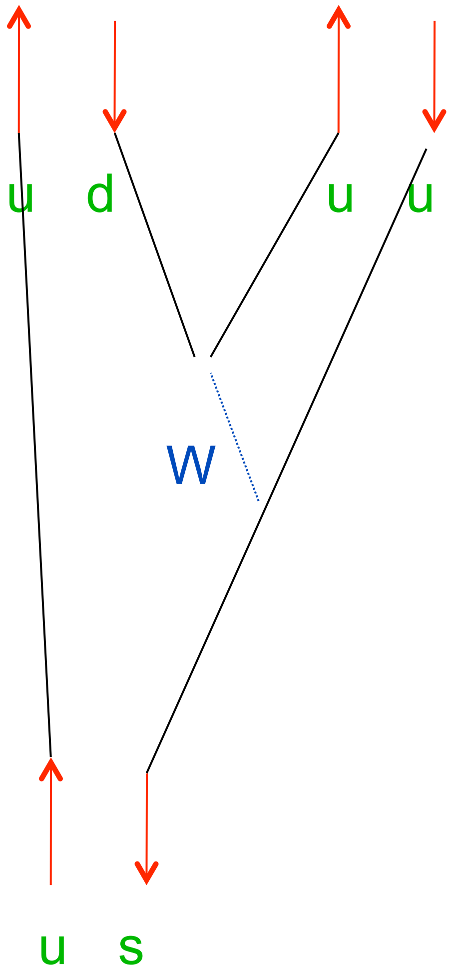
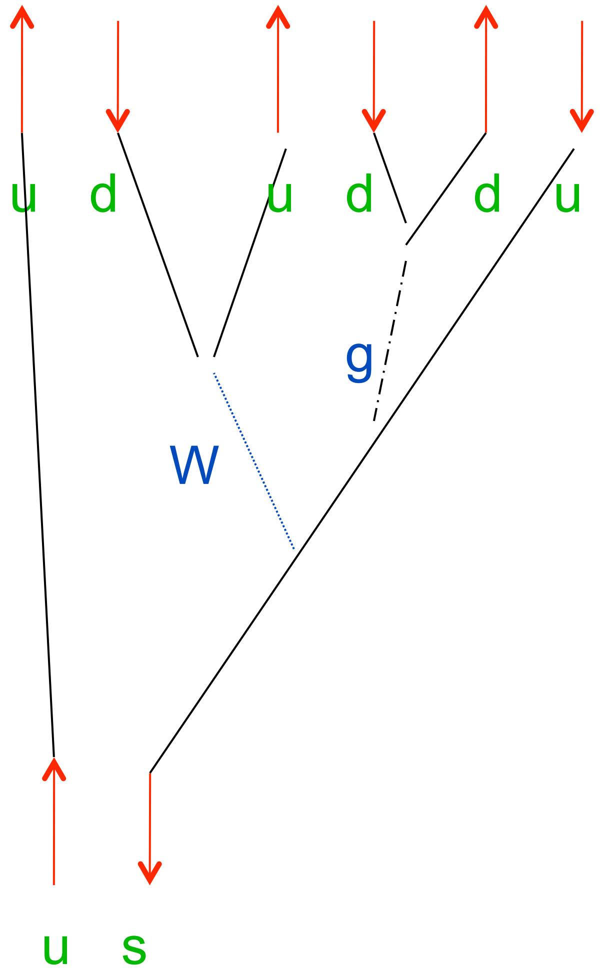
Esercizio decadimento del K^+ e K^0

$K^+ \rightarrow \pi^+\pi^0$



$K^+ \rightarrow \pi^+\pi^-\pi^+$



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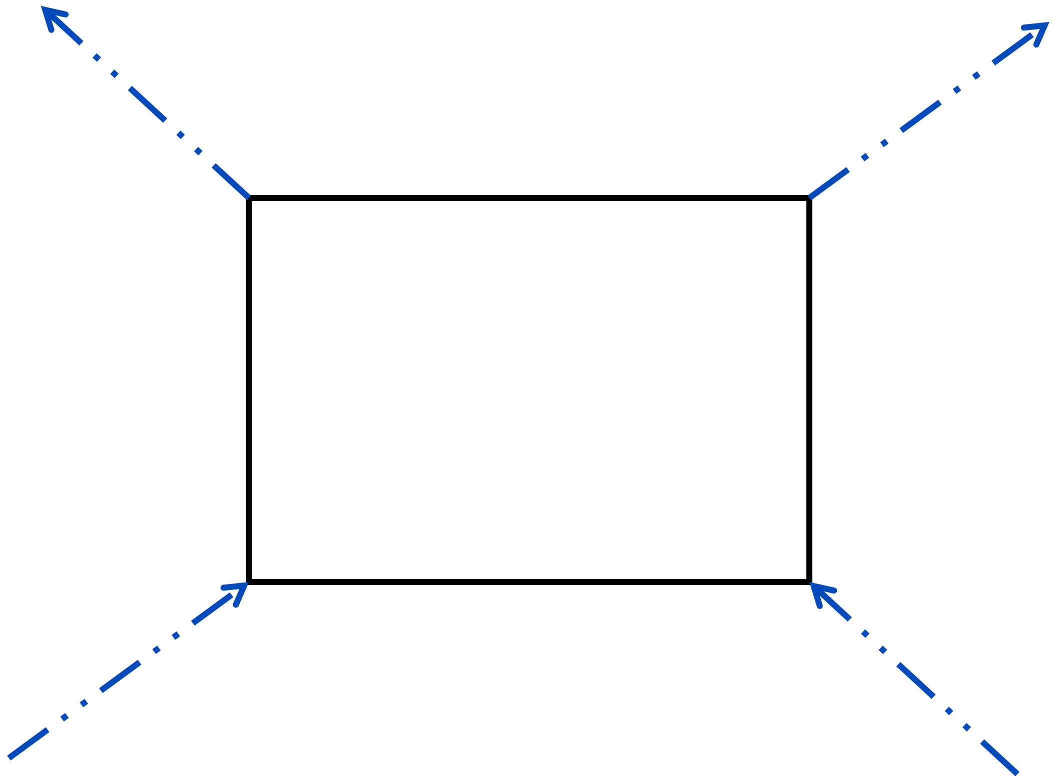
Esercizio: scattering Delbruck

$\gamma\,\gamma \longrightarrow \gamma\,\gamma$



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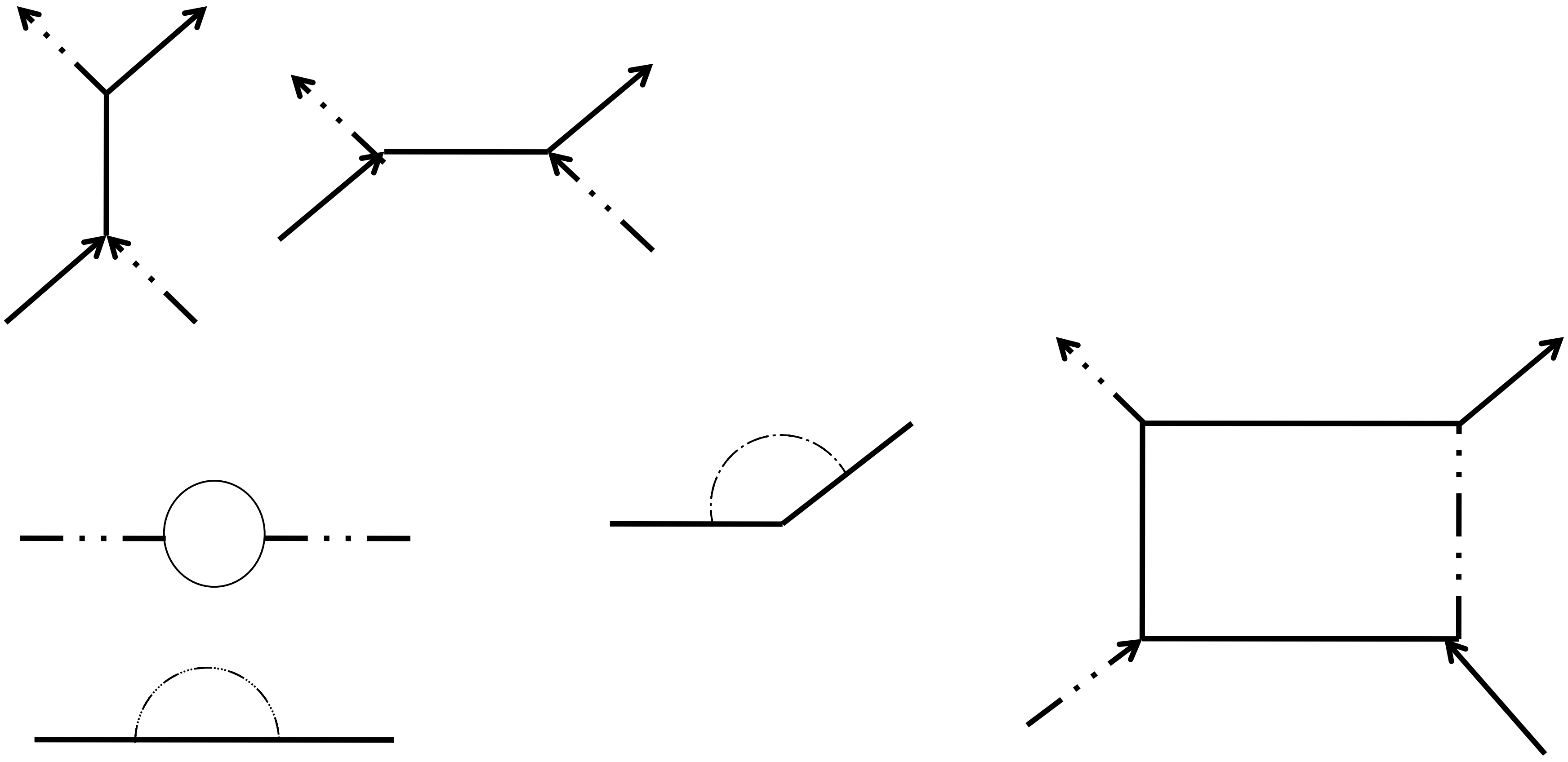
Esercizio: Compton scattering

$e\ \gamma \rightarrow e\ \ \gamma$ Scrivere i diagrammi a 4 vertici



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Esercizio

Determinare la massa e la velocita' del fotone virtuale nello scattering bhabha al LEP (45 GeV e+ e-)

Fare il diagramma per $\Xi^- \rightarrow n\ \pi$

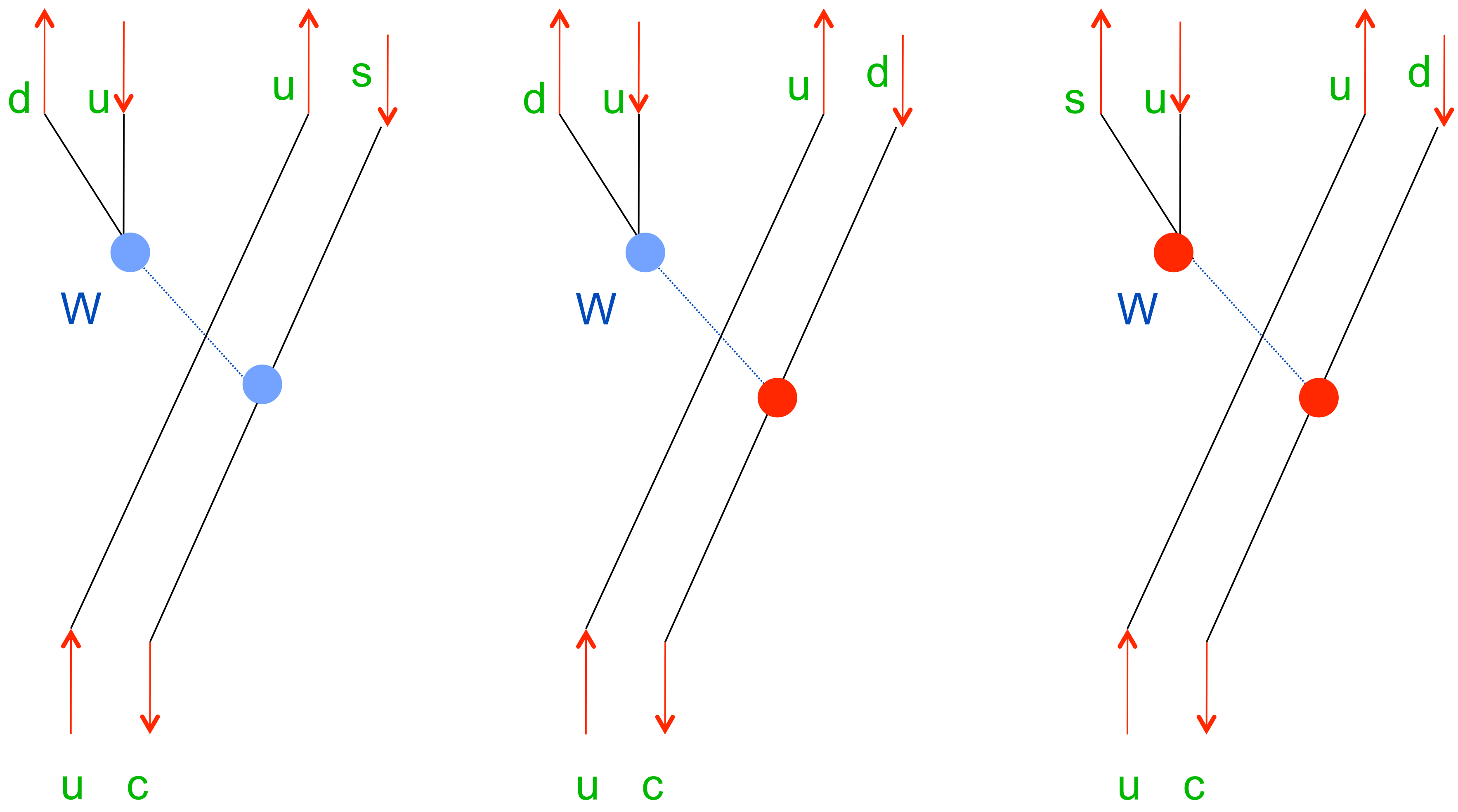
The charged current interaction si not diagonal !

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.9705 \text{ to } 0.9770 & 0.21 \text{ to } 0.24 & 0. \text{ to } 0.014 \\ 0.21 \text{ to } 0.24 & 0.971 \text{ to } 0.973 & 0.036 \text{ to } 0.070 \\ 0. \text{ to } 0.024 & 0.036 \text{ to } 0.069 & 0.997 \text{ to } 0.999 \end{pmatrix}$$

Esercizio Confrontare D decays

Confrontare $D^{0\text{-bar}}$ che va in $k^- \pi^+$ $\pi^+ \pi^-$ $k^+ \pi^-$



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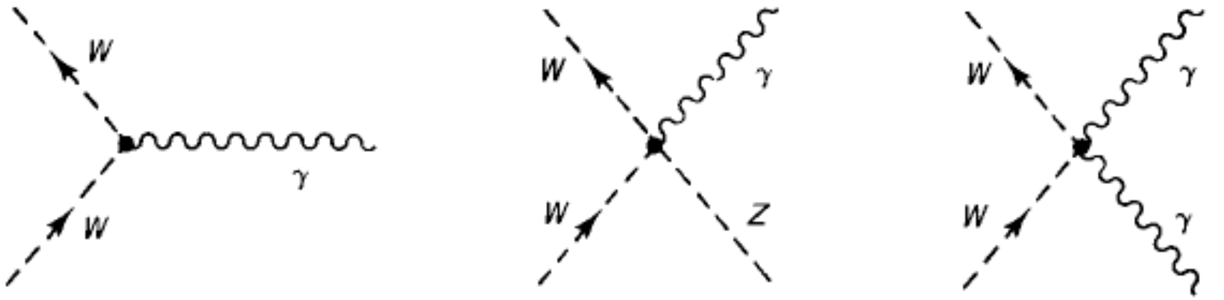
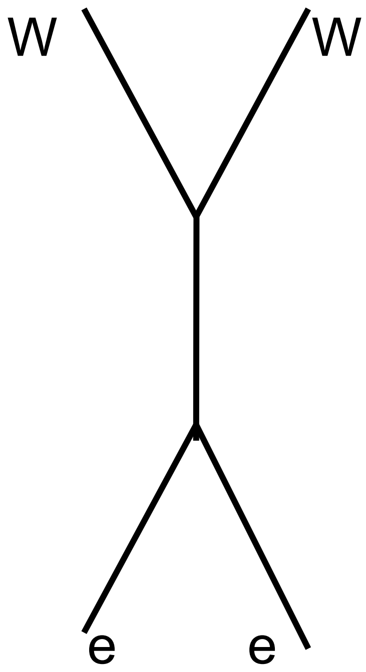
Interaction of Vector Bosons

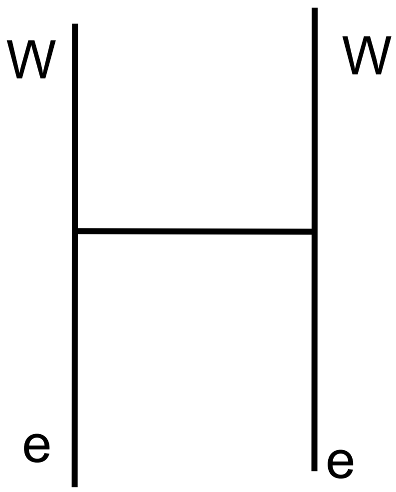
Moreover, because the W is charged, it couples to the photon:



Esercizio Disegnare I diagrammi

$e^+ e^- \rightarrow W^+ W^-$





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Conservation laws and Feynman graphs

- Conservation of energy and momentum
- Conservation of charge
- Conservation of color
- Conservation of quarks (aka conservation of barion number)
- Conservation of Leptonic numbers
- Approximate conservation of flavor (not for weak interactions)

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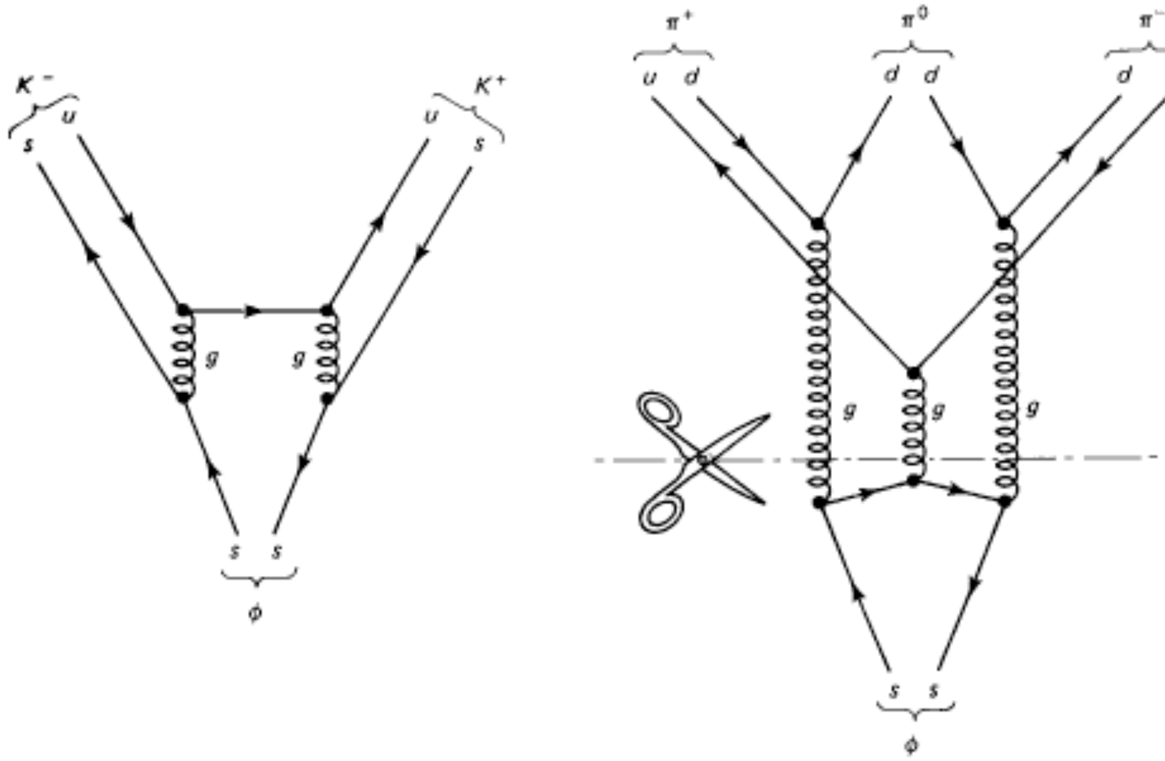
Decays and Conservation laws

(a) $p + \bar{p} \rightarrow \pi^+ + \pi^0$
(b) $\eta \rightarrow \gamma + \gamma$
(c) $\Sigma^0 \rightarrow \Lambda + \pi^0$
(d) $\Sigma^- \rightarrow n + \pi^-$
(e) $e^+ + e^- \rightarrow \mu^+ + \mu^-$
(f) $\mu^- \rightarrow e^- + \bar{\nu}_e$
(g) $\Delta^+ \rightarrow p + \pi^0$
(h) $\bar{\nu}_e + p \rightarrow n + e^+$
(i) $e + p \rightarrow \nu_e + \pi^0$
(j) $p + p \rightarrow \Sigma^+ + n + K^0 + \pi^+ + \pi^0$
(k) $p \rightarrow e^+ + \gamma$
(l) $p + p \rightarrow p + p + p + \bar{p}$
(m) $n + \bar{n} \rightarrow \pi^+ + \pi^- + \pi^0$
(n) $\pi^+ + n \rightarrow \pi^- + p$
(o) $K^- \rightarrow \pi^- + \pi^0$
(p) $\Sigma^+ + n \rightarrow \Sigma^- + p$
(q) $\Sigma^0 \rightarrow \Lambda + \gamma$
(r) $\Xi^- \rightarrow \Lambda + \pi^-$
(s) $\Xi^0 \rightarrow p + \pi^-$
(t) $\pi^- + p \rightarrow \Lambda + K^0$
(u) $\pi^0 \rightarrow \gamma + \gamma$
(v) $\Sigma^- \rightarrow n + e + \bar{\nu}_e$

Examine the following processes, and state for each one whether it is possible or impossible, according to the Standard Model In the former case, state which interaction is responsible—strong, electromagnetic , or weak; in the latter case cite a conservation law that prevents it from occurring.

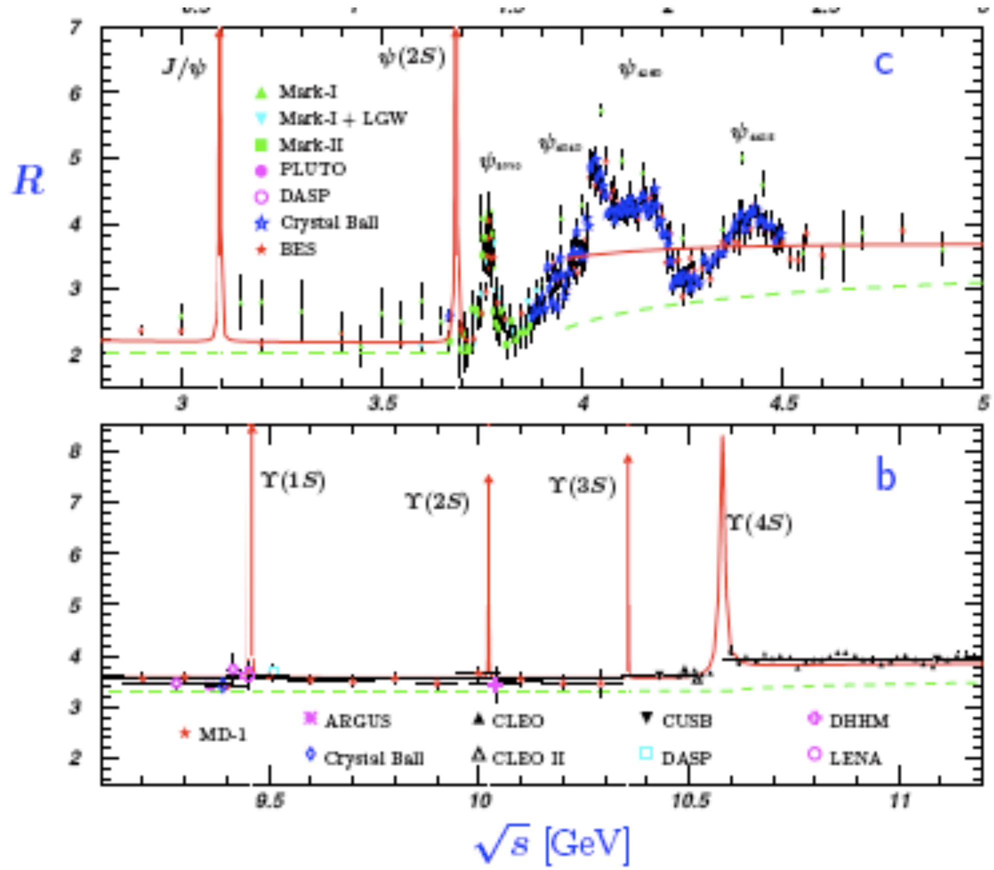
OZI Rule



The decay of the psi, which is a bound state of the charmed quark and its antiquark. The psi has an anomalously long lifetime (~10^{-20} sec); the question is, why? It has nothing to do with conservation of charm; the net charm of the psi is zero. The psi lifetime is short enough so that the decay is clearly due to the strong interactions. But why is it a thousand times slower than a strong decay "ought" to be? The explanation (if you call it that) goes back to an old observation by Okubo, Zweig, and Iizuka, known as the "OZI" rule.

Esercizi su OZI

The upsilon meson, bb, is the bottom-quark analog to the ψ, cc. Its mass is 9460 MeV/c2, and its lifetime is 1.5 X 10^{-20} sec. From this information, what can you say about the mass of the B meson. (The observed mass is 5270 MeV/c2.)



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Esercizi su OZI

The ψ' meson, at 3685 MeV/c2, has the same quark content as the ψ (i.e., cc). Its principal decay mode is ψ' —> ψ + π+ + π~. Is this a strong interaction? Is it OZI-suppressed? What lifetime would you expect for the ψ'! (The observed value is3 X 10^{-21} sec.)

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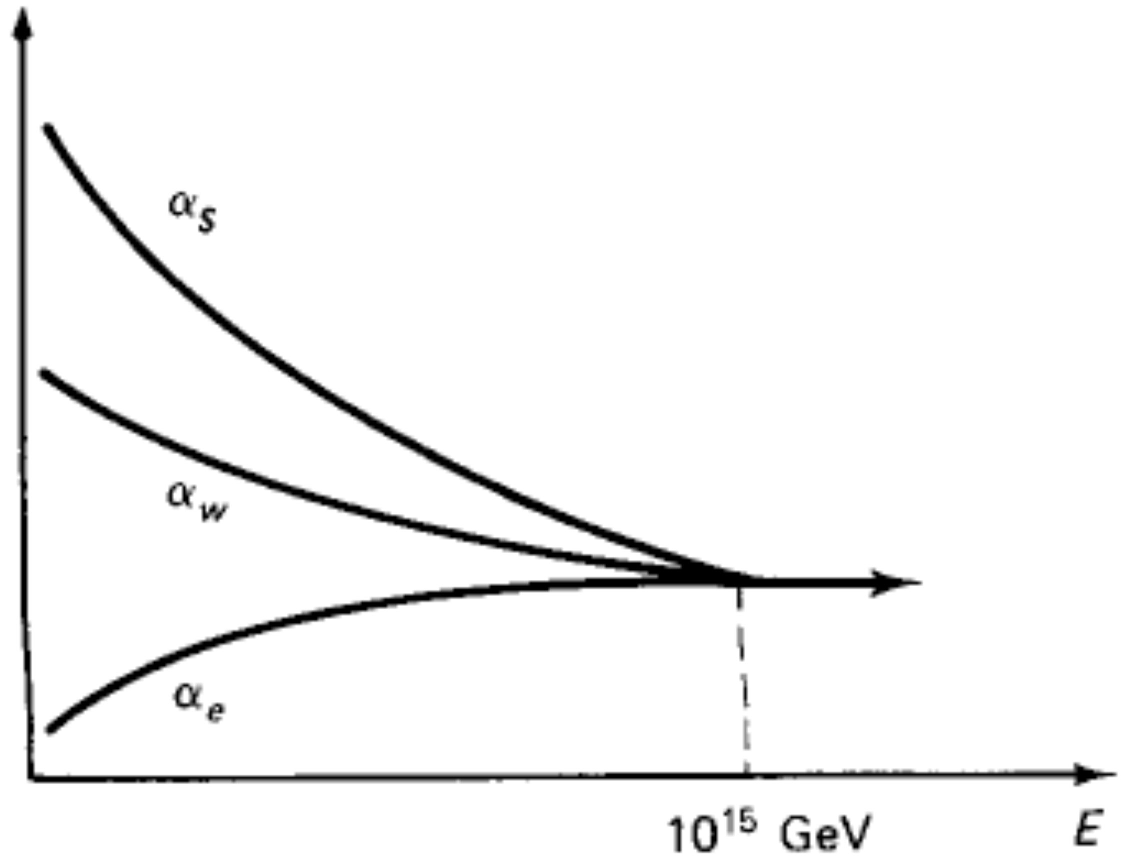
Unification



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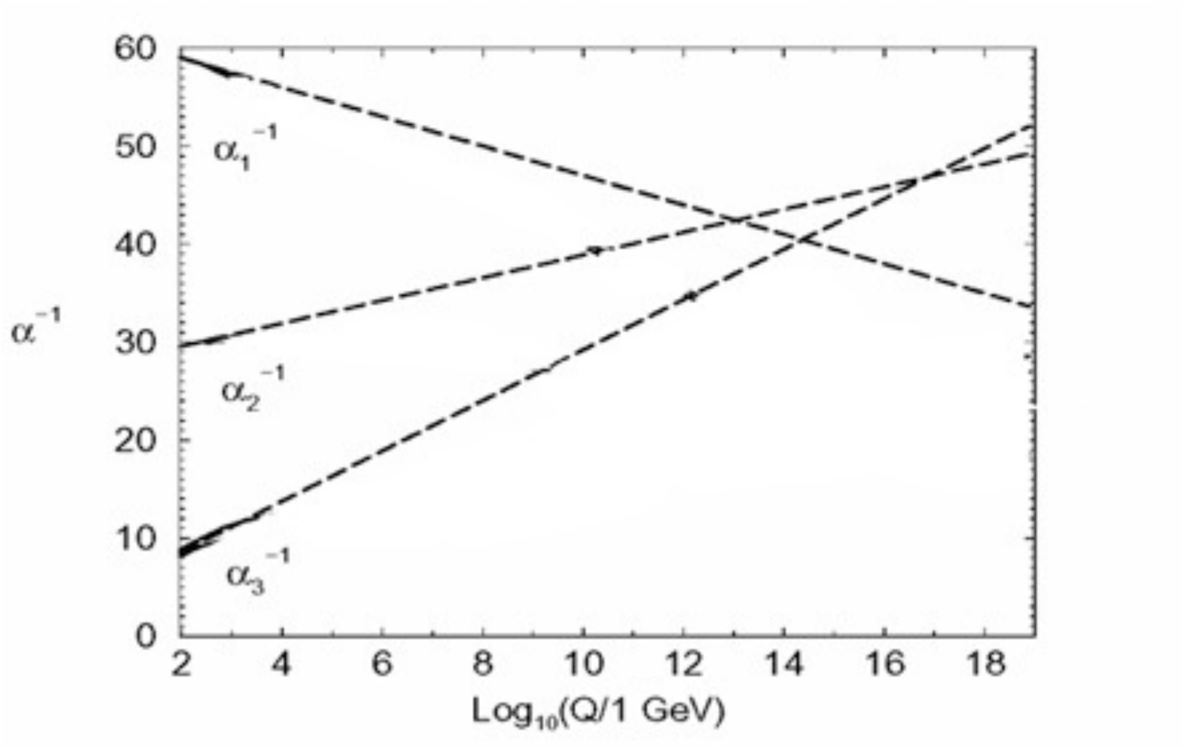

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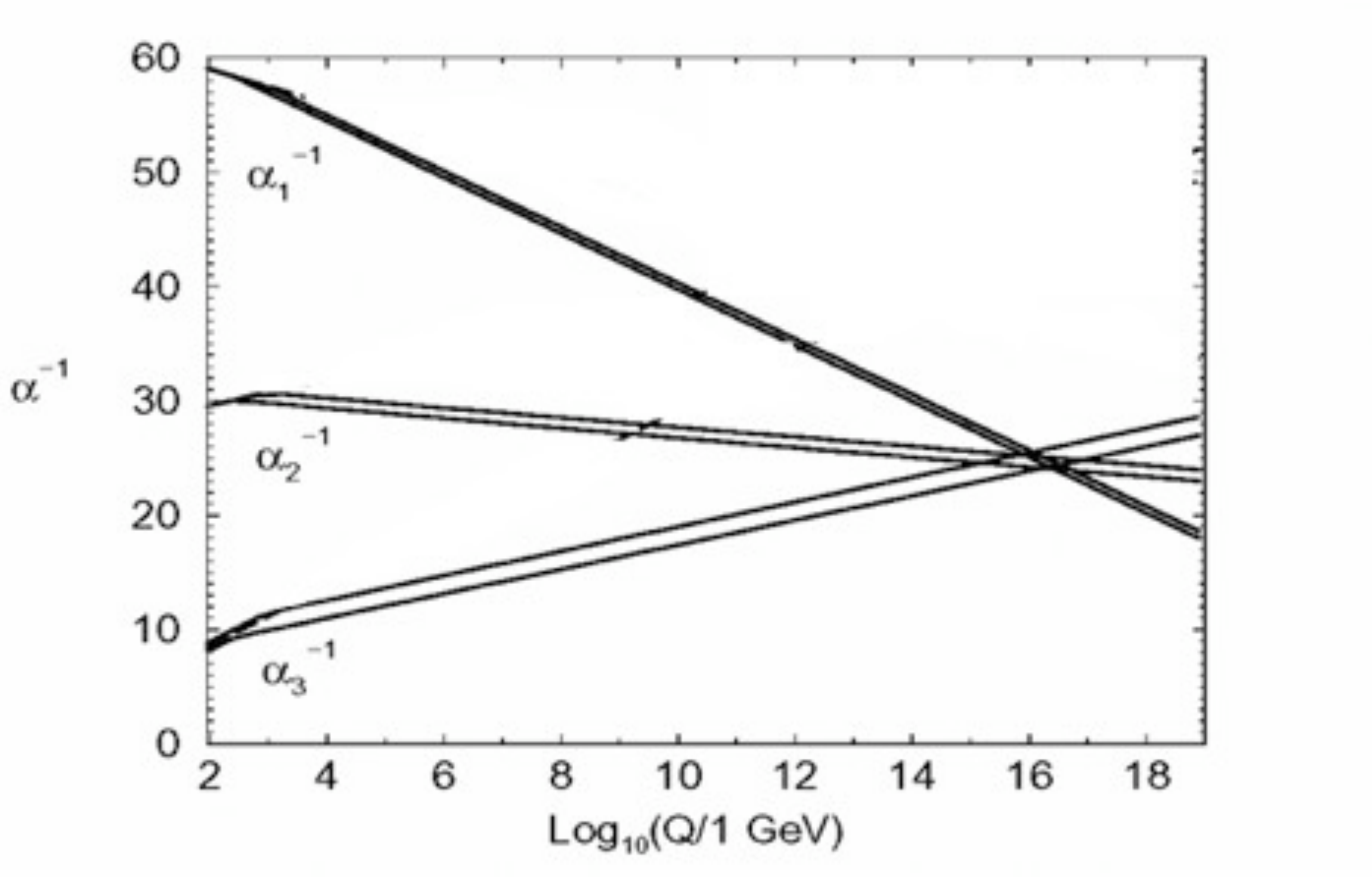

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