EP 228 Particle Physics, Lecture Notes on Conservation Laws, Oct 2020

This chapter we will revise the fundamental forces by which elementary particles interact, and discuss the Feynman diagrams at lowest level used to represent these interactions.
See also: *http://hst-archive.web.cern.ch/archiv/HST2002/feynman*

Four Forces
As far as we know, there are just four fundamental forces in nature:

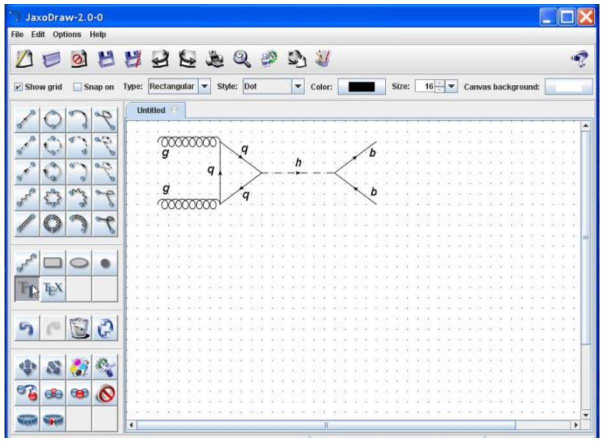
Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z
Gravitational	10^{-42}	Geometrodynamics	Graviton

Notes

- Most people assume that gravity is simply too weak to play a significant role in elementary particle physics.
- Classical formulation of electrodynamics was given by Maxwell. Maxwell's theory was already consistent with special relativity. The quantum theory of electrodynamics was perfected by Tomonaga, Feynman, and Schwinger in the 1940s.
- The weak forces account for nuclear beta decay, decay of pions, muons and many of strange particles.
- Strong force is reponsible for the interactions among quarks and and amoung hadrons.

In drawing Feynman Diagrams, one can use the program JaxoDraw. It has a complete graphical user interface that allows to carry out all actions in a mouse click-and-drag fashion.

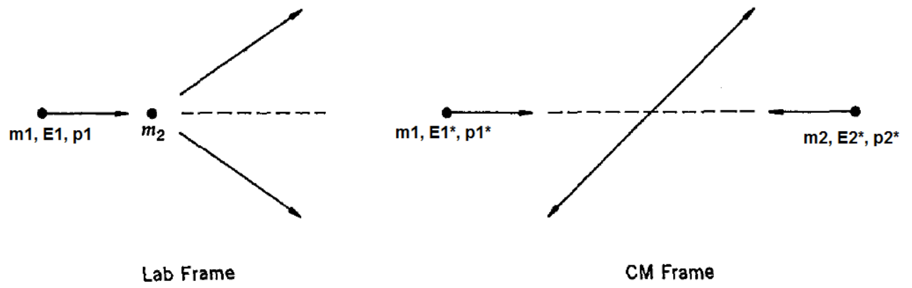
http://jaxodraw.sourceforge.net



Feynman Diagrams
A Feynman diagram is a pictorial representation of the mathematical expressions describing the behavior and interaction of subatomic particles. Consider the scattering process:

$$m_1 + m_2 \rightarrow m_1 + m_2$$

It can be shown in lab and CM frames as follows:



In discussing scattering, it is often convenient to define an invariant called t, the square of the four-momentum transfer in a collision:

$$t = \left(E_1^f - E_1^i\right)^2 - \left(\vec{P}_1^f - \vec{P}_1^i\right)^2 c^2$$

$$t = \left(E_2^f - E_2^i\right)^2 - \left(\vec{P}_2^f - \vec{P}_2^i\right)^2 c^2$$

One can think of t as the square of the mass of an exchanged particle that mediates the scattering. Consequently, we must conclude that if such an exchange process can be used to describe scattering, then the object being exchanged cannot be physical since it has an imaginary rest mass. This means that although this "virtual" object cannot be detected, if the picture is correct, its consequences can be calculated and observed. Diagrams of the two kinds shown below.

These diagrams were pioneered by Richard Feynman, in 1948, in the calculation of scattering amplitudes in quantum electrodynamics (QED) and are referred to as Feynman diagrams.

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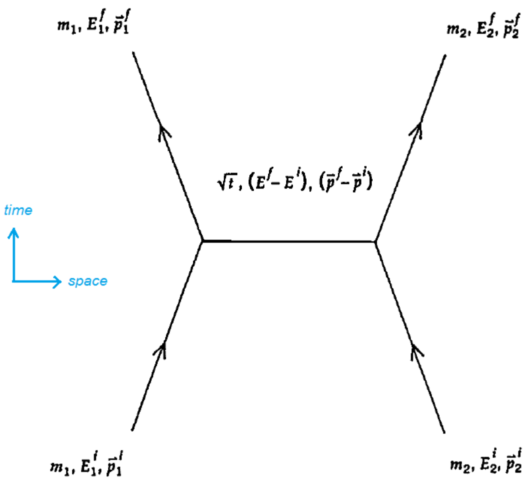
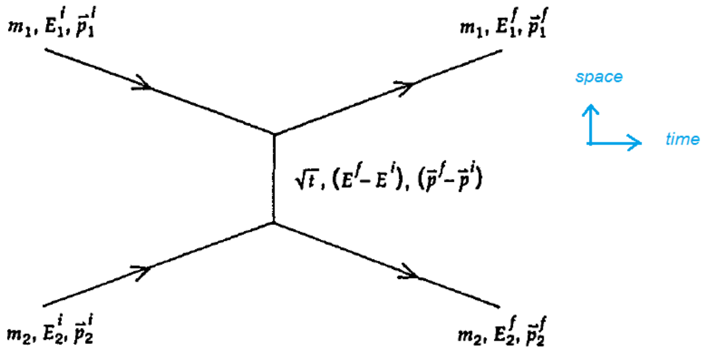
Time is flowing to upward

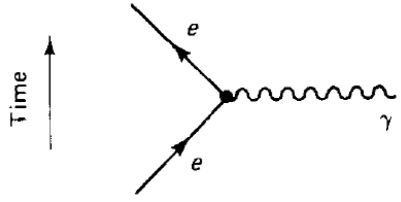


Time is flowing to right



QED (Quantum Electro-Dynamics)

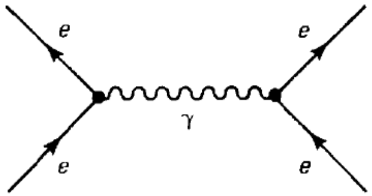
QED is the oldest, the simplest, and the most successful of the dynamical theories; the others are modeled on it. All electromagnetic phenomena are ultimately reducible to the following elementary process:



This diagram reads: Charged particle e enters, emits (or absorbs) a photon, γ, and exits.

To describe more complicated processes, we simply patch together two or more replicas of this *primitive vertex*.

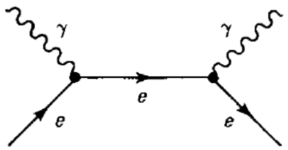
The Feynman Diagram of the Coulomb Repulsion (e-e scattering) $e^- + e^- \rightarrow e^- + e^-$



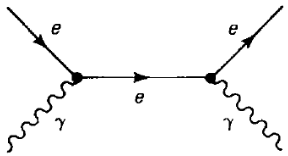
Here, two electrons enter, a photon passes between them and the two then exit. We say that the interaction is "mediated by the exchange of a photon". One can twist these Feynman diagrams around into any topological configuration you like. Note that anti-particles (positron) goes backward in time.

The follwing are example diagrams:

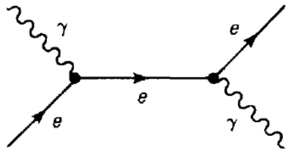
Pair annihilation
$e^- + e^+ \rightarrow \gamma + \gamma$



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



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



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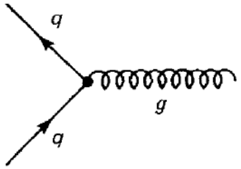
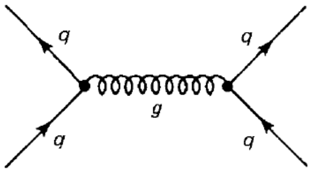
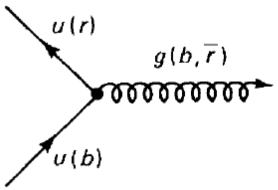
QCD (Quantum Chromo-Dynamics)
In chromodynamics color plays the role of charge: q →q + g. The primitive vertex is



Consider the interaction between two quarks. The force between two quarks is "mediated" by the exchange of gluons.

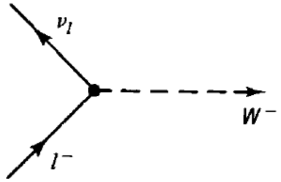


In the process q → q + g, the color of the quark (but not its flavor) may change. For example, a blue up-quark may convert into a red up-quark. Color (like charge) is always conserved.



Weak Interactions
Both leptons and quarks feels the weak force. Weak interactions are mediated by W and Z bosons.

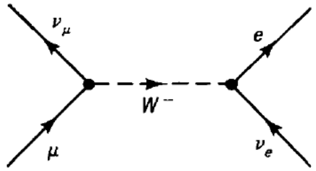
1. Leptons
The fundamental <u>charged vertex</u> looks like this:



A negative lepton (it could be e^-, μ^-, or τ^-) converts into the corresponding neutrino, with emission of a W^- boson (or absorption of a W^+): $l \rightarrow \upsilon_l + W^-$.

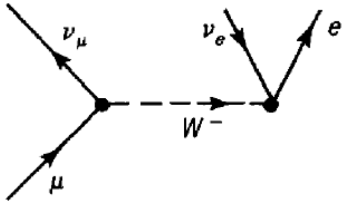
We can combine vertices to get real processes.

$$\mu^- + \nu_e \rightarrow e^- + \nu_\mu$$



By twisting the diagram we can obtain the muon decay.

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



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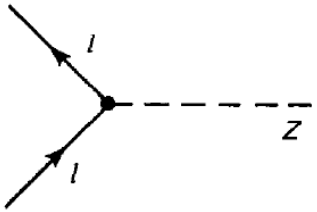
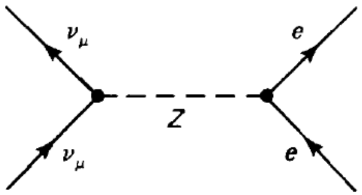
The fundamental <u>neutral vertex</u> is:

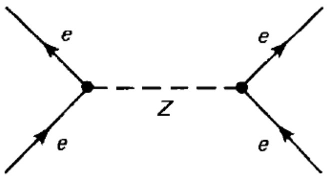


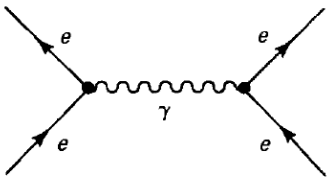
l can be any lepton including neutrinos. The Z mediates such processes as neutrino-electron scattering

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$



The Z can be exchanged between two electrons, but so can the photon. But the photon-mediated process overwhelmingly dominates.

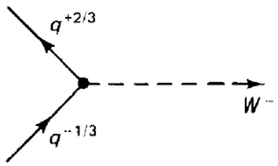




Notice that the leptonic weak vertices connect members of the same generation: e- converts to ν_e (with emission of W-) or μ- → μ- (emitting a Z), but e- never goes to μ- (nor μ- goes to ν_e). In this way the theory enforces the conservation of electron number, muon number, and tau number.

2. Quarks

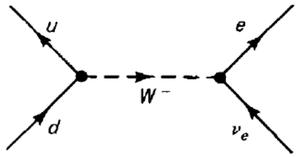
Primitive charged vertex is:



A quark with charge -1/3 (d, s, or b) converts into the corresponding quark with charge +2/3 (u, c or t respectively), with the emission of a W-. The outgoing quark carries the same color as the ingoing one, but a different flavor.

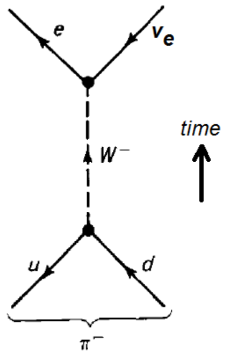
The far end of the W line can couple to leptons (a "semileptonic" process), or to other quarks (a purely hadronic process). The most important semileptonic process is as follows:

$$d + \nu_e \rightarrow u + e^-$$



Because of quark confinement, this process would never occur in nature as it stands. However, turned on its side, and with the <u>*u*</u> and *d* bound together (by the strong force), this diagram represents a possible decay of the charged pion.

$$\pi^- \rightarrow e^- + \nu_e$$



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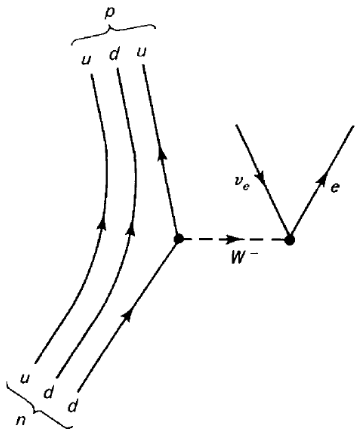
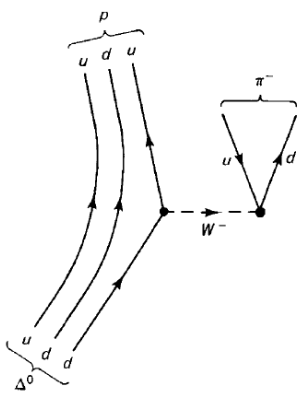
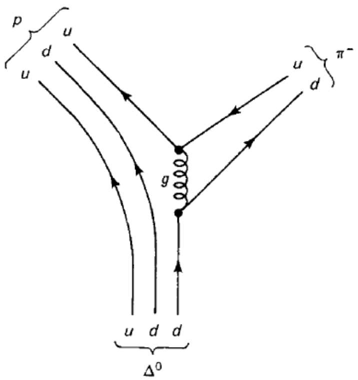
Another example is the beta decay $n \rightarrow p + e^{-} + \overline{\nu_e}$



The decay $\Delta^0 \rightarrow p + \pi^-$ can be represented by two diagrams:



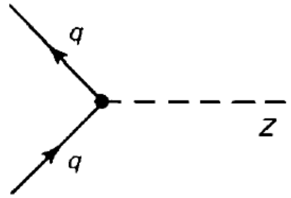
weak



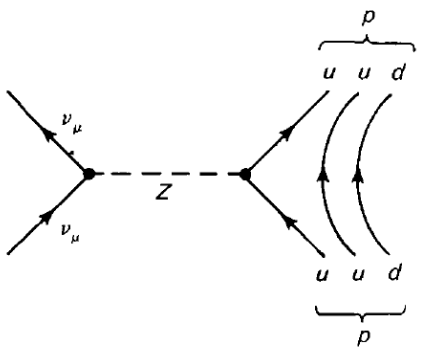
strong

First one is the hadronic weak interaction, second is the strong interaction. However, The weak mechanism is an immeasurably small contribution.

The primitive vertex for neutral vertex for leptons ($l \rightarrow l$+ Z) leaves the lepton species unchanged; again, it is natural to suppose that the same applies to quarks:



This leads to neutrino-scattering processes such as $\nu_\mu + p \rightarrow \nu_\mu + p$



Z exchange also makes a tiny contribution to the electron-proton force within an atom. As before, this contribution is masked by the dominant electromagnetic force, but it is detectable in certain carefully chosen atomic transitions.

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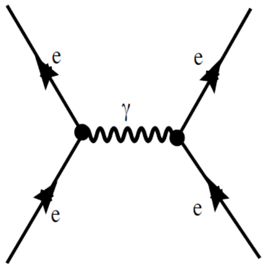
Solved Problems

Draw lowest order Feynman Diagrams for the following reactions or decays.

Reaction / Decay	Feynman Diagram
$e^- + \mu^- \to e^- + \mu^-$	
$\overline{\nu_e} + p \to n + e^+$	
$\pi^- \to \mu^- + \overline{\nu_\mu}$	
$\mu^- \to e^- + \overline{\nu_e} + \nu_e$	
$\Xi^0 \to \Lambda^0 + \pi^0$	
$\Sigma^0 \to \Delta^0 + \gamma$	

Problem 1.

Determine mass and velocity of the virtual photon for the following Bhabha Scattering. Assume that electrons are at rest.



Solution

$t = (E_{f1} - E_{i1})^2 - (\mathbf{p}_{f1} - \mathbf{p}_{i1})^2 c^2$

$= (E_{f1} - E_{i1})^2 - 0$

$= m_e c^2 - m_e c^2$

$= 0$

So, the mass of the photon is m = sqrt(t) = 0 and velocity of the photon v = 0.

Problem 2.

In problem 1, assume that one of the electron is at rest and it is fixed at $x = 0$. The other electron moves from infinity towards the first one with an initial speed of $0.01c$. Calculate the mass and velocity of the virtual photon when the distance between electrons is minimum.