How to draw Feynman diagrams in LaTeX

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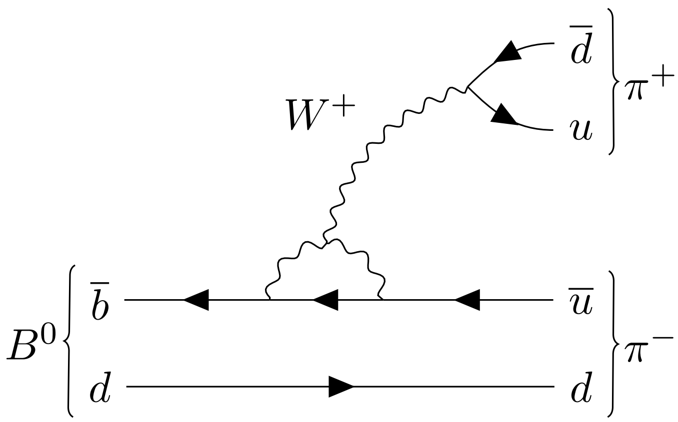
-



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Legal Information

You can recognize truth by its beauty and simplicity. When you get it right, it is obvious that it is right — at least if you have any experience — because usually what happens is that more comes out than goes in.

Richard P. Feynman

Preface

In this guide on **how to draw Feynman diagrams in LaTeX**, we won't go into too much detail, but we will look at some basic Feynman diagrams to begin writing lecture notes for our first Quantum Field Theory course. I will also show some advanced examples, but, as usual, all diagrams can be made as complex as you like. For more advanced commands, you can refer to the references listed in the *Preface*. These notes are a combination of various sources found online, with the following references:

- Feynman diagrams with TikZ
- Feynman diagrams on Overleaf
- Video tutorial *"Drawing Feynman Diagrams in LaTeX"*
- How to create these Feynman diagrams with TikZ?

Throughout the guide I will provide many examples, but you can find additional ones in my notes on Introduction to Quantum Field Theory and Fundamentals of Quantum Field Theory.

Of course, these should be regarded as personal notes written in a clean format. Any oversights, mistakes, or inaccuracies are due to my own lack of knowledge. Most importantly, I wrote these notes with the aim of *"explaining"* the subject to myself, so some parts may appear either too verbose or too superficial depending on the reader. In any case, I would be glad if they can help someone else. I sincerely hope I have managed to write a clear and well-structured document.

At times, I may not explicitly refer to a specific textbook or past course. In such cases, I am referring to MY personal notes on the topic. A collection of my notes can be found on my personal GitHub page: gCembalo.github.io.

Any mistakes/typos can be reported to my personal email:
`gabriele.cembalo02@gmail.com`.

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Contents

Chapter 1

Tutorial

1.1 Installation

In this guide we are going to use the `tick-feynman` package, but there are different packages and methods available on the internet to draw Feynman diagrams. I chose this option not only because it is the easiest choice, but also because it is compatible with *pdflatex*.

If you want to follow the package documentation you should know that the command `\feynman` is compatible with *lualatex*, which allow automatic positioning of the elements. With *pdfLaTeX*, instead, as we'll see, manual positioning is required.

We use the method described in the section 2.4.3 of the package documentation.

To draw our Feynman diagram we just have to install the package using `\usepackage{tikz-feynman}` in the preamble. In the package documentation is recommend place `\tikzfeynmanset{compat=1.0.0}` too, to that a new versions of TikZ-Feynman do not produce any undesirable changes without warning. So it's necessary add the following command to start to draw: We can compile the following code:

```
\usepackage[compat=1.0.0]{tikz-feynman}
```

Note that if you use a `pdflatex` compiler you will see a warning like:

> *Package tikz-feynman: LuaTeX is required if you wish to have vertices automatically placed. You can disable this warning by setting /tikzfeynman/warn luatex=false*

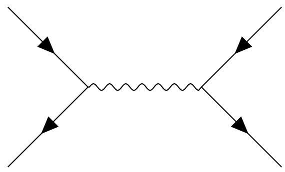
so, to fix this you can simply add to you preamble:

```
\tikzfeynmanset{warn luatex=false}
```

1.2 The first diagram and its elements

The best way to learn is through practice, so let's draw our first diagram and then analyze each element.

We can draw our first diagram:



compiling the following code:

```
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [above left=of a] (b);
    \vertex [below left=of a] (c);
    \vertex [right=of a] (d);
    \vertex [above right=of d] (f);
    \vertex [below right=of d] (g);
    \diagram{ (b) -- [fermion] (a) -- [fermion] (c);
    (a) -- [photon] (d);
    (f) -- [fermion] (d) -- [fermion] (g);
    };
    \end{feynman}
\end{tikzpicture}
```

Let's analyze all its part. Looking at the code, we can see:

- We have to position all the vertices manually. The command `\vertex (a)` does exactly that. We can also use the term `above`, `below=of`, `left=of` or `right=of`.
- To draw any edge we have to declare to vertex and write `--`.
- The fermion on the left side is drawn by declaring three vertices and connecting them with `--`. We can also specify if our particles are `fermion`, `boson` or some particular particle, like `photon` or `gluon`. Adding the term `fermion` is essential to add the arrow on the line (in fact the photon doesn't have any arrow).

- We always have to finish the declaration of the Feynman diagram using the semicolon (;).

Keep in mind that the order in which you declare the vertices or the diagram doesn't matter. You can also name the vertex as you prefer; the names `a`, `b`, etc. are arbitrary, you can name them as you want. The important thing is that the names are unique.

1.3 Adding elements

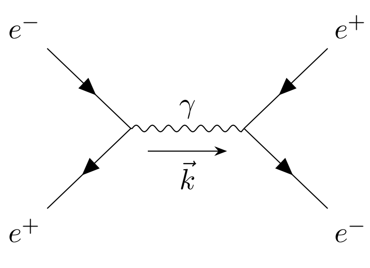
Obviously we can draw any Feynman diagram, complex as you like. We can add some style or elements to what we already know. For example we can add labels for each particle, specifing what they are. In the diagram drawn in the section 1.2, we can add the label for electron, positron and photon writing something like `{$e^-$}` in the definition of the vertex. This command adds the label to the vertex, but when we want to add the label of a mediator boson we can use the command `edge label=$\gamma$`, for example, to add γ in the middle of the edge instead of at the vertex.[1]

We can also remember that the virtual particle carry some momentum; we may want to include that information in our diagram. We can simply write `momentum'=$\vec{k}$` into the command `\diagram` with the type of the particle:[2]

```
...
(a) -- [boson, edge label=$\gamma$, momentum'=$\vec{k}$] (d);
...
```

We can obtain our "complete" diagram for the process:

$$e^+ + e^- \longrightarrow \mu^+ + \mu^- \tag{1.3.1}$$



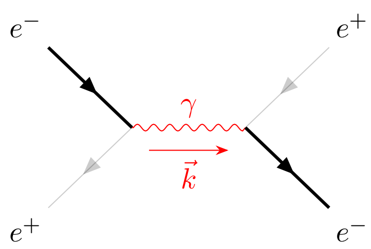
compiling the code:

[1]Note that you can use the command **small** to obtain a more elegan label; see Example 2.15.

[2]The term ' is necessary to ensure a better positioning. In facts it need if you want positioning something above or below the edge; see the example 2.3.

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [above left=of a] (b) {$e^-$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [right=of a] (d);
    \vertex [above right=of d] (f) {$e^+$};
    \vertex [below right=of d] (g) {$e^-$};
    \diagram{ (b) -- [fermion] (a) -- [fermion] (c);
    (a) -- [photon, edge label=$\gamma$, momentum'=$\vec{k}$] (d);
    (f) -- [fermion] (d) -- [fermion] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

Sometimes you can need to highlight parts of the diagram by coloring them differently, you can do whatever you want using commands like `thick`, `very thick`, `arrow style = blue`, `opacity = 0.5`, ... to obtain:



writing:

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [above left=of a] (b) {$e^-$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [right=of a] (d);
    \vertex [above right=of d] (f) {$e^+$};
    \vertex [below right=of d] (g) {$e^-$};
    \diagram{ (b) -- [fermion, very thick] (a) --
```

```
        [fermion, opacity=0.2] (c);
    (a) -- [red, photon, edge label=$\gamma$,
        momentum'={[arrow style = red]$\vec{k}$}] (d);
    (f) -- [fermion, opacity = 0.2] (d) --
        [fermion, very thick] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

Note that if, in the `\diagram` command, you use an option, such as `[fermion]` or `[momentum'=...]`, that contains characters such as brackets ([ ]) or commas (,), the whole ⟨name⟩ must be enclosed in braces ({ }); otherwise, the parser will interpret the comma as the end of the **⟨name⟩** and the start of the next key, or the closing bracket as the end of all optional arguments.

I report the easiest example, which is done in all the guide saw, but obviously the possibility are infinity. The `tick-feynman` package are based on `TikZ`, so every style (that you can find in TikZ manual) you can use in it you can import in your Feynman diagram.

In the section 2.4 the package documentation talk about *When the Algorithm Isn't Enough*, that is to say about all the situation where its method isn't enought. It isn't a section that we are interest to because we don't use the algorithm described in the documentation. You can see the section 2.4.3 where he shows the method - for him an *alternative method* - that we are using in this guide.

1.3.1 Commands

You can see different sections in the package documentation that explain some different commands and environments to draw better diagrams. In particular:

- In the section 3.1 discusses commands and enviroments.
- In the section 3.2 shows the different methods to customize diagrams.
- Section 3.2.1 explains some advanced commands to modify the placement of vertices and edges.
- Section 3.2.2 describes several methods for manually adjusting the vertices. For example he explains how to assign the elecric charge to the

vertex and let the algorithm do the positioning work. It's also described how to create a *tree layout*, which is usefull for the decay diagrams.

- Section 3.2.3 explains how to modify vertices. For instance, see the example in Section 1.3.3 and 2.2.

- Section 3.2.6 explains how to modify arrows in diagrams.

1.3.2 Different particle

Obviously there are different commands to draw different particles. I will show the list of different keys, but if you want a complete one you can see Section 3.2.4 of the package documentation or the end of the guide on Overleaf.

- We can rappresent *boson* with `[boson]`:

- We can rappresent *charged boson* with `[charged boson]`:

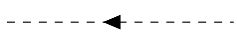
- We can rappresent the *anti charged boson* with `[anti charged boson]`:

- We can rappresent the *photon* with `[photon]`:

- We can rappresent the *scalar* with `[scalar]`:

- We can rappresent the *charged scalar* with `[charged scalar]`:

- We can rappresent the *anti charged scalar* with `[anti charged scalar]`:

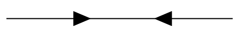


- We can rappresent the *ghost* with `[ghost]`:

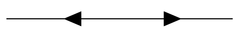
- We can rappresent the *fermion* with `[fermion]`:

- We can rappresent the *anti fermion* with `[anti fermion]`:

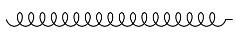
- We can rappresent the *Majorana particle* with `[majorana]`:



- We can rappresent the *anti Majorana particle* with `[anti majorana]`:

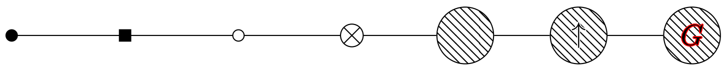


- We can rappresent the *gluon* with `[gluon]`:



1.3.3 The vertex

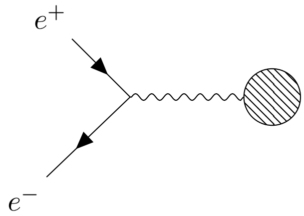
You can modify the vertices as you like, you can put a `dot`, `square dot` or you can create a `blob`. I will show to do a single example with some possible vertex in it. The only important thing to remember is to add the brackets `\{ \}` at the end of the definition; in those braket you can also add, thanks to `\usepackage{contour}` included in your preamble, some text or mathematical objects.




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex [dot] (a) {};
    \vertex [square dot, right=of a] (b) {};
    \vertex [empty dot, right=of b] (c) {};
    \vertex [crossed dot, right=of c] (d) {};
    \vertex [blob, right=of d] (e) {};
    \vertex [blob, right=of e] (f) {\contour{white}{$\uparrow$}};
    \vertex [blob, right=of f] (g) {\contour{red}{$G$}};
    \diagram{
        (a) -- (b) -- (c) -- (d) -- (e) -- (f) -- (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

1.4 Other methods

Sometimes you may get a broken diagram, but not because of a coding error. You can draw a simple Mott scattering like we learned to do, but when you compile you get this:



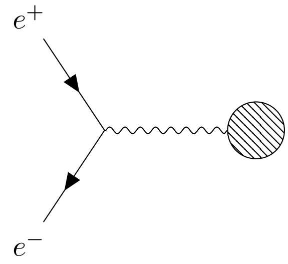

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) {$e^+$};
    \vertex [below right=of a] (b);
    \vertex [below left=of b] (c) {$e^-$};
    \vertex [blob, right=of b] (d) {};
    \diagram{ (a) -- [fermion] (b);
    (c) -- [anti fermion] (b);
    (b) -- [photon] (d) [blob];
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

This is not a beautiful diagram because of the asymmetry between the two edges. Fortunately, it's quite simple to solve this problem. You have two options:

- draw the diagram manually;
- reorder the vertex in a better way.

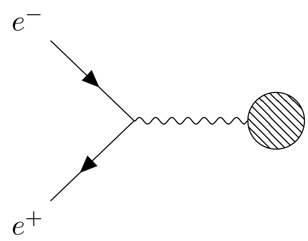
The first option is to set the position of the vertices using coordinates, such as `(1,2)`. In this way:

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
```




```
    \vertex (a) at (0,0) {$e^+$};
    \vertex (b) at (1,-1.5);
    \vertex (c) at (0,-3) {$e^-$};
    \vertex [blob] (d) at (3,-1.5) {};
    \diagram{ (a) -- [fermion] (b);
    (c) -- [anti fermion] (b);
    (b) -- [photon] (d) [blob];
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

I prefer the second option, which is to reorder the vertices in a better way. You can notice that if you put the first vertex `(a)` as the point where the e^- and e^+ annihilate, in this way you get a diagram symmetric and without an edge shorter than the other.




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [above left=of a] (b) {$e^-$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [blob, right=of a] (d) {};
```

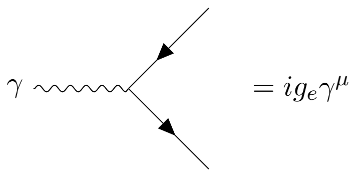
```
    \diagram{ (b) -- [fermion] (a);
    (c) -- [anti fermion] (a);
    (a) -- [photon] (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

Chapter 2

Some example

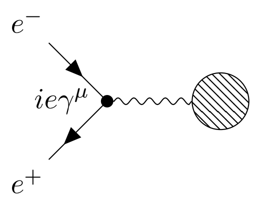
In this chapter I want to present some examples to better understand of the `tick-feynman` package.

2.1 Example 1



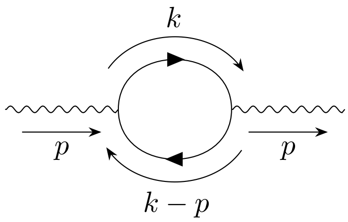

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) {$\gamma$};
    \vertex [right=of a] (b);
    \vertex [below right=of b] (c);
    \vertex [above right=of b] (d);
    \vertex [right=of b] (v2) {$=ig_e\gamma^\mu$};
    \diagram{ (a) -- [photon] (b);
    (b) -- [fermion] (c);
    (b) -- [anti fermion] (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.2 Example 2, Mott cross section



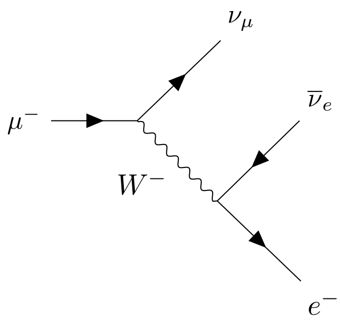

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex [dot] (a) {};
    \node at (-0.6,0) {$ie\gamma^\mu$};
    \vertex [above left=of a] (b) {$e^-$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [blob, right=of a] (d) {};
    \diagram{ (b) -- [fermion] (a);
    (c) -- [anti fermion] (a);
    (a) -- [photon] (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.3 Example 3



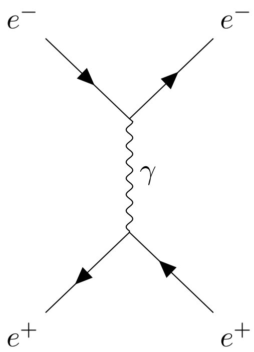

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [right=of a] (b);
    \vertex [right=of b] (c);
    \vertex [right=of c] (d);
    \diagram{
        (a) -- [boson, momentum'=$p$] (b);
        (b) -- [fermion, half left, momentum=$k$,
            looseness=1.5] (c) -- [fermion, half left,
            momentum=$k-p$, looseness=1.5] (b);
        (c) -- [boson, momentum'=$p$] (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.4 Example 4



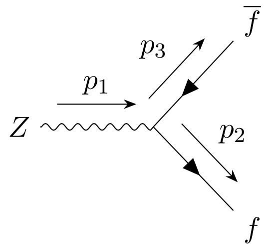

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) {\small $\mu^-$};
    \vertex [right=of a] (b);
    \vertex [above right=of b] (c) {\small $\nu_\mu$};
    \vertex [below right=of b] (d);
    \vertex [above right=of d] (e) {\small $\overline{\nu}_e$};
    \vertex [below right=of d] (f) {$e^-$};
    \diagram{
        (a) -- [fermion] (b) -- [fermion] (c);
        (b) -- [boson, edge label'=$W^-$] (d);
        (e) -- [fermion] (d) -- [fermion] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.5 Example 5



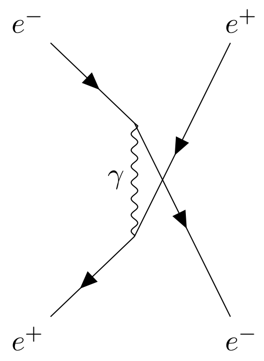

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [below right=of a] (b) {$e^+$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [above=of a] (d);
    \vertex [above left=of d] (e) {$e^-$};
    \vertex [above right=of d] (f) {$e^-$};
    \diagram{
        (a) -- [anti fermion] (b);
        (c) -- [anti fermion] (a);
        (a) -- [photon, edge label'=$\gamma$] (d);
        (e) -- [fermion] (d);
        (d) -- [fermion] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.6 Example 6



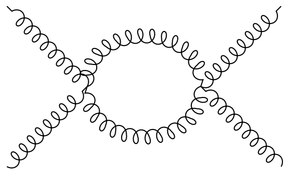

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [left=of a] (b) {$Z$};
    \vertex [above right=of a] (c) {$\overline{f}$};
    \vertex [below right=of a] (d) {$f$};
    \diagram{
        (b) -- [boson, momentum=$p_1$] (a);
        (a) -- [anti fermion, momentum=$p_3$] (c);
        (a) -- [fermion, momentum=$p_2$] (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.7 Example 7



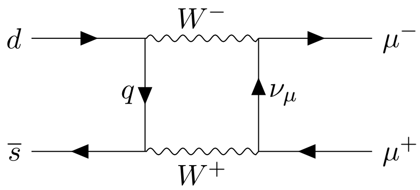

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [below right=of a] (b) {$e^-$};
    \vertex [below left=of a] (c) {$e^+$};
    \vertex [above=of a] (d);
    \vertex [above left=of d] (e) {$e^-$};
    \vertex [above right=of d] (f) {$e^+$};
    \diagram{
        (c) -- [anti fermion] (a);
        (a) -- [photon, edge label=$\gamma$] (d);
        (e) -- [fermion] (d);
        (d) -- [fermion] (b);
        (a) -- [anti fermion] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.8 Example 8



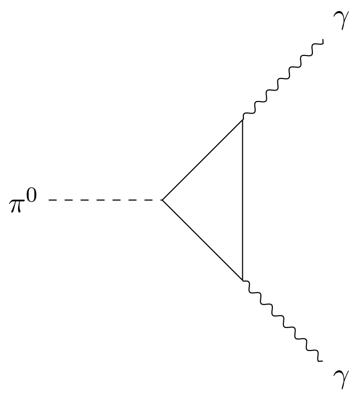
```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a);
    \vertex [below left=of a] (b);
    \vertex [above left=of a] (c);
    \vertex [right=of a] (d);
    \vertex [below right=of d] (e);
    \vertex [above right=of d] (f);
    \diagram{
        (b) -- [gluon] (a) -- [gluon] (c);
        (a) -- [gluon, half left, looseness=1.5] (d) --
            [gluon, half left, looseness=1.5] (a);
        (e) -- [gluon] (d) -- [gluon] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.9 Example 9



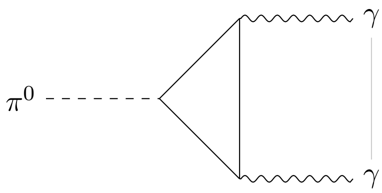

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$d$};
    \vertex [right=of a] (c);
    \vertex [below=of a] (d);
    \vertex [right=of d] (e);
    \vertex [left=of d] (f) {$\overline{s}$};
    \vertex [right=of e] (g) {$\mu^+$};
    \vertex [right=of c] (h) {$\mu^-$};
    \diagram{
        (b) -- [fermion] (a) -- [boson, edge label=$W^-$] (c)
            -- [fermion] (h);
        (f) -- [anti fermion] (d) -- [boson,
            edge label'=$W^+$] (e) -- [anti fermion] (g);
        (a) -- [fermion, edge label'=$q$] (d);
        (c) -- [anti fermion, edge label=$\nu_\mu$] (e);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.10 Example 10



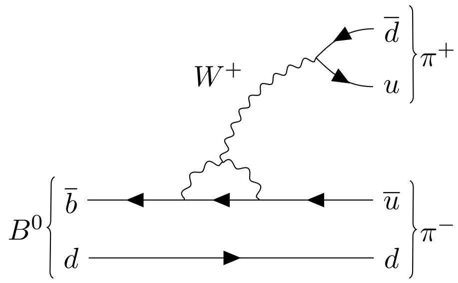

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$\pi^0$};
    \vertex [above right=of a] (c);
    \vertex [below right=of a] (d);
    \vertex [above right=of c] (e) {$\gamma$};
    \vertex [below right=of d] (f) {$\gamma$};
    \diagram{
        (b) -- [scalar] (a) -- (c) -- [photon] (e);
        (a) -- (d) -- [photon] (f);
        (c) -- (d);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.11 Example 11




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$\pi^0$};
    \vertex [above right=of a] (c);
    \vertex [below right=of a] (d);
    \vertex [right=of c] (e) {$\gamma$};
    \vertex [right=of d] (f) {$\gamma$};
    \diagram{
        (b) -- [scalar] (a) -- (c) -- [photon] (e);
        (a) -- (d) -- [photon] (f);
        (c) -- (d);
        (e) -- [opacity=0.2] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

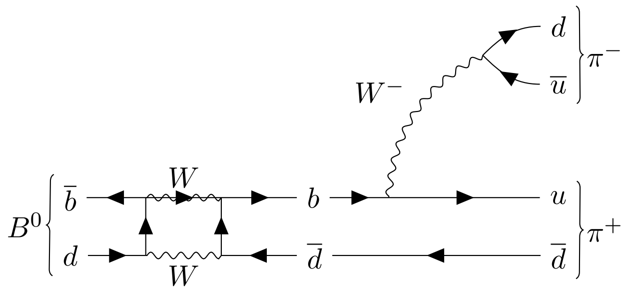
2.12 Example 12




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
\begin{feynman}
    \vertex (a1) {\(\overline b\)};
    \vertex[right=1.5cm of a1] (a2);
    \vertex[right=1cm of a2] (a3);
    \vertex[right=1.5cm of a3] (a4) {\(\overline u\)};
    \vertex[below=2em of a1] (b1) {\(d\)};
    \vertex[below=2em of a4] (b2) {\(d\)};
    \vertex at ($(a2)!0.5!(a3)!0.5cm!90:(a3)$) (d);
    \vertex[above=of a4] (c1) {\(u\)};
    \vertex[above=2em of c1] (c3) {\(\overline d\)};
    \vertex at ($(c1)!0.5!(c3) - (1cm, 0)$) (c2);
    \diagram* {
        (a4) -- [fermion] (a3) -- [fermion] (a2) --
            [fermion] (a1),
        (b1) -- [fermion] (b2),
        (c3) -- [fermion, out=180, in=45] (c2) --
            [fermion, out=-45, in=180] (c1),
        (a2) -- [boson, quarter left] (d) --
            [boson, quarter left] (a3),
        (d) -- [boson, bend left, edge label=\(W^{+}\)] (c2),
    };
    \draw [decoration={brace}, decorate] (b1.south west) --
        (a1.north west)
    node [pos=0.5, left] {\(B^{0}\)};
    \draw [decoration={brace}, decorate] (c3.north east) --
        (c1.south east)
    node [pos=0.5, right] {\(\pi^{+}\)};
    \draw [decoration={brace}, decorate] (a4.north east) --
```

```
        (b2.south east)
    node [pos=0.5, right] {\(\pi^{-}\)};
\end{feynman}
\end{tikzpicture}
\end{figure}
```

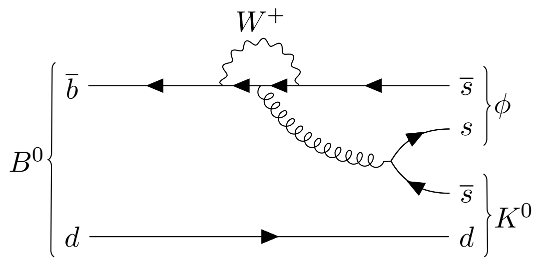
2.13 Example 13




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
\begin{feynman}
    \vertex (a1) {\(\overline b\)};
    \vertex[right=1cm of a1] (a2);
    \vertex[right=1cm of a2] (a3);
    \vertex[right=1cm of a3] (a4) {\(b\)};
    \vertex[right=1cm of a4] (a5);
    \vertex[right=2cm of a5] (a6) {\(u\)};
    \vertex[below=2em of a1] (b1) {\(d\)};
    \vertex[right=1cm of b1] (b2);
    \vertex[right=1cm of b2] (b3);
    \vertex[right=1cm of b3] (b4) {\(\overline d\)};
    \vertex[below=2em of a6] (b5) {\(\overline d\)};
    \vertex[above=of a6] (c1) {\(\overline u\)};
    \vertex[above=2em of c1] (c3) {\(d\)};
    \vertex at ($(c1)!0.5!(c3) - (1cm, 0)$) (c2);
    \diagram* {
        {[edges=fermion]
        (b1) -- (b2) -- (a2) -- (a1),
        (b5) -- (b4) -- (b3) -- (a3) -- (a4) -- (a5) -- (a6),
        (a2) -- [boson, edge label=\(W\)] (a3),
    },
        (b2) -- [boson, edge label’=\(W\)] (b3),
        (c1) -- [fermion, out=180, in=-45] (c2) --
            [fermion, out=45, in=180] (c3),
        (a5) -- [boson, bend left, edge label=\(W^{-}\)] (c2),
    };
    \draw [decoration={brace}, decorate] (b1.south west) --
```

```
        (a1.north west)
    node [pos=0.5, left] {\(B^{0}\)};
    \draw [decoration={brace}, decorate] (c3.north east) --
        (c1.south east)
    node [pos=0.5, right] {\(\pi^{-}\)};
    \draw [decoration={brace}, decorate] (a6.north east) --
        (b5.south east)
    node [pos=0.5, right] {\(\pi^{+}\)};
\end{feynman}
\end{tikzpicture}
\end{figure}
```

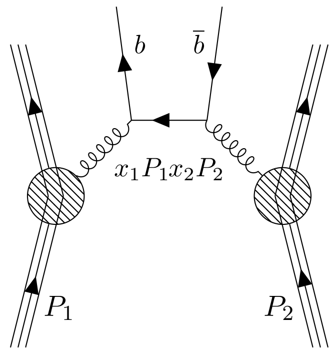
2.14 Example 14




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a1) {\(\overline b\)};
    \vertex[right=2cm of a1] (a2);
    \vertex[right=0.5cm of a2] (a3);
    \vertex[right=0.5cm of a3] (a4);
    \vertex[right=2cm of a4] (a5) {\(\overline s\)};
    \vertex[below=2cm of a1] (b1) {\(d\)};
    \vertex[below=2cm of a5] (b2) {\(d\)};
    \vertex[below=1.5em of a5] (c1) {\(s\)};
    \vertex[above=1.5em of b2] (c3) {\(\overline s\)};
    \vertex at ($(c1)!0.5!(c3) - (1cm, 0)$) (c2);
    \diagram* {
    {[edges=fermion]
        (a5) -- (a4) -- (a3) -- (a2) -- (a1),
        (b1) -- [fermion] (b2),
        (c3) -- [fermion, out=180, in=-60] (c2) --
            [fermion, out=60, in=180] (c1),
    },
        (a3) -- [gluon, bend right] (c2),
        (a4) -- [boson, out=90, in=90, looseness=2.0,
            edge label'=\(W^{+}\)] (a2)
    };
    \draw [decoration={brace}, decorate] (b1.south west) --
        (a1.north west)
    node [pos=0.5, left] {\(B^{0}\)};
    \draw [decoration={brace}, decorate] (a5.north east) --
        (c1.south east)
    node [pos=0.5, right] {\(\phi\)};
```

```
    \draw [decoration={brace}, decorate] (c3.north east) --
        (b2.south east)
    node [pos=0.5, right] {\(K^{0}\)};
\end{feynman}
\end{tikzpicture}
\end{figure}
```

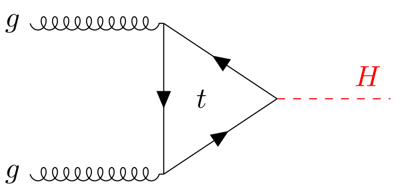
2.15 Example 15




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
%\pgfdeclarelayer{foreground}
%\pgfsetlayers{main,foreground}
    \begin{feynman}
    \vertex at (0,0) (a) ;
    \vertex [blob] at (0.5,2) (b) {};
    \vertex at (0,4) (c);
    \vertex at (1.5,3) (d);
    \vertex at (1.3,4.5) (e);
    \vertex at (2.5,3) (f);
    \vertex at (2.7,4.5) (g);
    \vertex [blob] at (3.5,2) (h) {};
    \vertex at (4,0) (i);
    \vertex at (4,4) (j);
    %double the fermion line
    \vertex at (-0.1,0) (a1);
    \vertex at (0.1,0) (a2);
    \vertex at (0.4,2) (b1);
    \vertex at (0.6,2) (b2);
    \vertex at (3.9,0) (i1);
    \vertex at (4.1,0) (i2);
    \vertex at (3.4,2) (h1);
    \vertex at (3.6,2) (h2);
    \vertex at (-0.1,4) (c1);
    \vertex at (0.1,4) (c2);
    \vertex at (3.9,4) (j1);
    \vertex at (4.1,4) (j2);
```

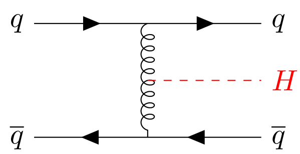
```
    \diagram{
        %double the fermion line
        (a1) -- (b1);
        (a2) -- (b2);
        (i1) -- (h1);
        (i2) -- (h2);
        (c1) -- (b1);
        (c2) -- (b2);
        (j1) -- (h1);
        (j2) -- (h2);
        %the normal diagram
        (a) -- [fermion, edge label'=$P_1$] (b) --
            [fermion] (c);
        (b) -- [gluon, edge label'={\small $x_1 P_1$}] (d) --
            [fermion, edge label'={\small $b$}] (e);
        (d) -- [anti fermion] (f) -- [anti fermion,
            edge label={\small $\overline{b}$}] (g);
        (f) -- [gluon, edge label'={\small $x_2 P_2$}] (h) --
            [fermion] (j);
        (h) -- [anti fermion, edge label'=$P_2$] (i);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.16 Example 16



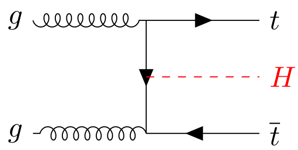

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex at (0, 1) (i1) {\(g\)};
    \vertex at (0,-1) (i2) {\(g\)};
    \vertex at (2, 1) (a);
    \vertex at (2,-1) (b);
    \vertex at (3.5, 0) (c);
    \vertex at (5, 0) (f);
    \vertex at (2.5,0) () {\(t\)};
    \vertex[red] at (4.7,.3) () {\(H\)};
    \diagram*{
        (i1) -- [gluon] (a),
        (i2) -- [gluon] (b),
        (a) -- [fermion] (b) -- [fermion] (c) -- [fermion] (a),
        (c) -- [scalar, red] (f),
    };
\end{feynman}
\end{tikzpicture}
\end{figure}
```

2.17 Example 17



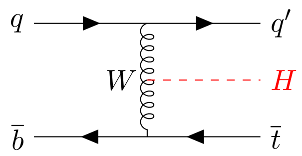

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$q$};
    \vertex [right=of a] (c) {$q$};
    \vertex [below=of a] (d);
    \vertex [left=of d] (e) {$\overline{q}$};
    \vertex [right=of d] (f) {$\overline{q}$};
    \vertex at (0,-0.75) (h);
    \vertex [red, right=of h] (g) {$H$};
    \diagram{
        (b) -- [fermion] (a) -- [fermion] (c);
        (a) -- [gluon] (d) -- [fermion] (e);
        (d) -- [anti fermion] (f);
        (h) -- [scalar, red] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.18 Example 18



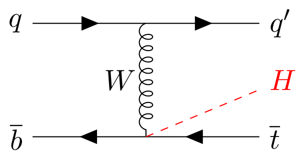

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$g$};
    \vertex [right=of a] (c) {$t$};
    \vertex [below=of a] (d);
    \vertex [left=of d] (e) {$g$};
    \vertex [right=of d] (f) {$\overline{t}$};
    \vertex at (0,-0.75) (h);
    \vertex [red, right=of h] (g) {$H$};
    \diagram{
        (b) -- [gluon] (a) -- [fermion] (c);
        (a) -- [fermion] (d) -- [gluon] (e);
        (d) -- [anti fermion] (f);
        (h) -- [scalar, red] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.19 Example 19



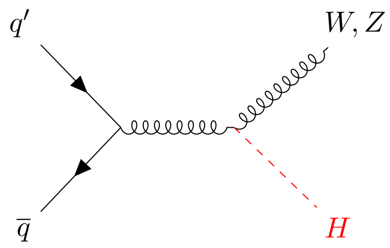

```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$q$};
    \vertex [right=of a] (c) {$q^\prime$};
    \vertex [below=of a] (d);
    \vertex [left=of d] (e) {$\overline{b}$};
    \vertex [right=of d] (f) {$\overline{t}$};
    \vertex at (0,-0.75) (h);
    \vertex [red, right=of h] (g) {$H$};
    \diagram{
        (b) -- [fermion] (a) -- [fermion] (c);
        (a) -- [gluon, edge label'=$W$] (d) -- [fermion] (e);
        (d) -- [anti fermion] (f);
        (h) -- [scalar, red] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.20 Example 20




```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [left=of a] (b) {$q$};
    \vertex [right=of a] (c) {$q^\prime$};
    \vertex [below=of a] (d);
    \vertex [left=of d] (e) {$\overline{b}$};
    \vertex [right=of d] (f) {$\overline{t}$};
    \vertex at (0,-0.75) (h);
    \vertex [red, right=of h] (g) {$H$};
    \diagram{
        (b) -- [fermion] (a) -- [fermion] (c);
        (a) -- [gluon, edge label'=$W$] (d) -- [fermion] (e);
        (d) -- [anti fermion] (f);
        (d) -- [scalar, red] (g);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.21 Example 21

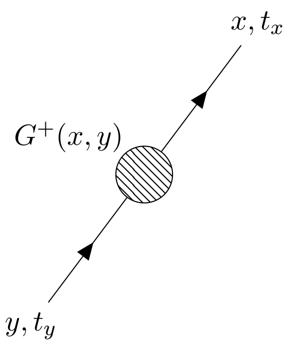



```
\begin{figure}[ht!]
\centering
\begin{tikzpicture}
    \begin{feynman}
    \vertex (a) ;
    \vertex [above left=of a] (b) {$q^\prime$};
    \vertex [below left=of a] (c) {$\overline{q}$};
    \vertex [right=of a] (d);
    \vertex [above right=of d] (e) {$W,Z$};
    \vertex [red, below right=of d] (f) {$H$};
    \diagram{
        (b) -- [fermion] (a) -- [fermion] (c);
        (a) -- [gluon] (d);
        (d) -- [gluon] (e);
        (d) -- [scalar, red] (f);
    };
    \end{feynman}
\end{tikzpicture}
\end{figure}
```

2.22 Diagram of "Introduction to QFT"

I collect here the diagram that I used in my lecture notes for the MSc course Introduction to Quantum Field Theory.

2.22.1 Figure 8.2




```
\begin{figure}[ht!]
    \centering
    \begin{tikzpicture}
        \begin{feynman}
        \vertex at (0,0) (a) {$y,t_y$};
        \vertex [blob] at (1.5,2) (b) {};
        \vertex at (0.5,2.5) (v) {$G^+(x,y)$};
        \vertex at (3,4) (c) {$x,t_x$};
        \diagram{
            (a) -- [fermion] (b) -- [fermion] (c);
        };
        \end{feynman}
    \end{tikzpicture}
\end{figure}
```