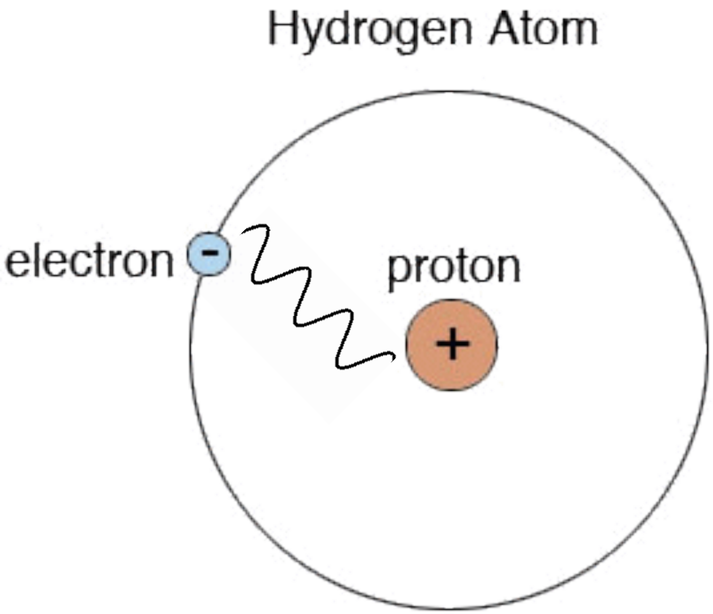
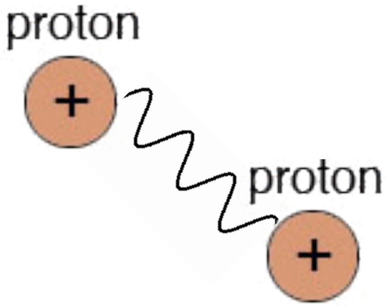
On to Feynman diagrams

Reminder of what we mean by force carriers



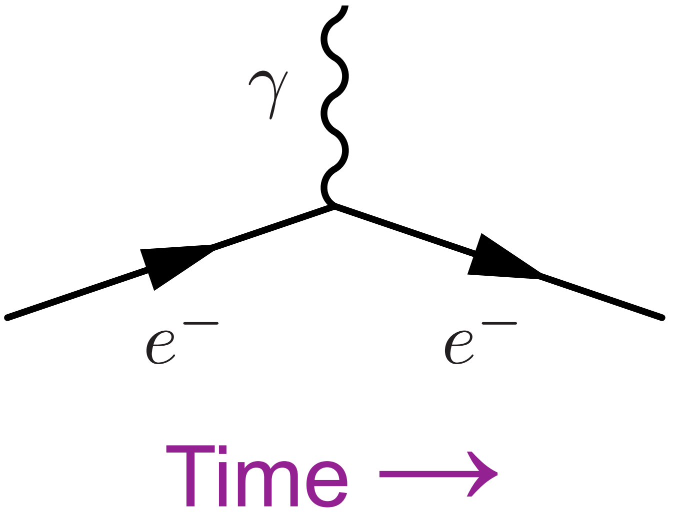
Photon as a particle (classical). But of course, what we really mean is that the field is quantized (here providing an attractive force), and the quantized unit of the field transmits some momentum from one object to another

But these forces can also be repulsive (more intuitive, actually)



Photon are still exchanged here, but now they transmit a repulsive force. It’s a bit counterintuitive to think of forces being transmitted (or even better, ‘mediated’) by particles, especially on a macroscopic scale, but we are anyway talking about single particles

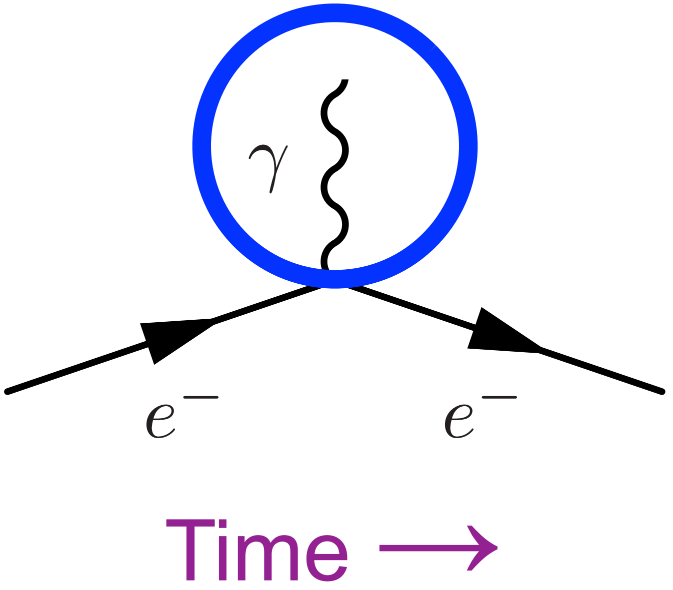
Feynman diagram



Think of time “passing” to the right, so initially, we start with an electron. And in the final state, we end with an electron, and at some intermediate time, there is a photon interacting with this electron (whether it emits it or absorbs it). We can combine multiple such diagrams

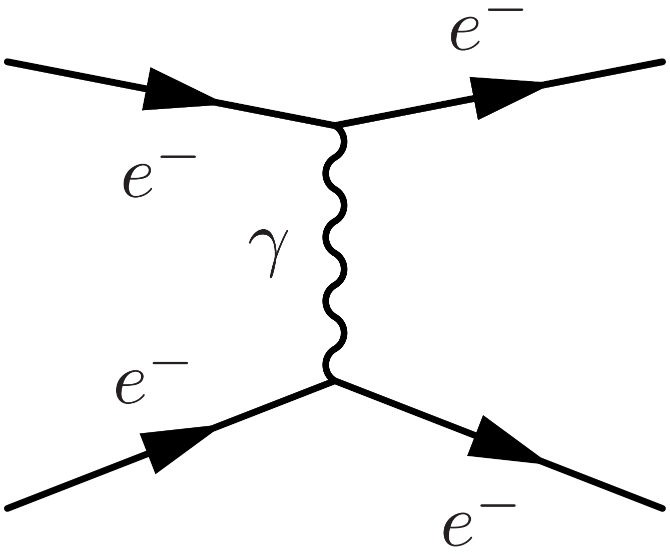
Feynman diagram

Note: Photon gets a squiggly line!



Think of time “passing” to the right, so initially, we start with an electron. And in the final state, we end with an electron, and at some intermediate time, there is a photon interacting with this electron (whether it emits it or absorbs it). We can combine multiple such diagrams

Feynman diagram

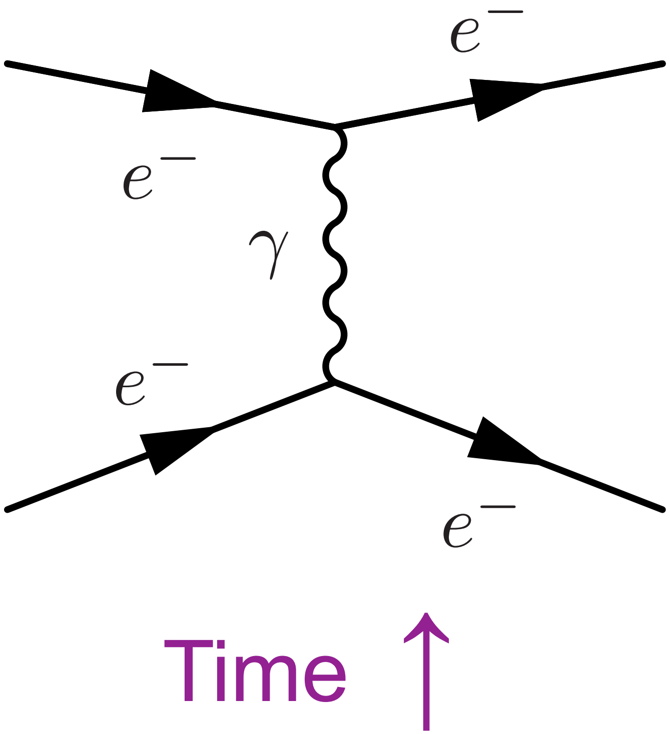


Time $\longrightarrow$

At some initial time, there were two separate electrons. At a later time, there were also two electrons. At an intermediate time, they were exchanging a photon between them (repulsive force)

Møller scattering

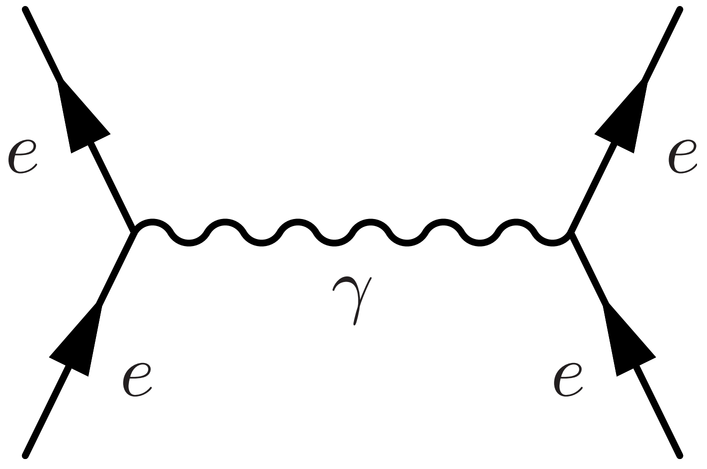
Feynman diagram



What happens if we just change the direction of time? Everyone turn your heads now :)

Does this remind you of anything from earlier in the course?

Feynman diagram (I turned things for you)



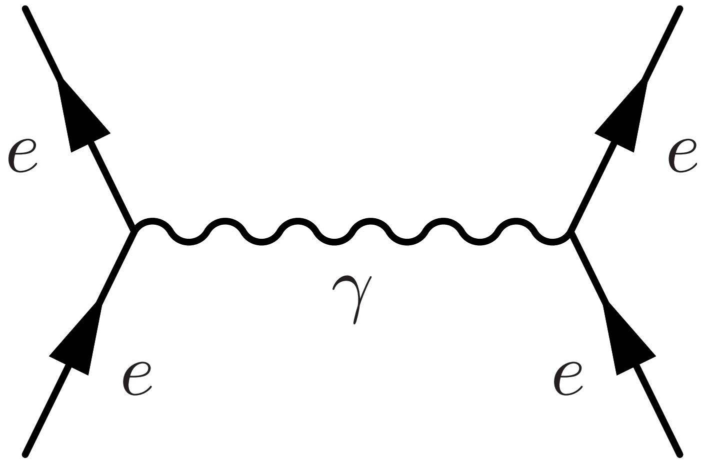
Time ⟶

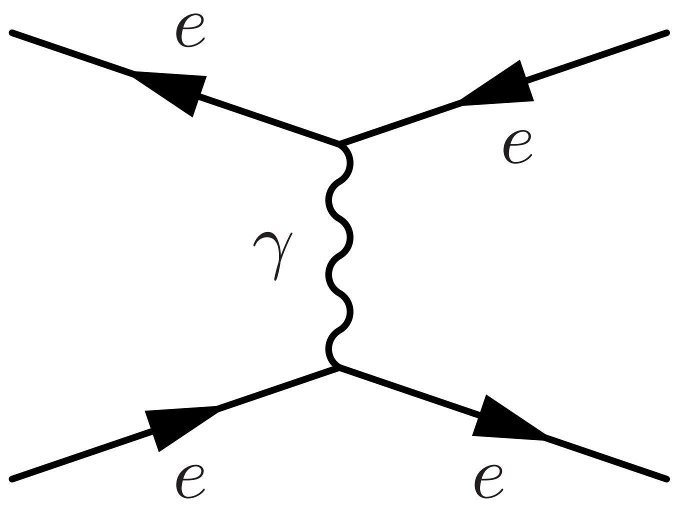
Electron vs positron should now be more obvious/automatic

Here I put things back such that time moves to the right. Note that in the initial time (on left) there is a fermion line moving backwards! This is an antiparticle moving forwards in time. And on the right there is a fermion line also going backwards, this is again an anti-particle

Feynman diagrams

Bhaba scattering

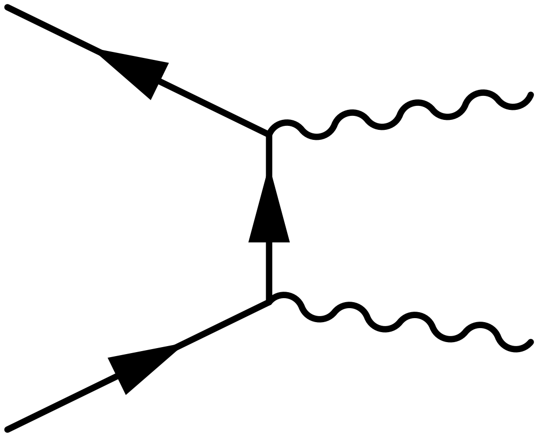




Note the second diagram below... start with e^+e^- and end with e^+e^- ... these two diagrams are both needed (same initial and same final states, so they must interfere quantum mechanically!)

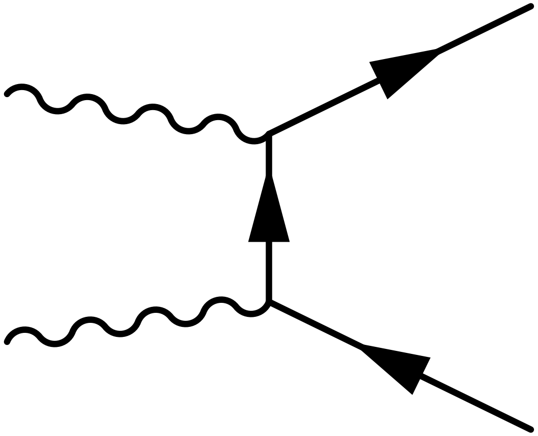
Feynman diagrams (note crossing symmetry again!)

Pair annihilation



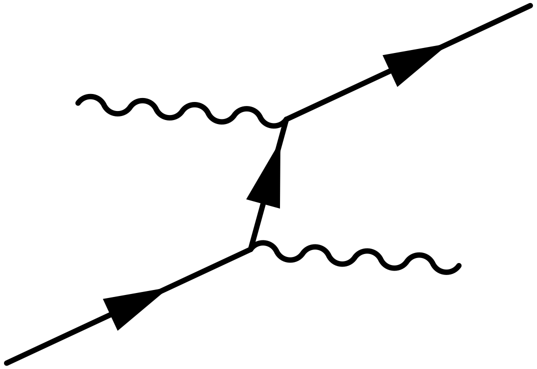
$e^-e^+\rightarrow\gamma\gamma$

Pair production



$\gamma\gamma\rightarrow e^-e^+$

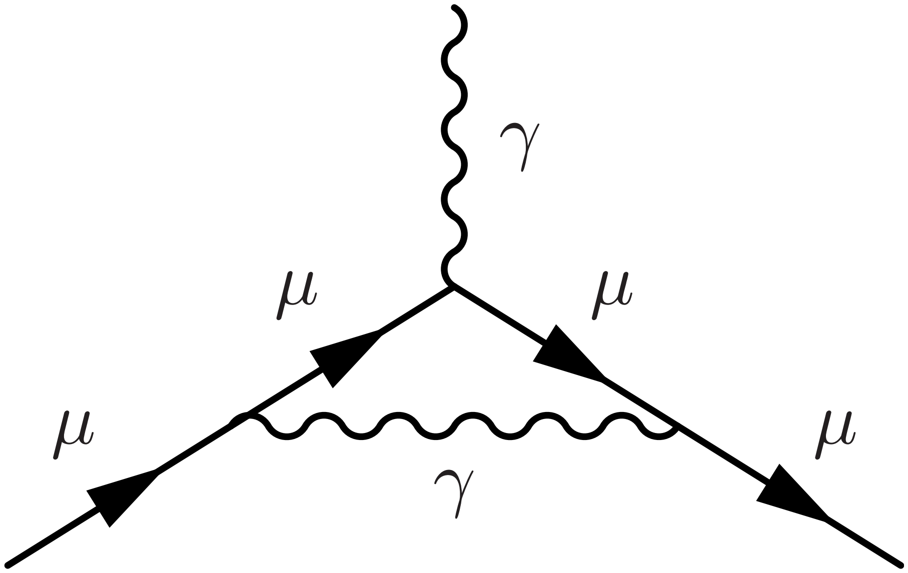
Compton scattering



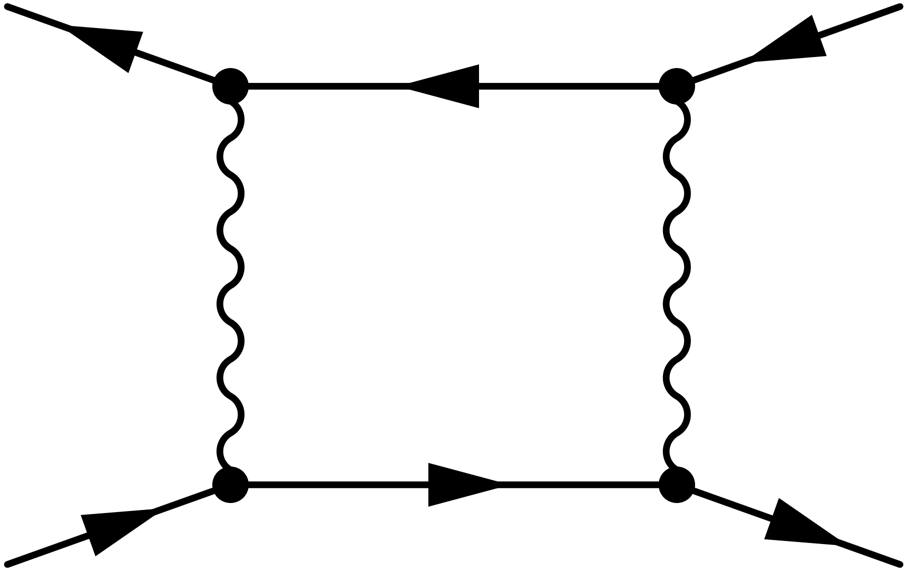
$e^-\gamma\rightarrow\gamma e^-$

Electrons here could be replaced by other objects with electric charge. Note that Feynman diagrams so far just look like pictorial ways to represent processes, but they can be used for much more as we'll see

We can start to combine these...

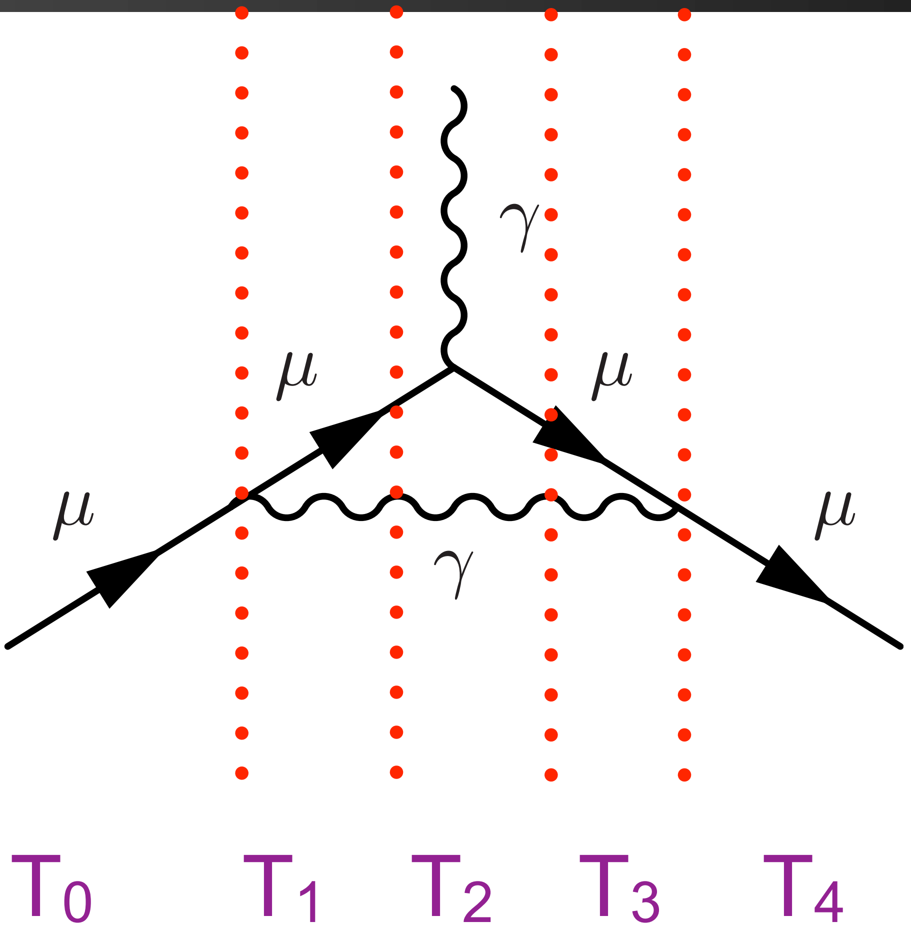


What is this? Does it remind you of any experiment that NIU works on? :)



Modification to Møller scattering (same initial and final states, different diagram)

Let’s take a closer look at these diagrams

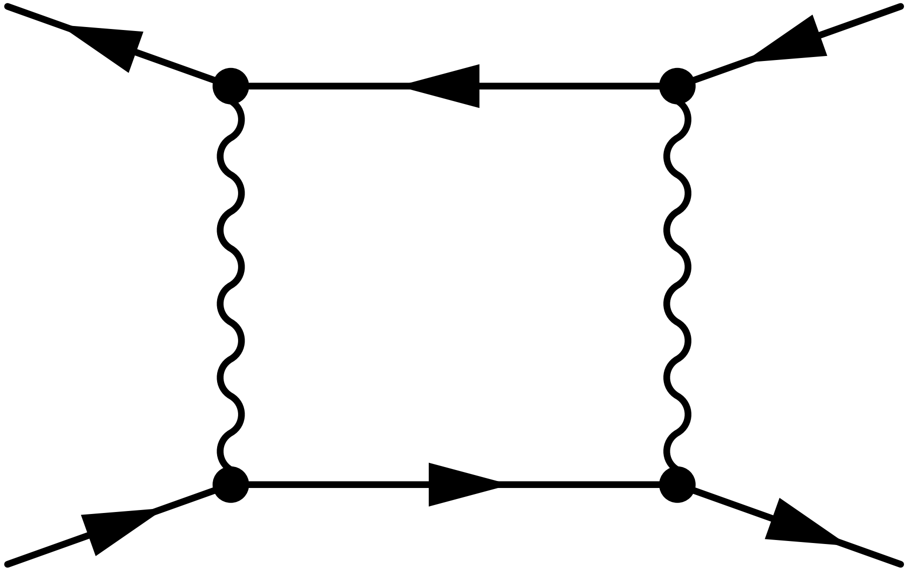


T_0: Single initial muon
T_1: Muon after interaction with photon, and that photon
T_2: Some external photon, muon after interaction with one or two photons, the internal photon
T_3: Muon after interaction with external photon, before reabsorbing the internal photon
T_4: Single final muon

Let’s slice this up into different time bins

Can cleanly divide into internal and external particles

Let’s take a closer look at these diagrams

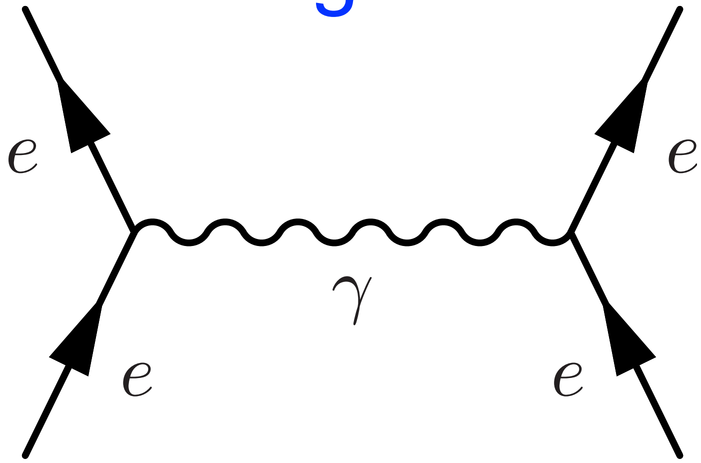


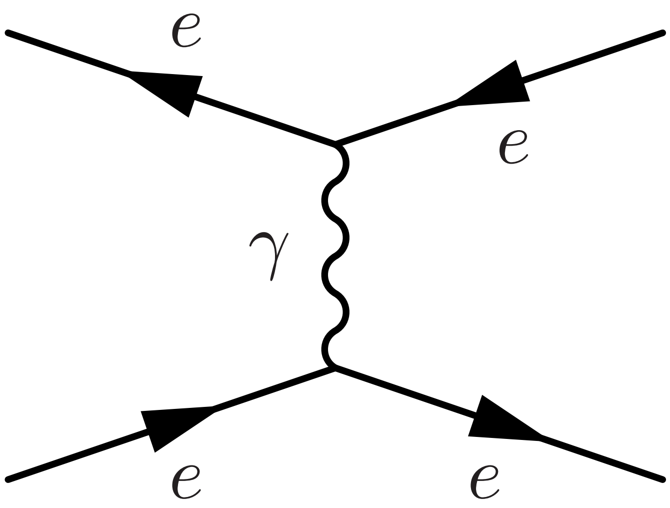
There are eight different particles in this diagram. Four of them are external to the diagram and can be observed.

The other four are internal to the digram and are called virtual particles and do **not** have to have on-shell mass

On virtual particles

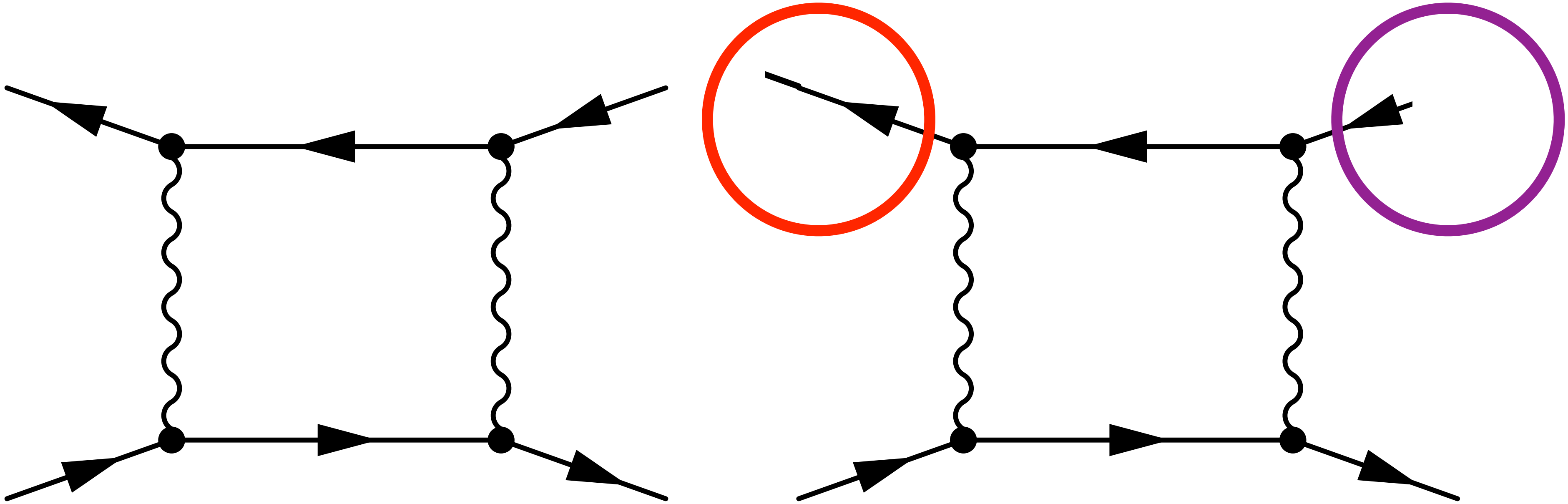
Bhaba scattering again





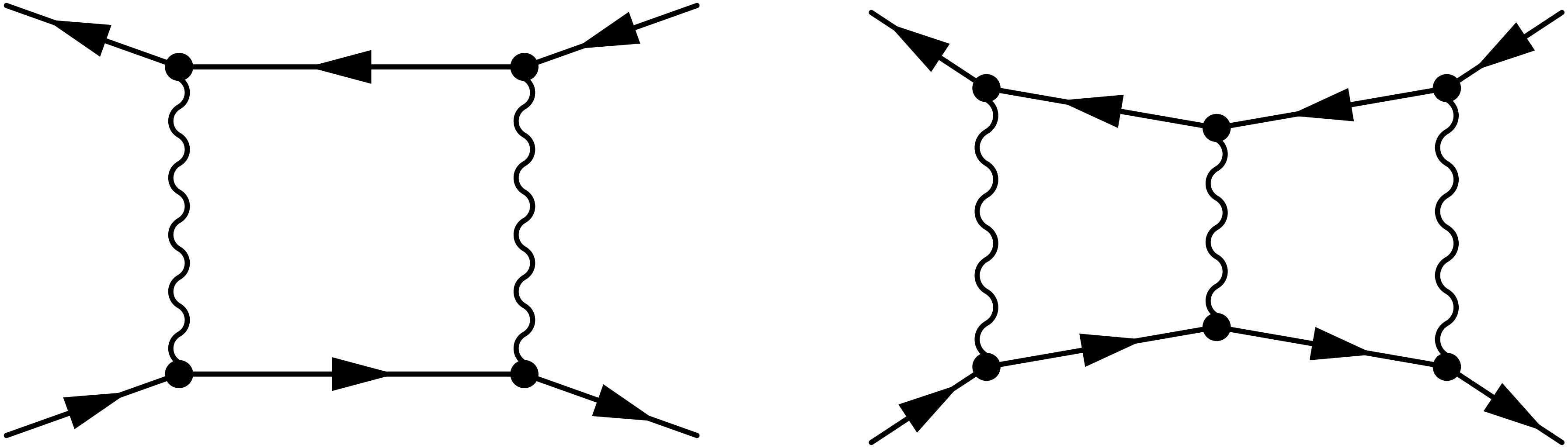
Virtual particles here (the photon in each diagram) cannot be observed, since the initial and final states are the same, so these much have interfering matrix elements

On diagrams



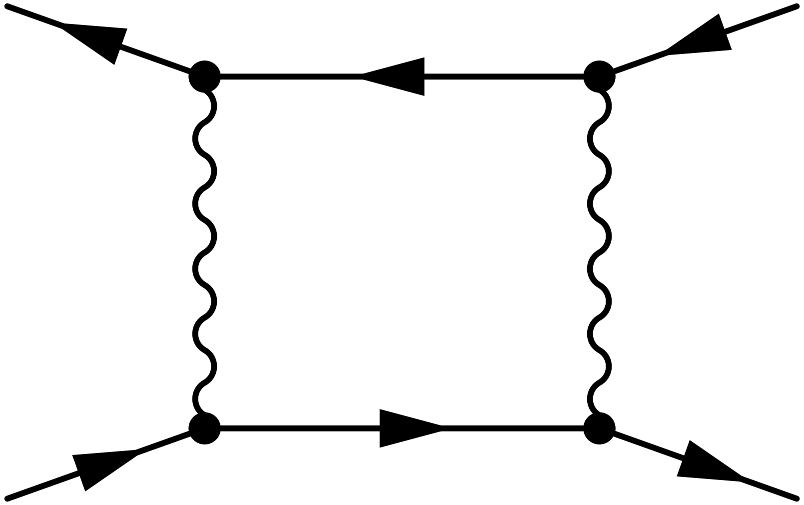
Have extended one line and shrunk another. Could have spaced things further apart or closer together - we do not differentiate between these sorts of things, nor to the angle of the lines, etc

On diagrams

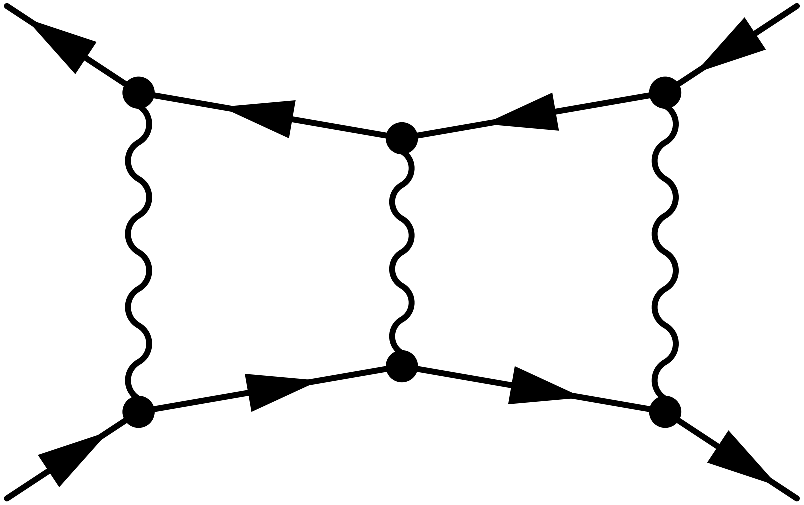


Again, can’t distinguish these diagrams. So the observable scattering amplitude must be due to the sum of all such diagrams: but there are an infinite number of them!

On diagrams



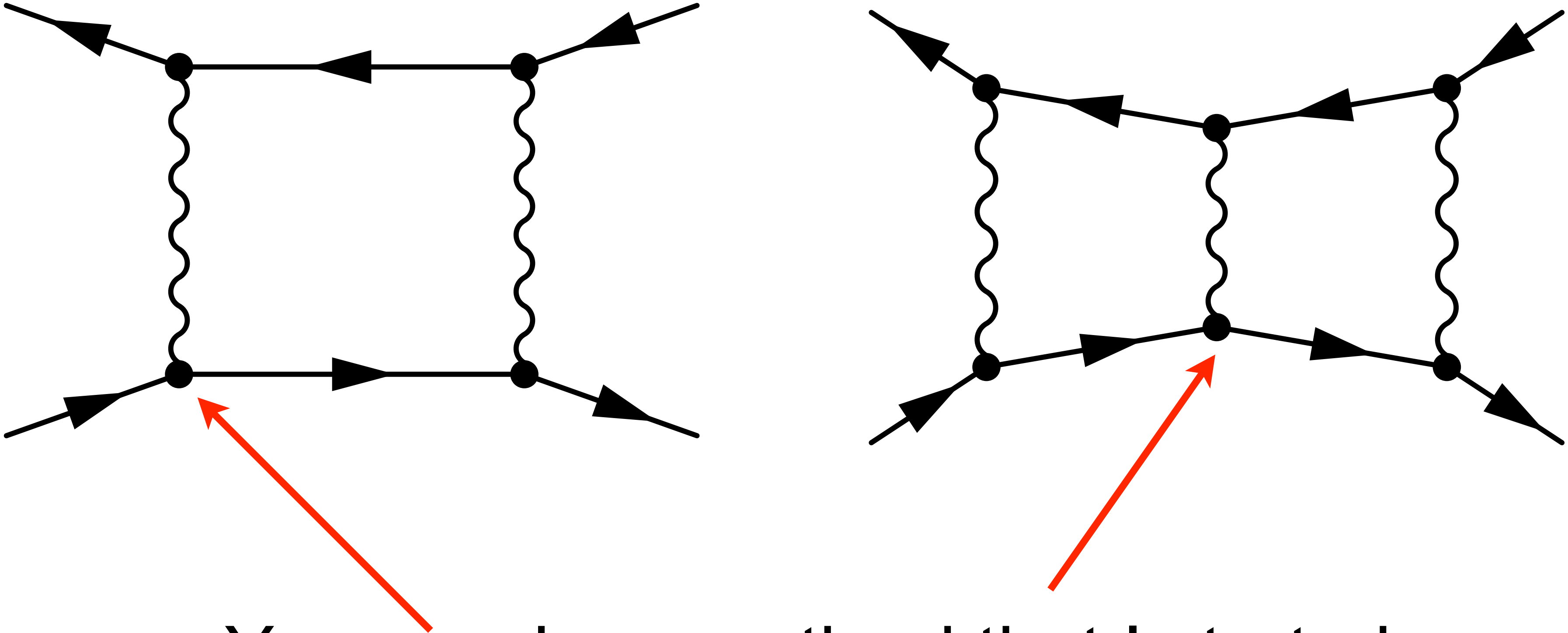
$e^+e^-\to e^+e^-\to e^+e^-$



$e^+e^-\to e^+e^-\to e^+e^-\to e^+e^-$

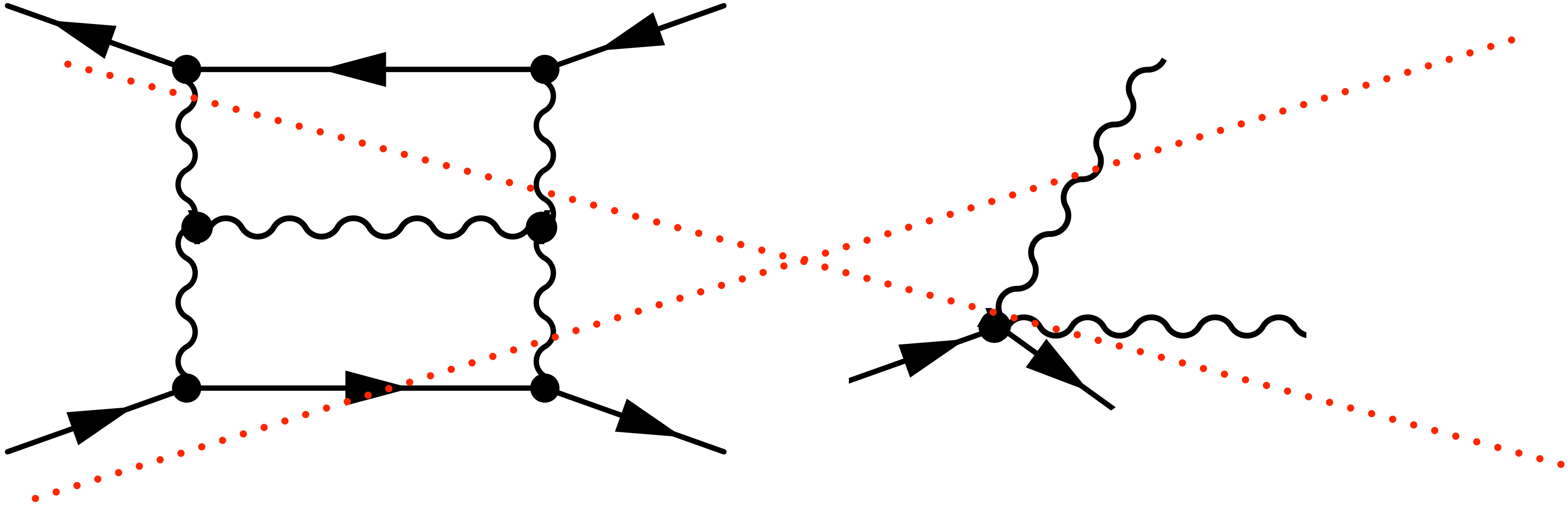
$e^+e^-\to e^+e^-$ in both cases, since intermediate states are not observable. You might ask why we’re bothering to draw pictures (I am not much of an artist), but they will shortly become an invaluable computation tool. Each of these represents a single number!

On diagrams



You may have noticed that I started putting circles at each interaction point - these are vertices and describe a point in space-time where an interaction occurs.

NOT valid

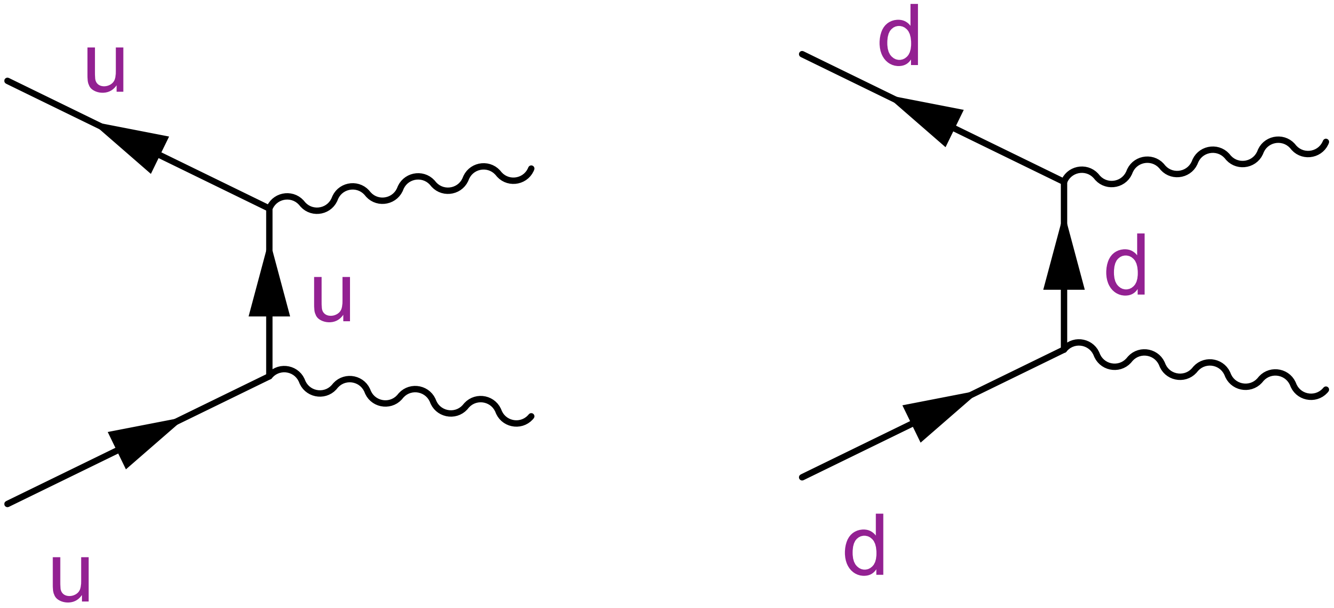


There is no such photon-photon-photon vertex in the SM (of course, you should know that already - the photon does not carry electric charge)

Muons can emit multiple photons, but not at the same vertex (note that the solid lines here represent any particle with electric charge)

Neutral pion decay

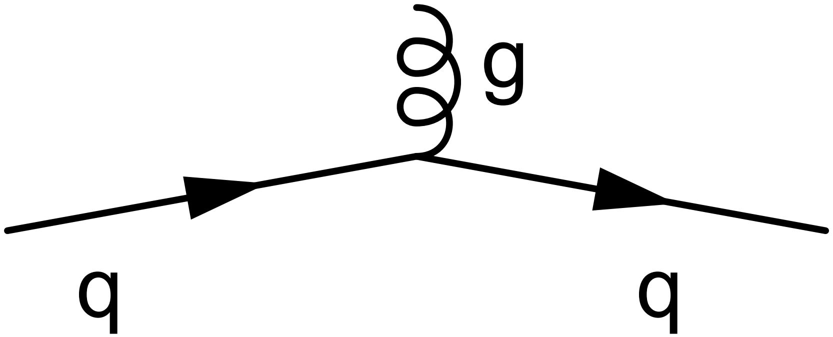
Pair annihilation again, with quarks



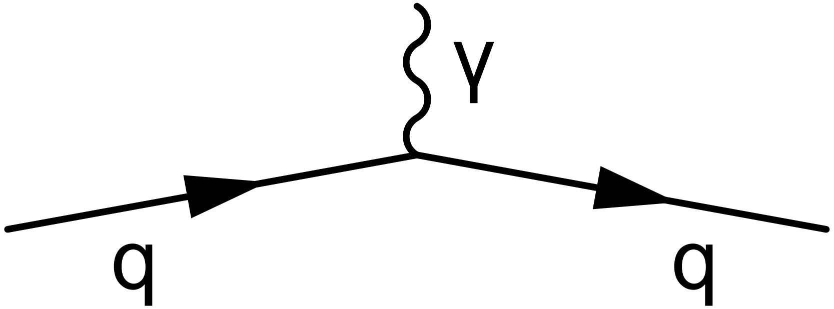
Now we can see why neutral pions decay 99% of the time to a pair of photons, and also why this happens so quickly (any good answers?)

From QED to QCD

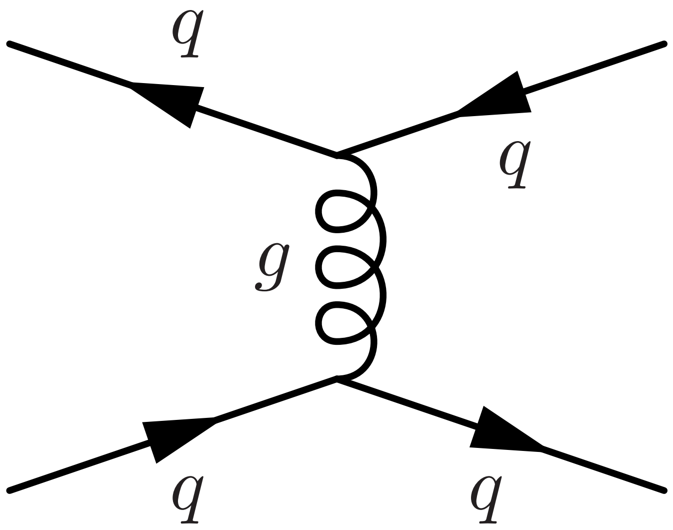
Start with common building block:



Note the similarity with the common building block of QED:

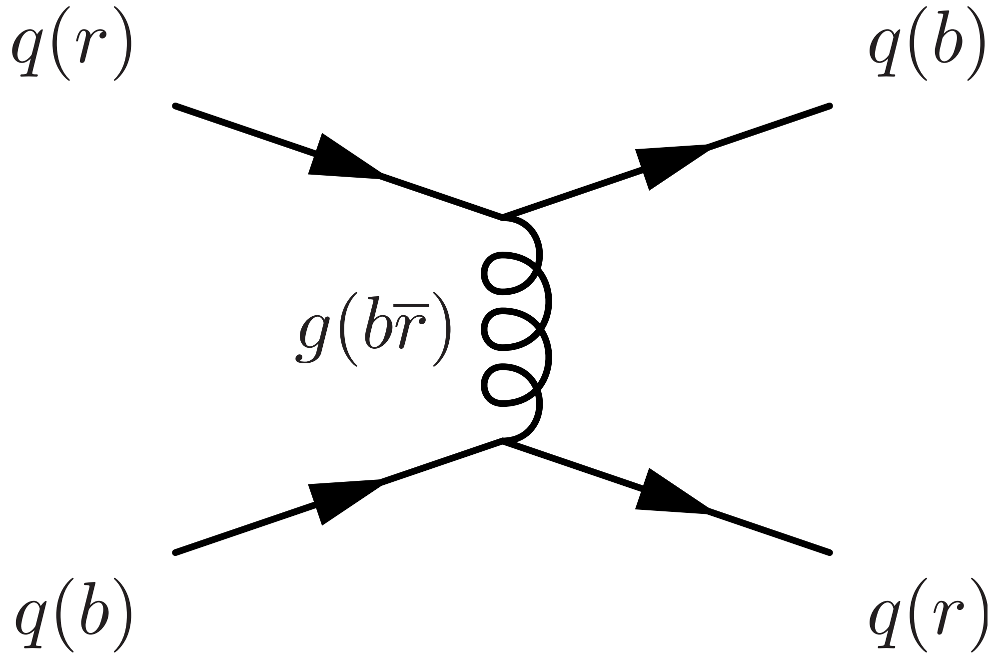


Gluon exchange between quark and anti-quark:



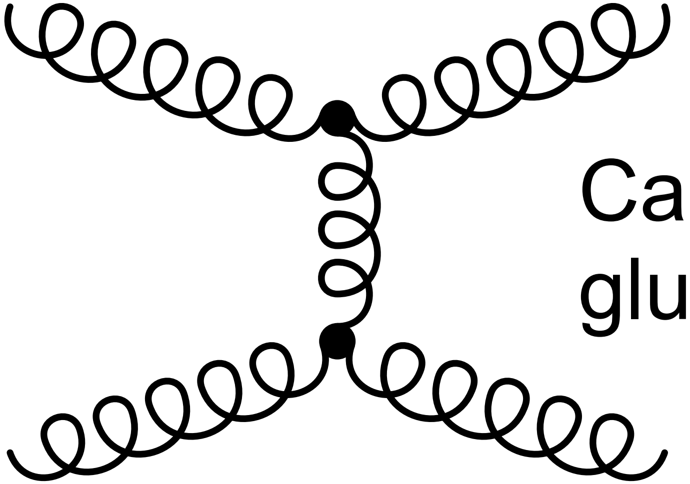
A few fundamental differences, though, between QED and QCD...

Gluon exchange between quarks:



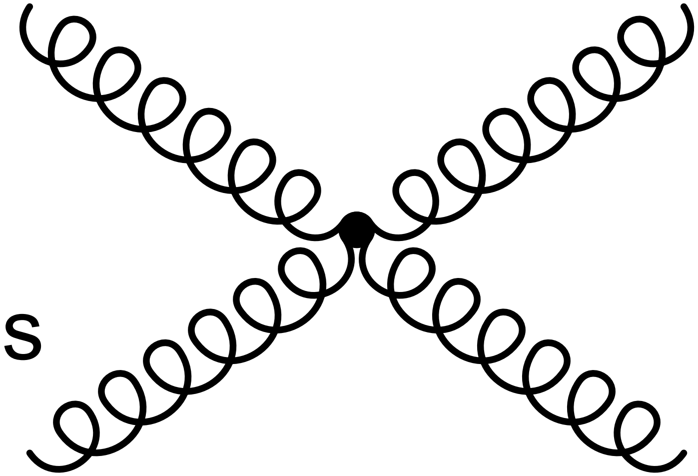
Remember that quarks have color (and so do gluons!) Try and follow the color lines (always a good thing to check)

Remember that gluons themselves have QCD color, so they self-couple!



Can have three-gluon vertices

And four-gluon vertices

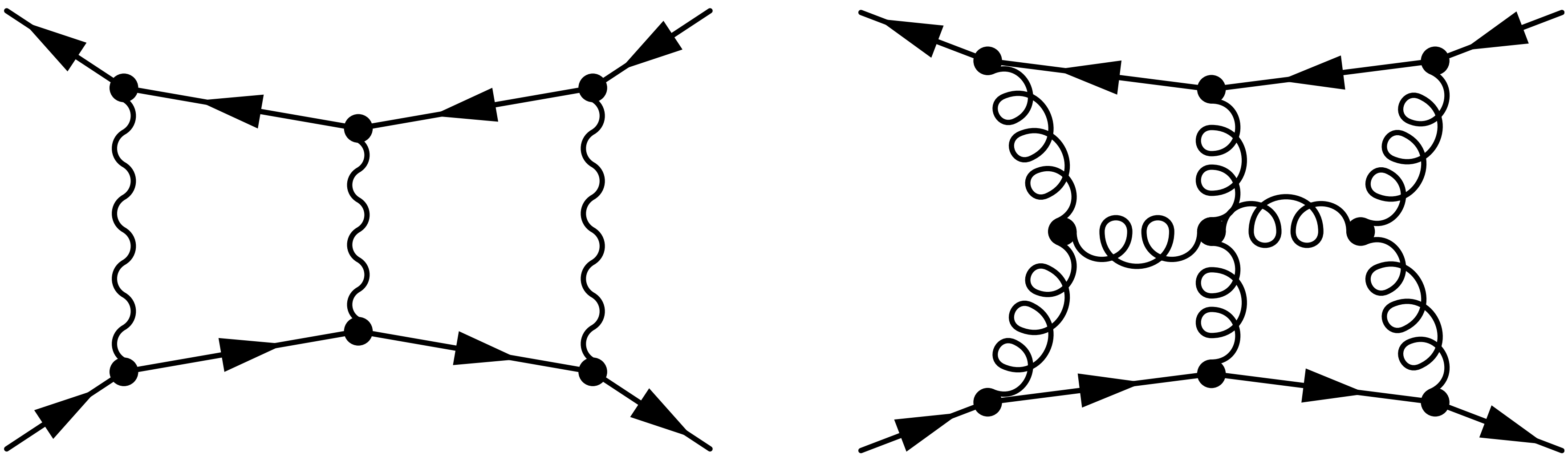


One other QED vs QCD differences

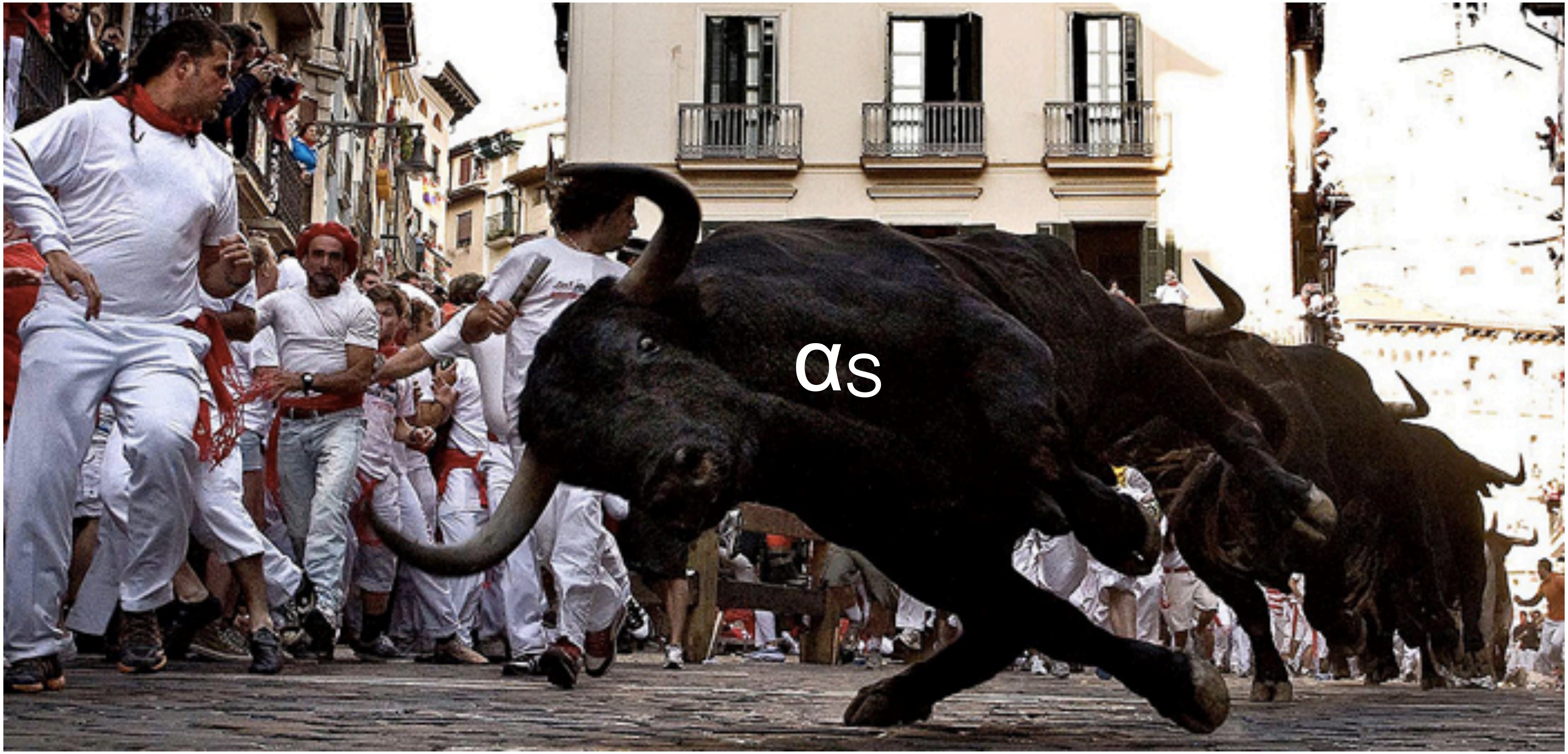
Each vertex describes an emission/absorption of a force carrier.

In QED, the probability of this is governed by the unit-less number $\alpha=1/137$, which is good, since it means the probability for many of these is small

In QCD, the probability of this is governed by the unit-less number $\alpha_S>1$, which means the diagrams with more vertices contribute more!



Running of the coupling constant



Running of the coupling constant

The value of the coupling constant is indeed strong, but only at large distances. At small distances (such as inside of a proton), the strong coupling constant gets very small and we can calculate quantities

The property that the coupling gets weaker at smaller distances (aka at larger energies) is known as asymptotic freedom

Nobel prize for Wilczek, Gross and Politzer

As Griffiths points out...

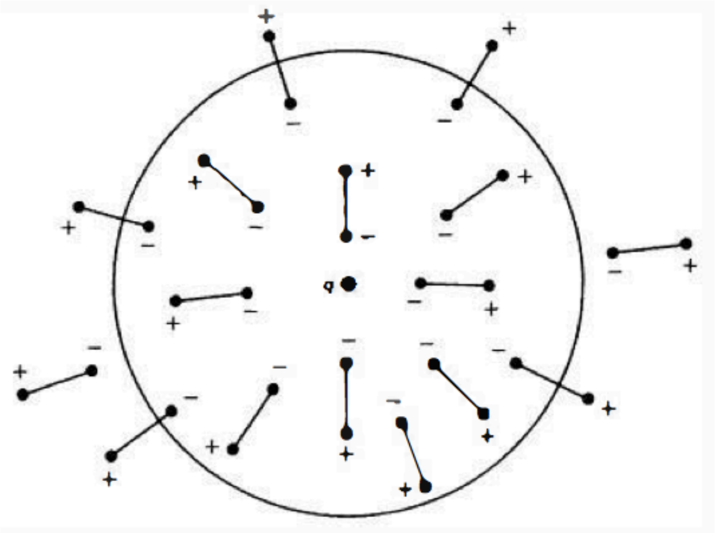


Fig. 2.1 Screening of a charge *q* by a dielectric medium.

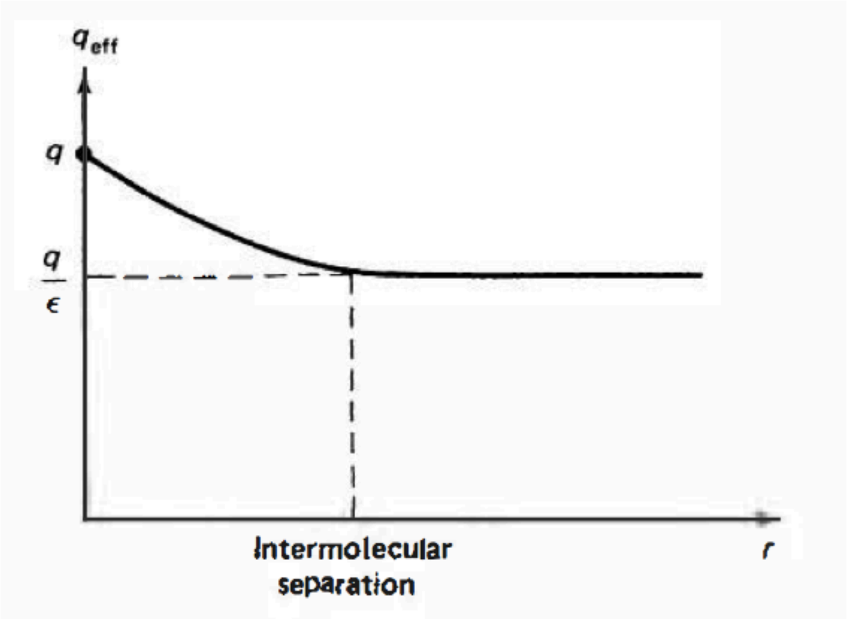
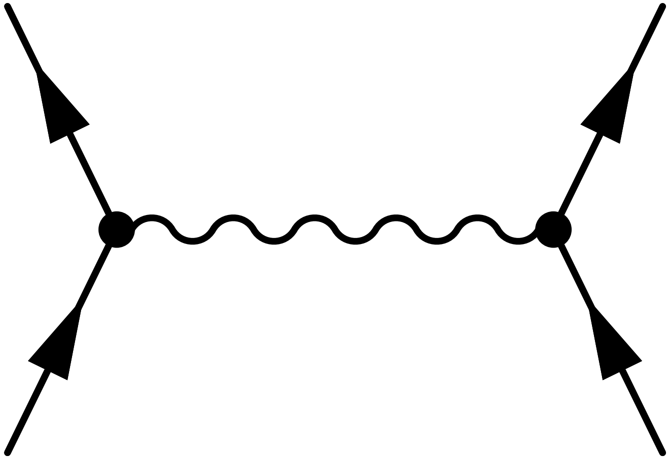


Fig. 2.2 Effective charge as a function of distance.

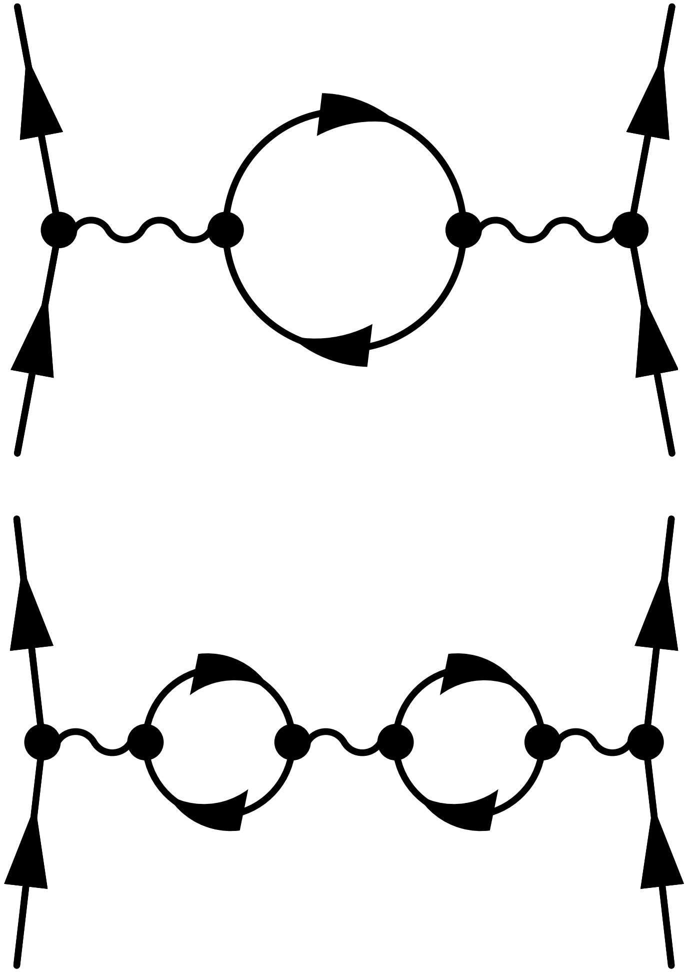
In classical E&M, the coupling is given by the charge q, and this is reduced at large distances by a dielectric

QED and screening effects

Bhaba scattering again



Virtual diagrams contributing

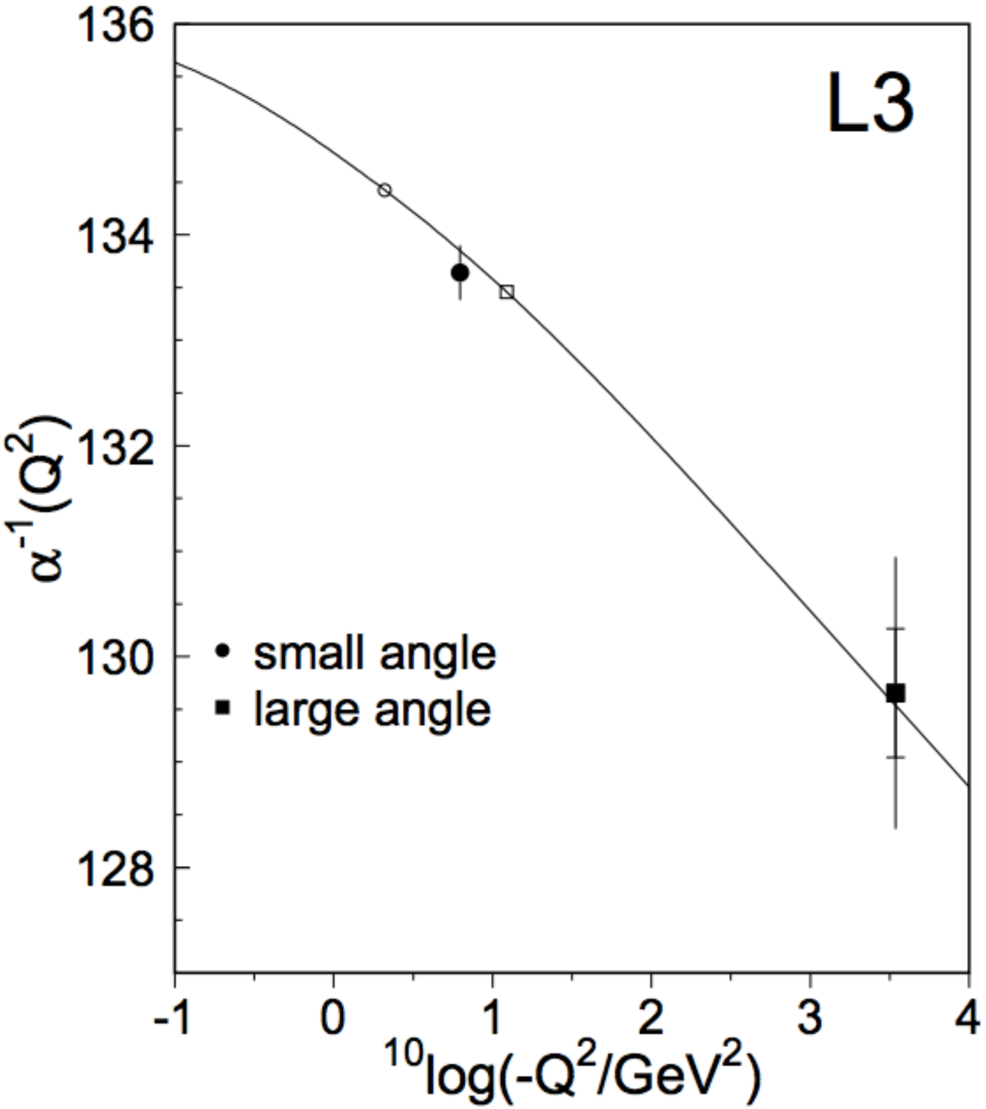


Running of the E&M fine structure constant

~1/137 at zero momentum transfer

~1/127 at the Z boson mass!

These are vacuum polarization effects

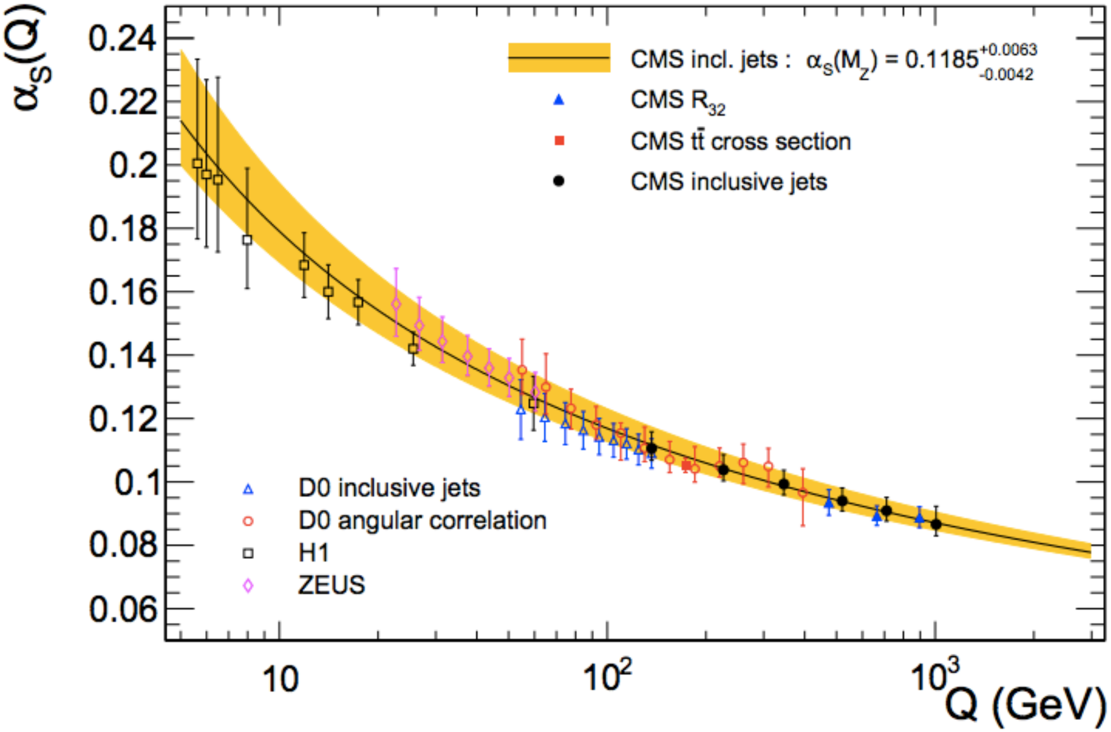


hep-ex/0002035v1

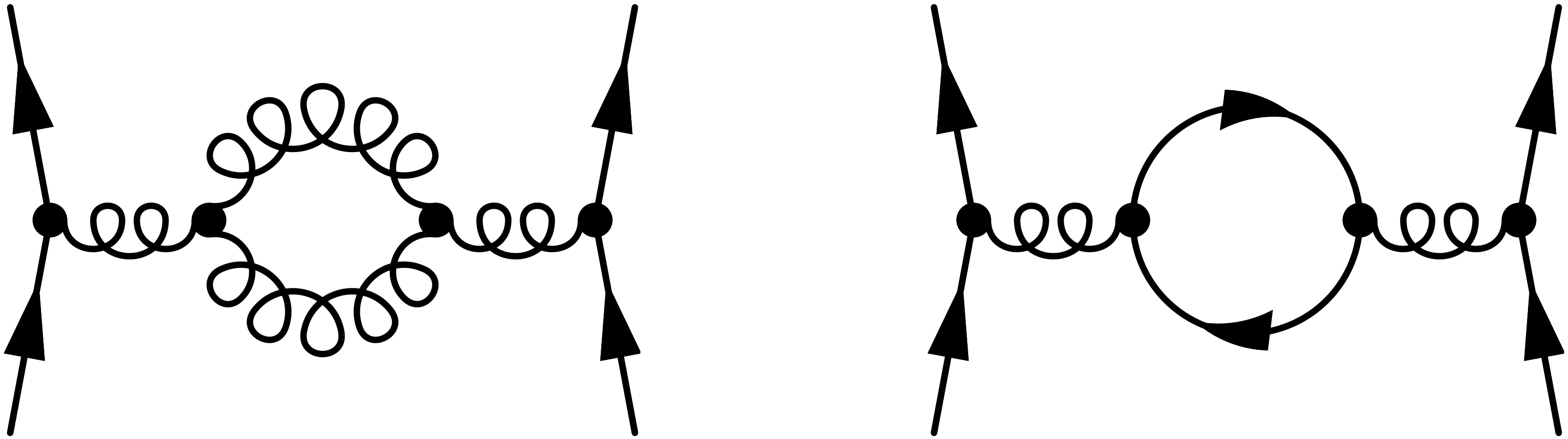
Running of the QCD strong coupling constant

arXiv:1410.6765

At 1 GeV, it’s already ~0.5, and approaches 1 at ~250 MeV



Vacuum polarization in QCD



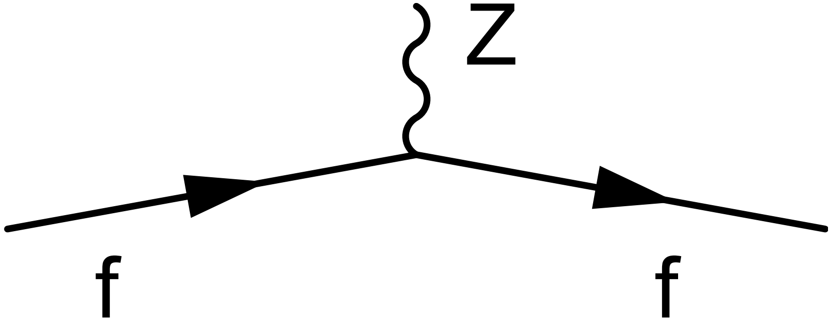
Effects from quark polarization and gluon polarization give opposite effects!

a=2f-11n (f=number of flavors, n=number colors) defines whether coupling increases or decreases at short distances

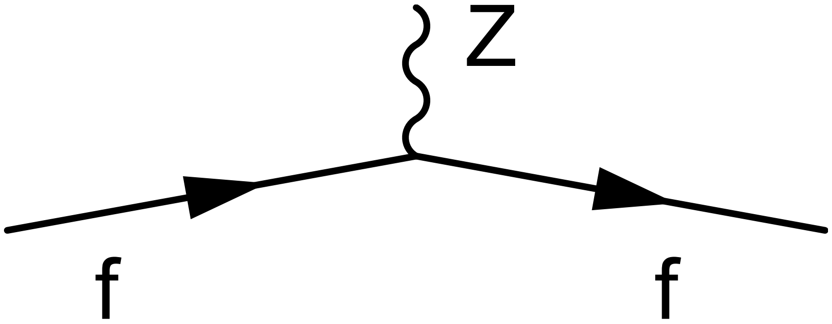
f=6,n=3 →a<0→asymptotic freedom (upper limit on no more than 17 generations of quarks)

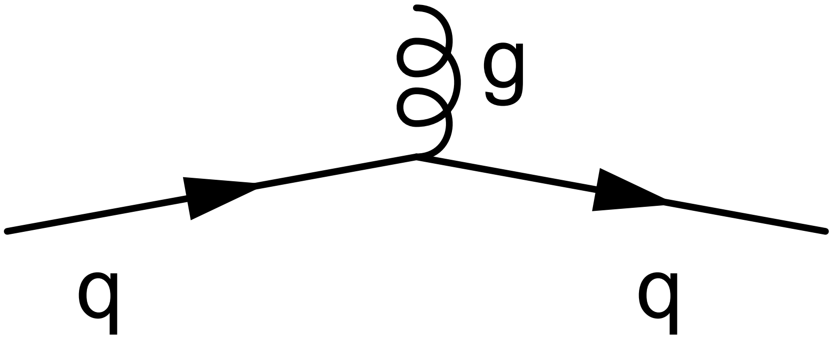
On to the weak interactions (start with neutral)

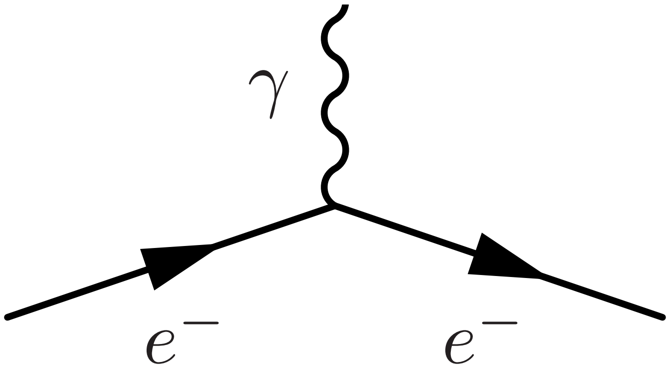
where f here
is any fermion (Z boson couples to all quarks, charged leptons and neutral leptons)



Aside to be careful of



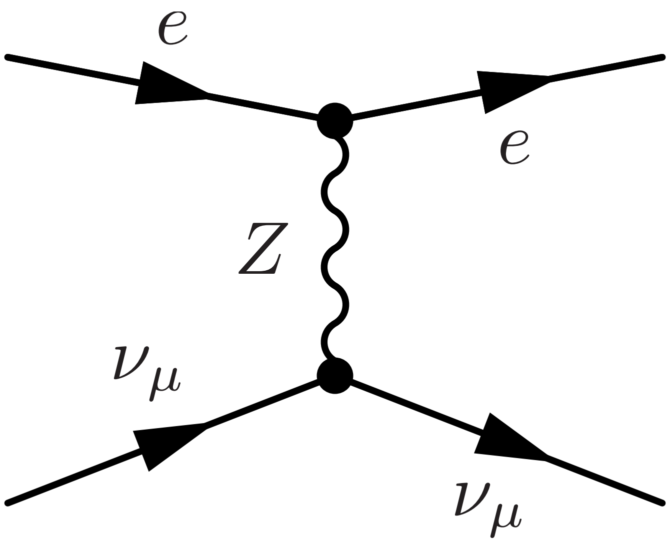




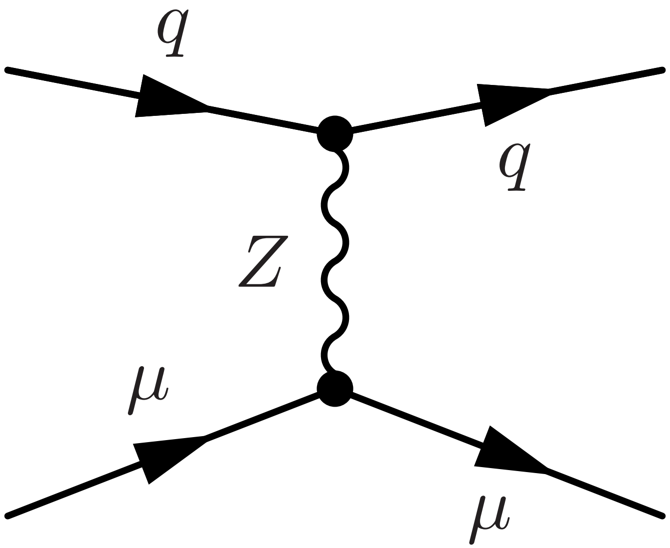
Griffiths uses a jagged straight line for EW bosons, but I will not. Just be careful, regardless of your choice!

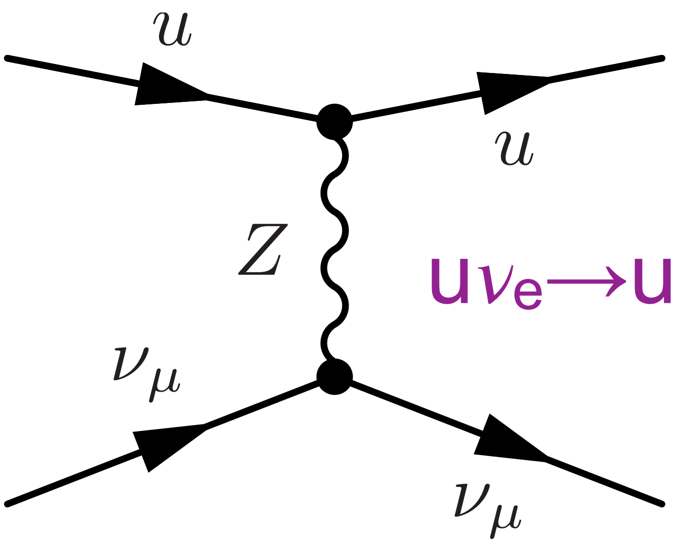
What processes can the Z boson mediate?

$e^-\nu_e \rightarrow e^-\nu_e$

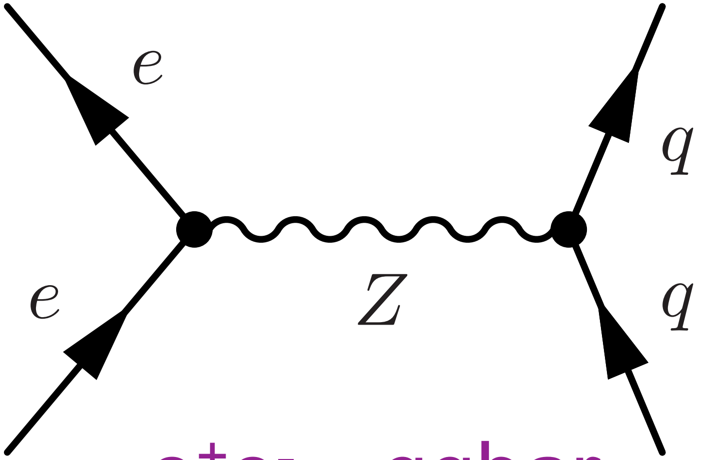


$\mu^-q \rightarrow \mu^-q$





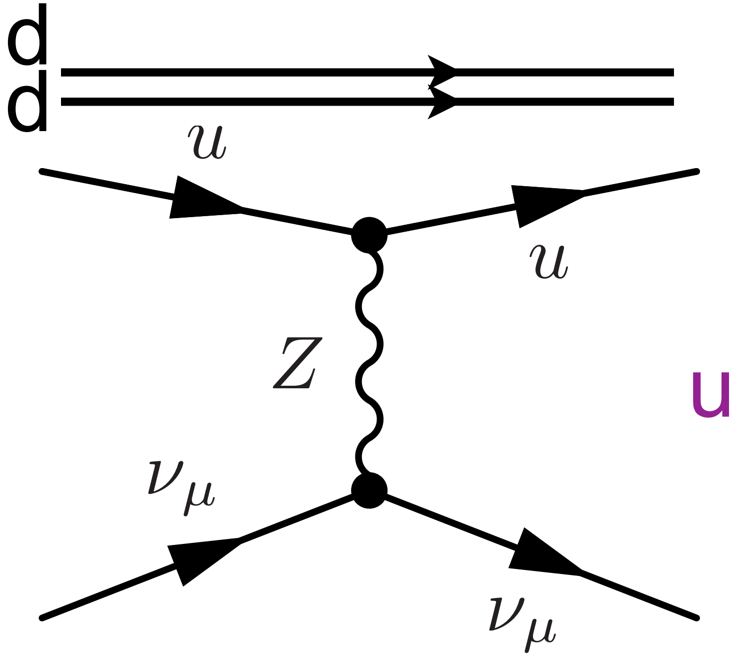
$u\nu_e \rightarrow u\nu_e$



$e^+e^- \rightarrow$ qqbar

What processes can the Z boson mediate?

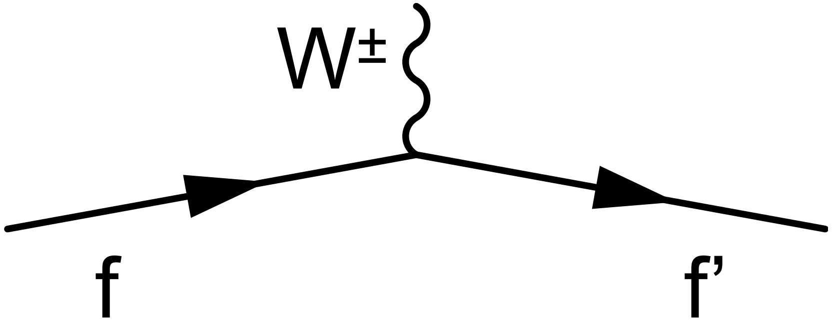
We of course don't scatter the bare quarks, but quarks inside hadrons (here inside a neutron)



$u\nu_e \longrightarrow u\nu_e$

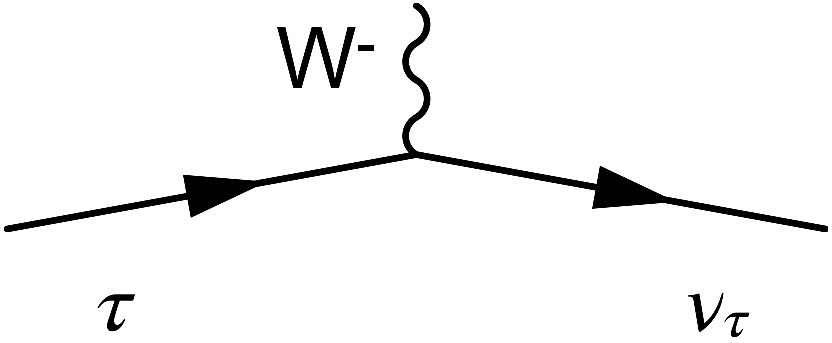
Charged weak interactions

Remember that W bosons are the only ones involved in change of flavor or type of matter



Charged weak interactions

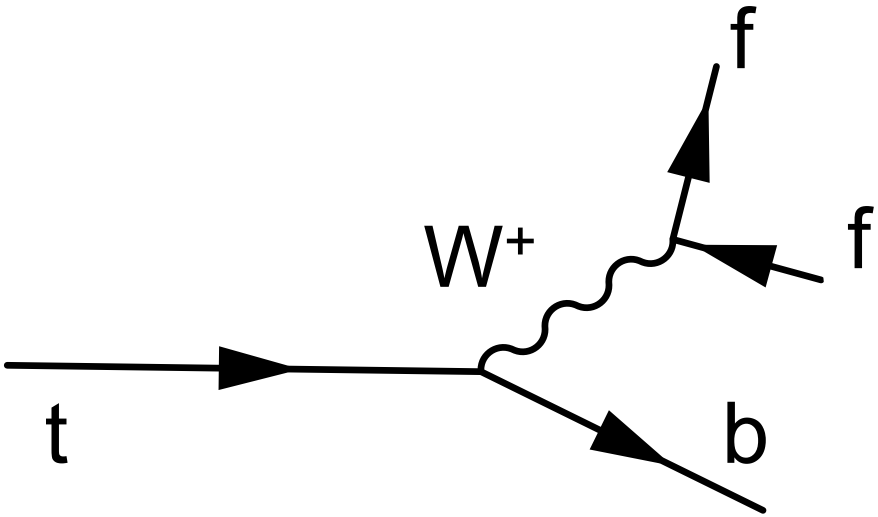
Remember that W bosons are the only ones involved in change of flavor or type of matter. Example, a tau converts into a tau neutrino and a W boson:



Charged weak interactions

Top quarks decay nearly ~100% of the time to a W boson and a bottom quark. The W boson can decay to a quark-antiquark pair, or to a charged lepton and a neutrino

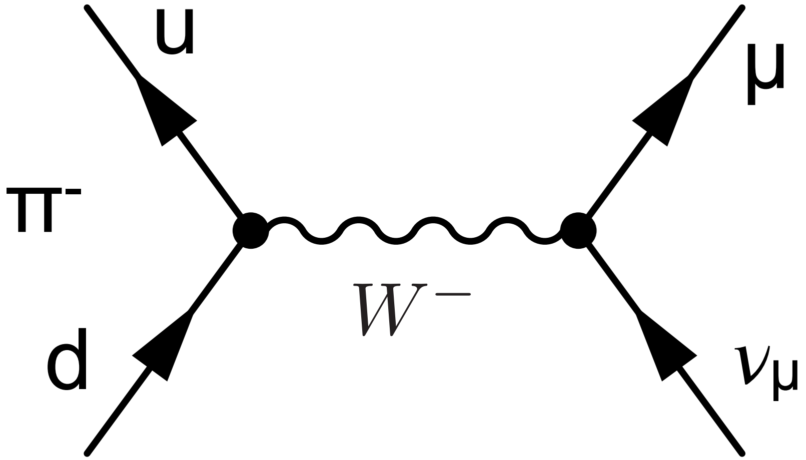
Check lepton flavor numbers and EM charge!



Charged weak interactions

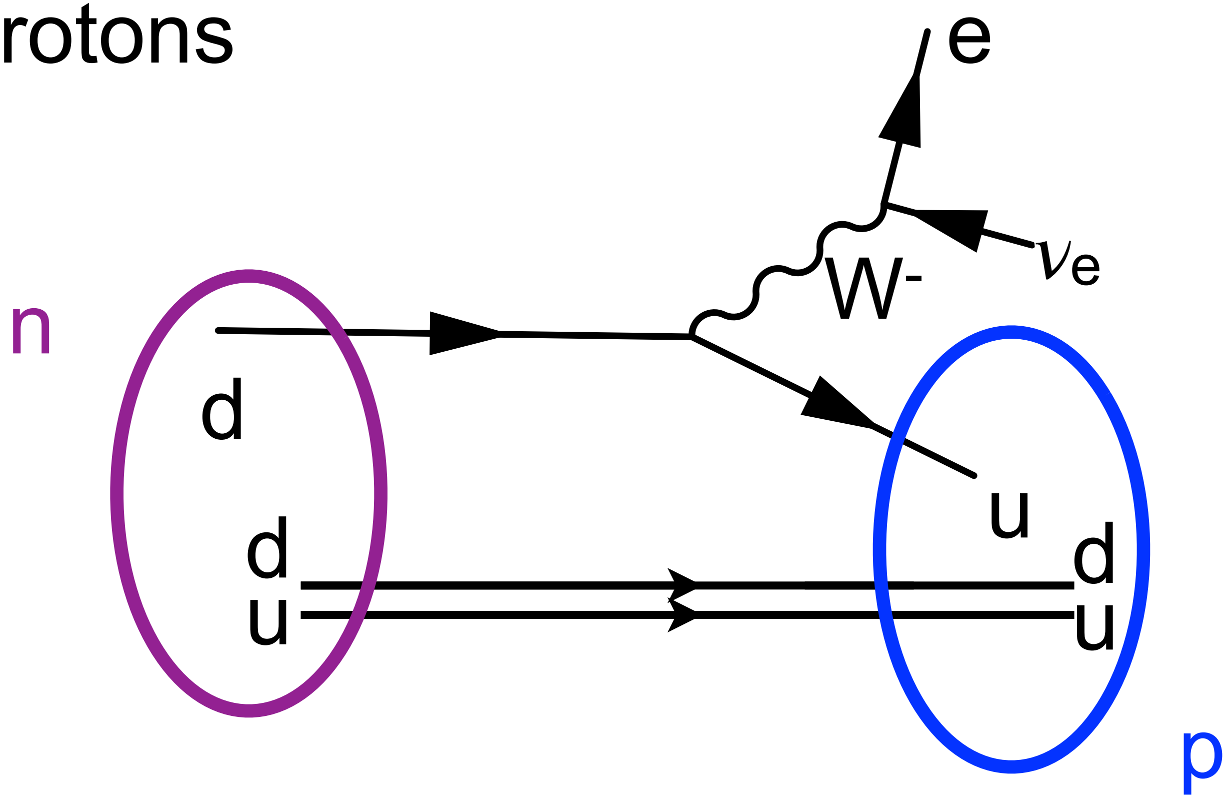
This is how a charged pion can decay to a muon (and an anti-muon neutrino). Could have guessed W boson involvement, because it involves a change of flavor (here charged pion decay is much slower than neutral pion decay)

Check lepton flavor numbers and EM charge!



What processes can the W boson mediate?

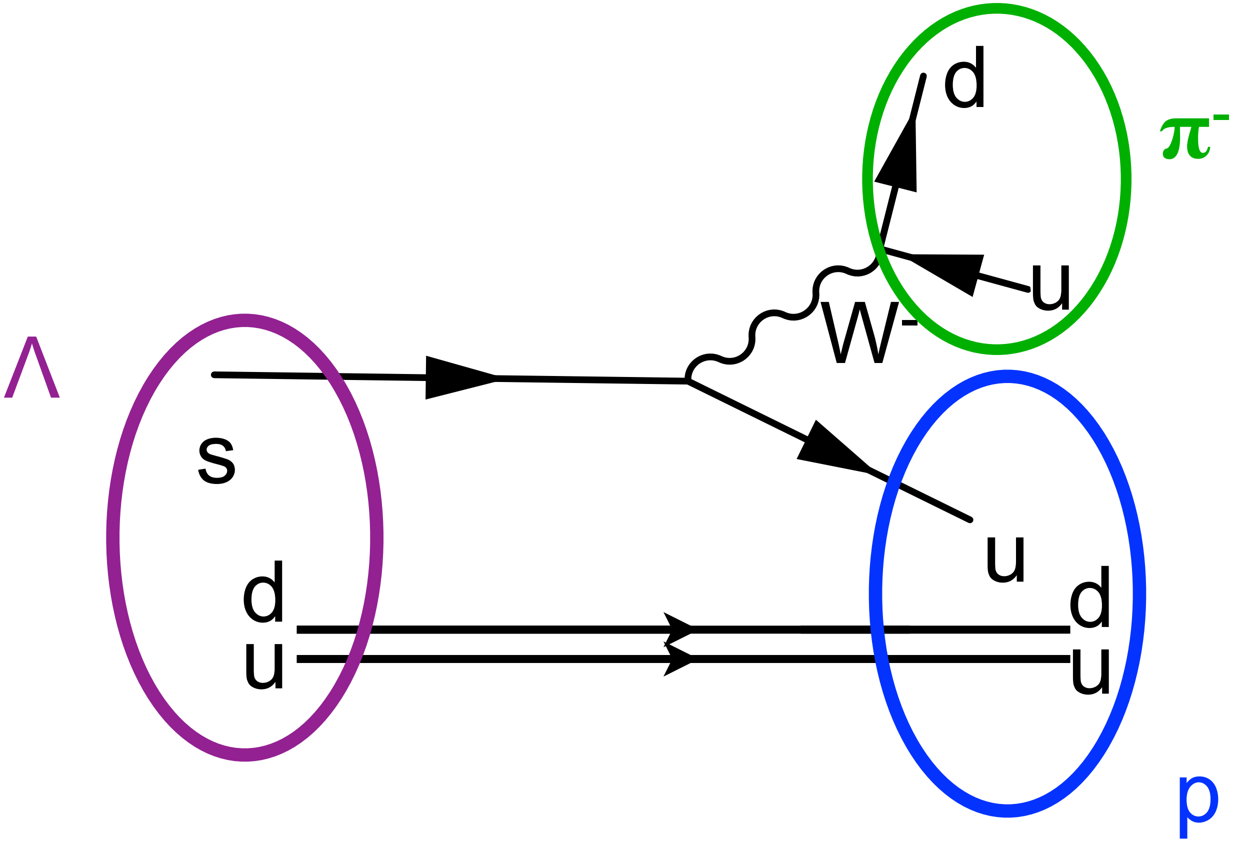
We of course don’t scatter the bare quarks, but quarks inside hadrons (here inside a neutron) This is how neutrons beta-decay to protons



The important question...

How do we account for strangeness-changing weak interactions? (We know they have to come via the weak force, but so far we have only seen decays within a matter generation)

$\Lambda \to p\pi^-$



The Kobayashi-Maskawa matrix

The weak force couples not to eigenstates of quarks that we observe, but to a slightly skewed set instead:

What we observe

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

What weak force couples to

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

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

The Cabibbo-Kobayashi-Maskawa matrix

What we observe

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

What weak force couples to

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

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

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.0041 \\ 0.225 & 0.986 & 0.041 \\ 0.0084 & 0.040 & 1.021 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2014 PDG

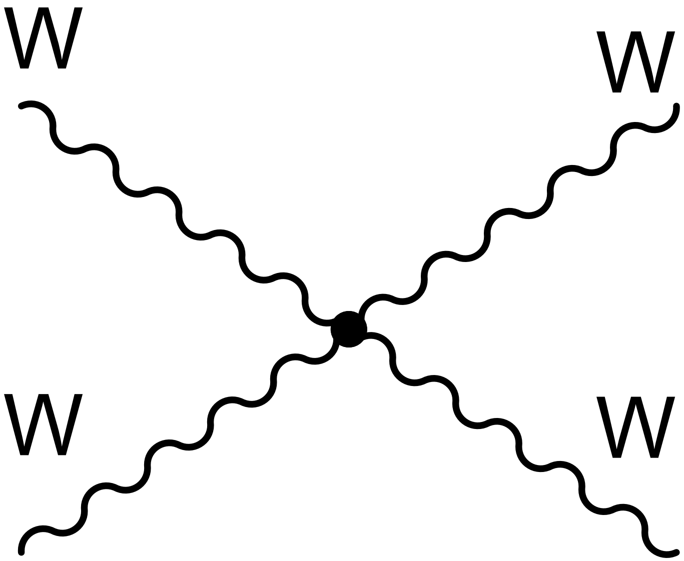
The Cabibbo-Kobayashi-Maskawa matrix

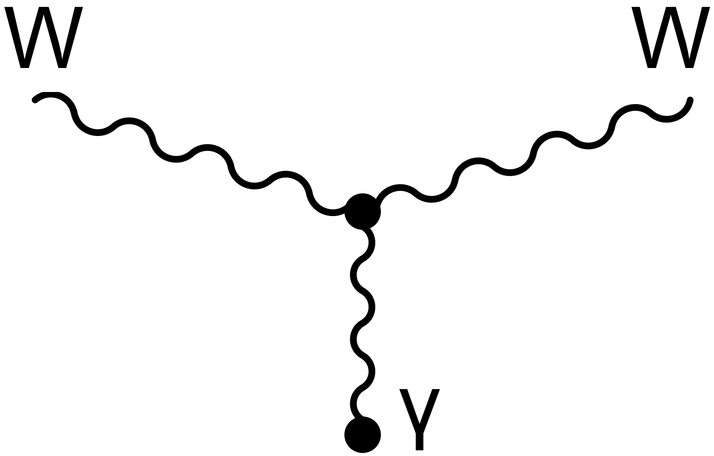
Off-diagonal numbers are small, which has implications for which decays happen more/less frequently. The matrix has to be unitary. Note that I've cheated a bit, because there are phases in the matrix that I have ignored so far

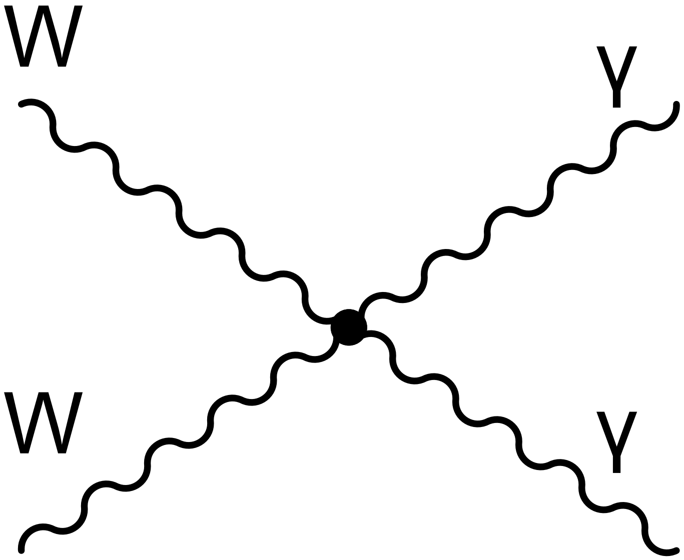
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.0041 \\ 0.225 & 0.986 & 0.041 \\ 0.0084 & 0.040 & 1.021 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2014 PDG

Boson couplings in weak theory

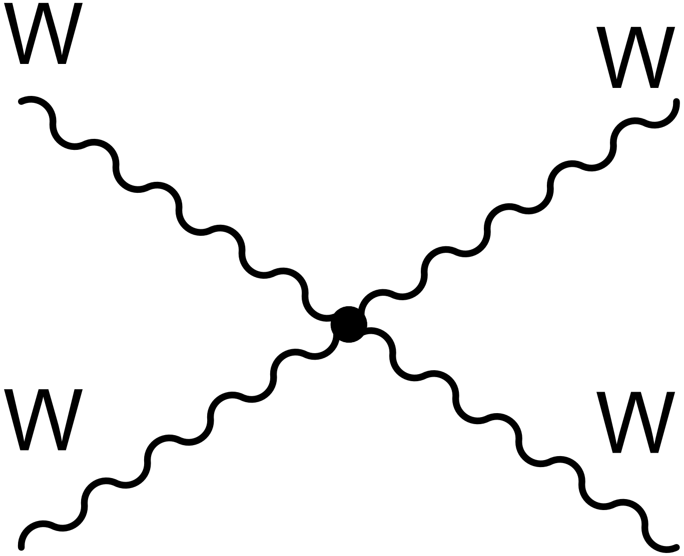


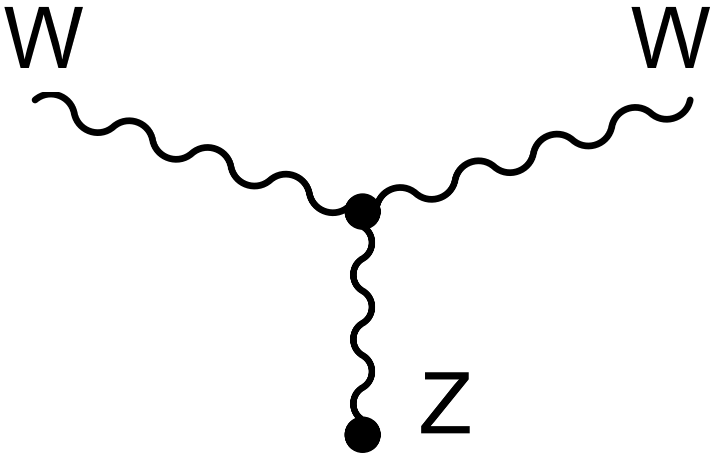


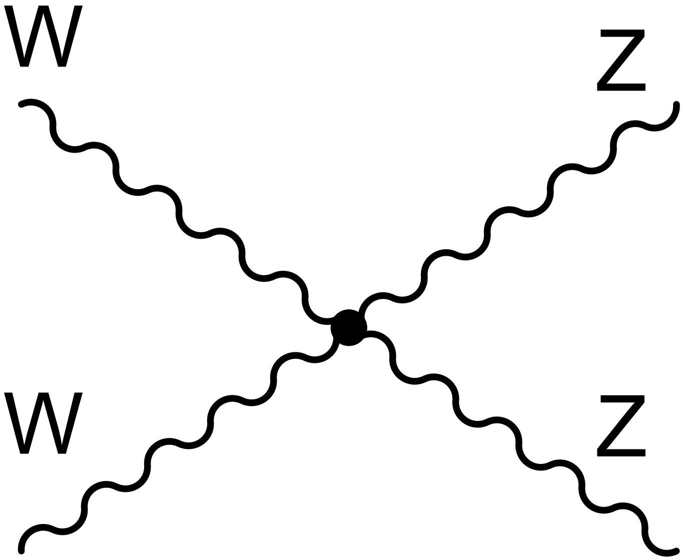


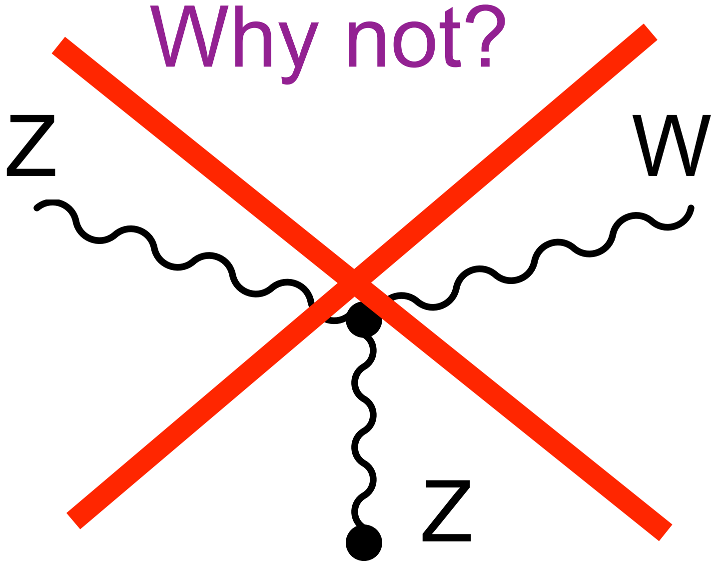
In general, can always replace a photon by a Z boson in a diagram. What about the reverse?

Boson couplings in weak theory









Decays

Particles... like to decay to lighter objects, unless there is a reason that they can’t decay (such as a conservation law)

What is the most obvious reason for non-decay?

Why can’t this decay occur?

$$p^+ \rightarrow n e^+ \nu_e$$

Hint, look at the energy in the rest frame

Beyond conservation of energy

Momentum conservation

Angular momentum conservation

Conservation of charge

Conservation of color

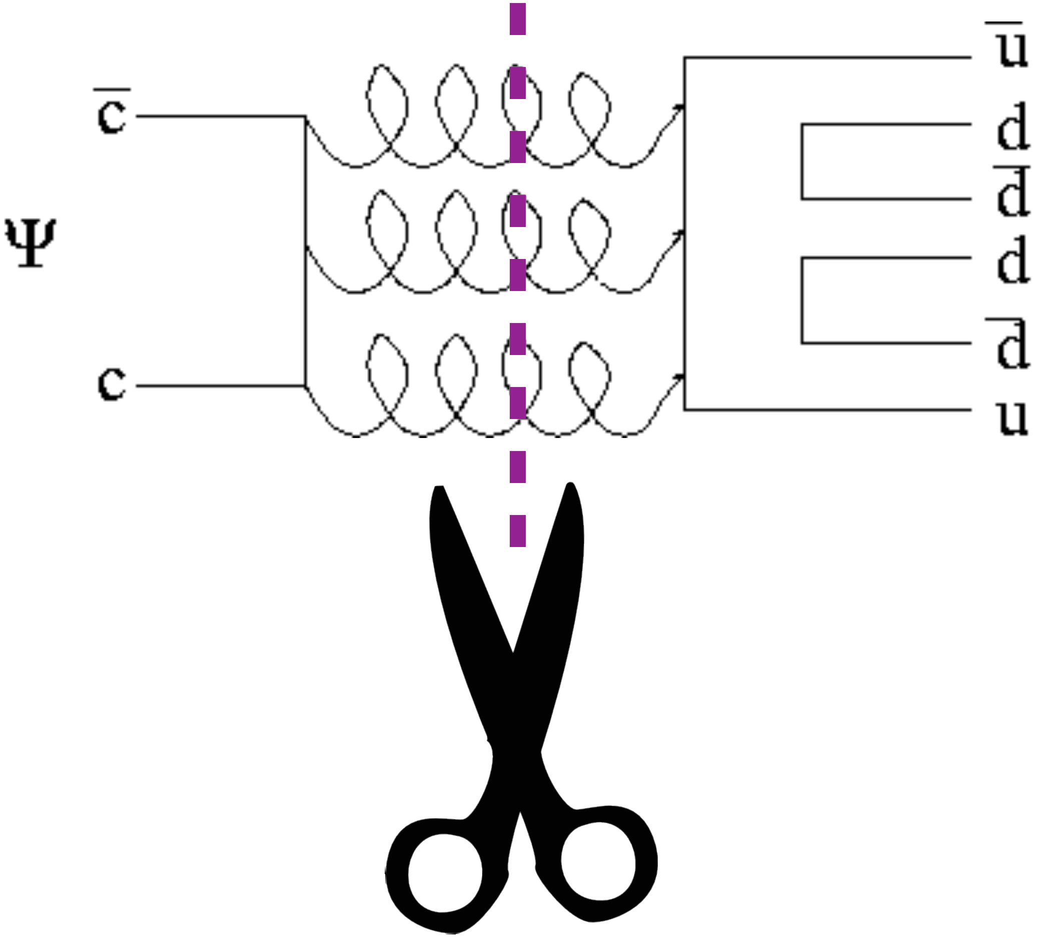
Conservation of baryon number

Conservation of lepton (electron/muon/tau) number

Quark flavor (not quite conserved)

OZI rule

http://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/QCD/Equations/jpsidecay.gif



OZI rule explains why the J/Psi takes so long to decay.
What does this have to do with asymptotic freedom?

Decays

Photons can’t decay (they already have zero mass - nothing lighter to decay into)

Protons are the lightest baryon, so baryon conservation tells us that they are stable

This is why the world is made up of protons, neutrons (which are stable inside nucleii), electrons and neutrinos

Lifetimes

Decays are probabilistic - you never know when an object will decay, but you can say on average how long a type of object will take to decay

μ: 2.2x10^{-6} s
π^{+}: 2.6x10^{-8} s
π^{0}: 8.3x10^{-17} s
τ: 2.9x10^{-13} s
n (free): 880 s
top quark: 4x10^{-25} s

Many of these objects will decay to multiple final states with different, predicted branching ratios

Why so different?

Typical decay times

Strong decays: 10^{-23} s (top quark)

EM decays: 10-16 s (π^0)

Weak decays: longer (neutron and muon)

The more (less) phase space for a decay, the faster (slower) it will occur. See the free neutron

Phase space

Photos: Internet screengrabs

Phase space

Photos: Internet screengrabs

OK, not a real physics explanation, but a good way to remember things