Project 1 FYS4560

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February 16, 2016

1 SM and beyond: Allowed, forbidden and discovery process

The feynman diagrams are showed below. Every process is allowed according to conserved quantities, with the possible exception of number 5 where there should be a muon neutrino, but because of neutrino oscilliation it could be allowed depending on how long after the reaction the final particles were measured.

- Electromagnetic
  - 1, 2, 3, 4, 6, 8, 11, 12, 13, 14, 15, 16, 20
- Weak
  - 3, 4, 5, 7, 8, 10, 11, 13, 15, 18, 19, 20
- Strong
  - 1, 2, 4, 6, 8, 9, 12, 14, 16, 17

There are four decays present, τ^+, two H and a $\Upsilon(3s)$.
$\tau^+ \to \mu^+ \nu_e \bar{\nu}_\tau$
Since the branching ratio for τ to μ is about the same as with μ to e and their mass difference is large we can use the relationship

$$\frac{1}{\tau_l} = G_f^2 m_l^5 \tag{1}$$
$$\frac{\tau_\tau}{\tau_\mu} = \frac{m_\mu^5}{2m_\tau^5} \tag{2}$$
$$\text{the factor 2 comes from that } \tau \text{ has 2 leptonic decays} \tag{3}$$
$$\tau_\tau = \frac{\tau_\mu}{2}\left(\frac{m_\mu}{m_\tau}\right)^5 \approx 2.0 \times 10^{-12} \tag{4}$$

For the branching ratio for three-body weak decay, Sargent rule states

$$\frac{\Gamma_i/\Gamma}{\tau_\tau} = G_f^2 m_\tau^5 \tag{5}$$
$$\Gamma_i/\Gamma = \tau_\tau G_f^2 m_\tau^5 \tag{6}$$

$H \to gg$, $H \to Z\gamma$
The lifetime of the higgs goes as $1/m_H^2$ which is of the order 10^{-22} As for the branching ratio it goes proportional as the vertex matrix element $\mathcal{M}$

$$\frac{BR}{\tau_H} = \left(\frac{m_f}{V}\right)^2$$

where $V = (\sqrt{2}G_f)^{-1/2}$

Suppresion/forbidding In process 9, 11, 12 and 20 there are a large mass difference from initial to final, which can cause supression of these processes.

Importance:

Process 3 This process would show that supersymmetric particles exists and there be a breakthrough in particle physics.

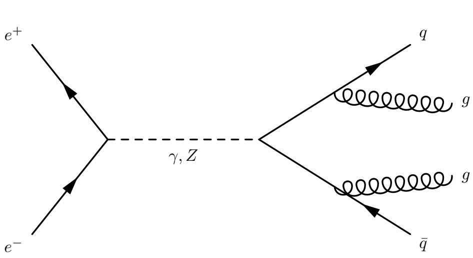
Process 4 & 8 These are of interest because of our circular accelerators and these reactions are there plentiful and much studied.

Process 10 Quarks going into pure weak bosons shows the ability of the $W^{\pm}$ to change the quarks from particle to anti particle and vice versa.

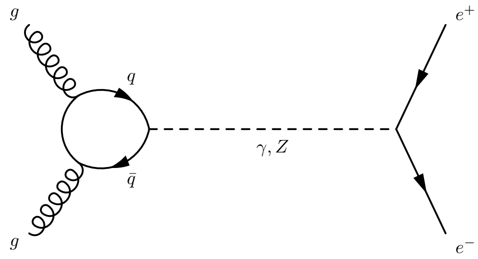
Process 11

Process 14 Both top and higgs production is of interest since they are our heavy weight champions and therefore has limitd lifetime. The uniqeness of the tops ability to be single due to its short lifespan is a golden oppurtunity to see quarks alone.

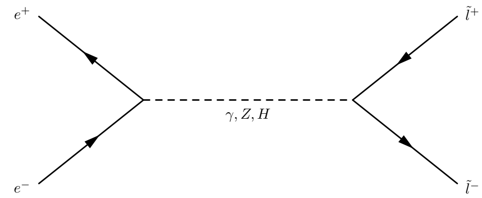
Process 18 J/ψ is a highly measured and has a narrow width, so it has been used as a calibartion particle when setting up new detectors.



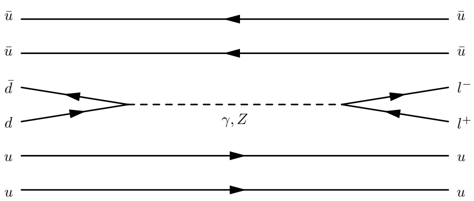
(1) $e^+e^- \to q\bar{q}gg$



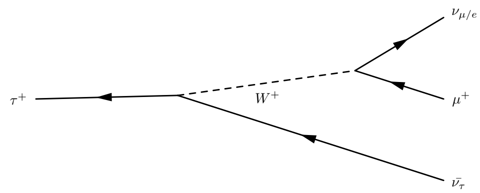
(2) $gg \to e^+e^-$



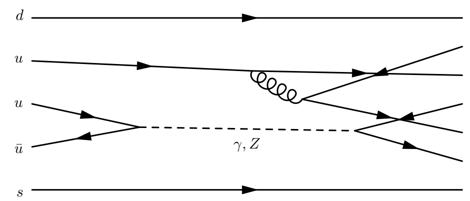
(3) $e^+e^- \to \tilde{l}^+\tilde{l}^-$



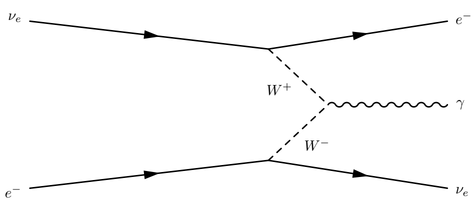
(4) $p\bar{p} \to l^+l^-x$



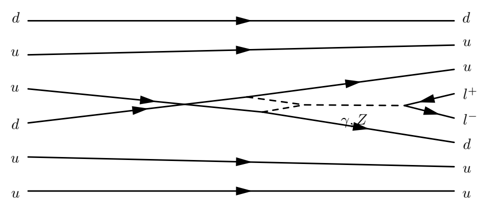
(5) $\tau^+ \to \mu^+\bar{\nu}_\tau\nu_{e/\mu}$



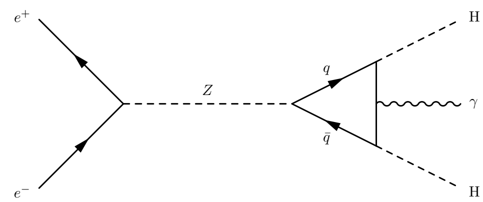
(6) $k^-p \to \omega^-k^+k^0$



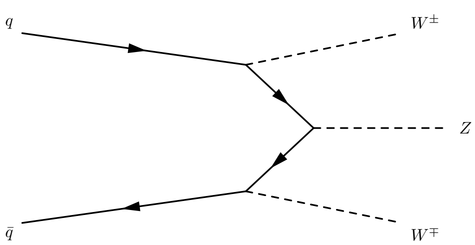
(7) $e^-\nu_e \to \nu_e\gamma e^-$



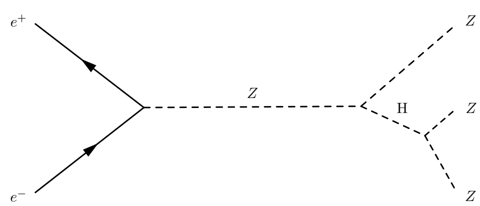
(8) $pp \to ppl^+l^-$



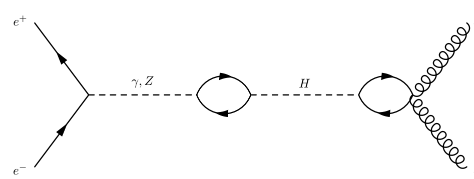
(9) $e^-e^+ \to \gamma HH$



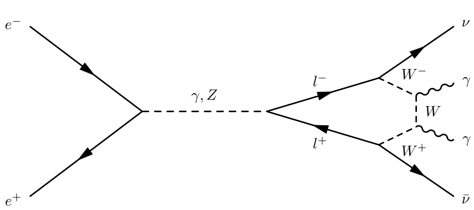
(10) $qq \to W^\pm W^\mp Z$



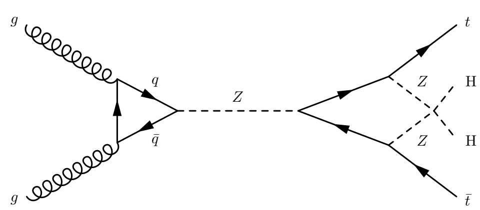
(11) $e^-e^+ \to ZZ$



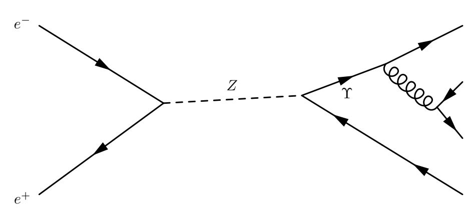
(12) $e^-e^+ \to H \to gg$



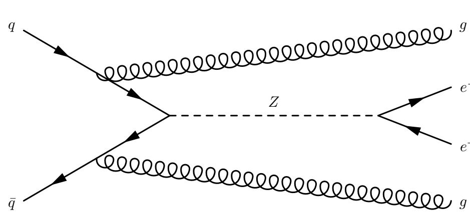
(13) $e^+e^- \to \nu\bar{\nu}\gamma\gamma$



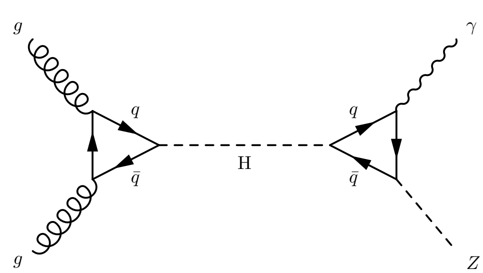
(14) $gg \to t\bar{t}HH$



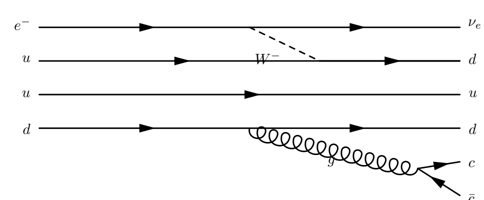
(15) $e^+e^- \to \Upsilon(3s) \to B^0\bar{B}^0$



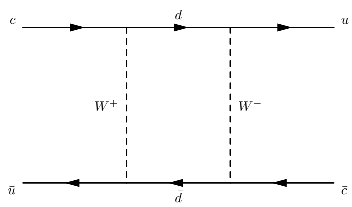
(16) $q\bar{q} \to gge^-e^+$



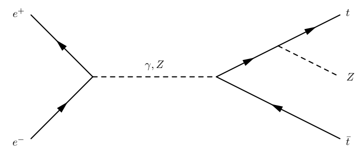
(17) $gg \to Z\gamma$



(18) $gg \to t\bar{t}HH$



(1) $D^0 \longleftrightarrow \bar{D}^0$



(2) $e^+e^- \rightarrow t\bar{t}Z$

2 Top quark and W boson

2.1 CKM and W-boson

The CKM-matrix is a unitary matrix where each element holds information about the strength of the flavour changing weak deacys which happens between quarks. These changes are mediated with the $W^\pm$ boson. When four quarks were discovered it was created two sets of equation describing the decay from down and strange into top and charm. Seeing that with CP-violation could not be explained with these four quarks, they added another generation to create the CKM-matrix:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \tag{7}$$

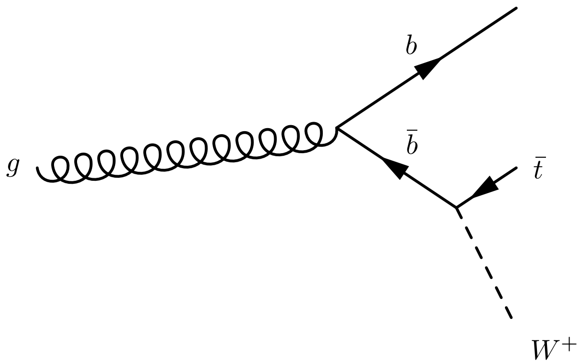
The W boson is a mediater of the weak force, it has either $+1$ or -1 charge so it can react with charged particles. In regards to the CKM-matrix it is the mediator for decaying quarks between up and down types as well as changing flavours. V_{ud} can be experimentally shown from the ratio between netron decay and μ decay.
V_{us} is shown in the $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay process.
V_{cs} is experimentally shown in hadronic decays of $W^\pm$ and $D \rightarrow \bar{K} e^+ \nu_e$ process.

2.2 Top quark production

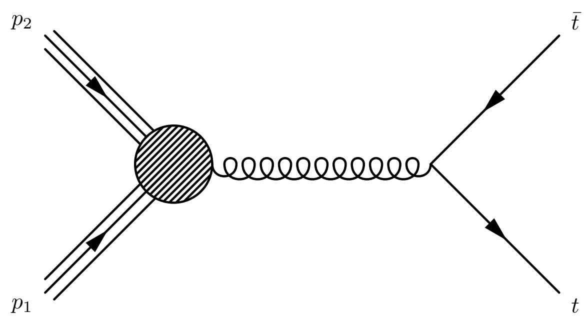
- In an $e^- e_+$ anihilation there will be produced a γ or Z which in turn can decay into a $q\bar{q}$. The quark pair could be $t\bar{t}$, but because of its high mass and the relativistic speed the electrons must reach, this process will be supressed

- As for the pp-collison there are alot that can happen. Gluons, g, can be produced which in turn creates a $t\bar{t}$-pair $g \rightarrow t\bar{t}$, and g going into $b\bar{b}$ in which one of the bs interacts with a W to become a singel t, $g \rightarrow b\bar{b} \rightarrow Wbt$.

- When a $p\bar{p}$ annihilation occurs there will be produced high energy gluons that create $t\bar{t}$, and $b\bar{b}$ to W and bt for a single top. Same as a pp collison but with more energy leftover to produce the top pairs.



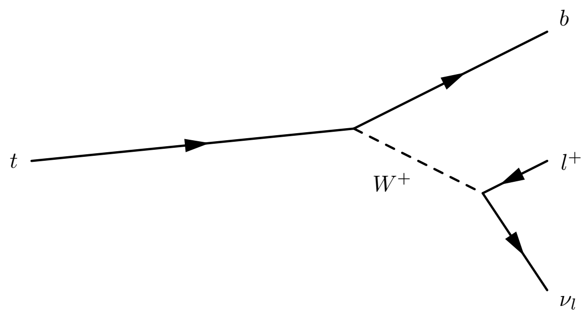
(1) $pp \to W^+\bar{t}b$



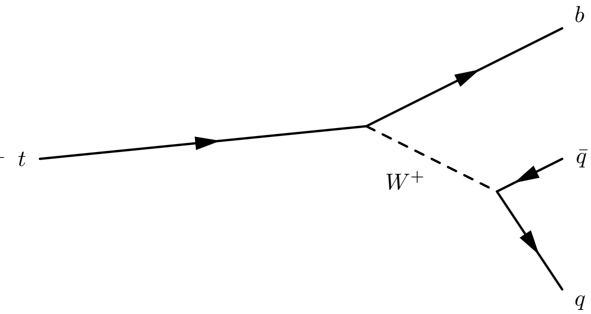
(2) $pp \to \bar{t}t$

2.3 Top quark decay

The top quark is very heavy compared to the other elementary particles in the standard model. Due to this mass it only as a lifetime of $5 \times 10^{-25}\ s$, and therefore do not have time to create hadrons, and is the only quark we can observe alone in some sense. Because of that it deacys into a W and a bottom, strange or down quark, which is also the only observed decay mode of the t quark. The branching ratio of it decaying into a b compared to the other quarks are about 99%.
The t decays therefore into a W boson which means it can have a leptonic or hadronic final state.



(1) $t \to bl^{+}\nu_l$



(2) $t \to b\bar{q}q$

$$t \to W^{+}b \to q\bar{q}b \tag{8}$$
$$\bar{t} \to W^{-}\bar{b} \to l^{-}\bar{\nu}\bar{b} \tag{9}$$

2.4 Branching ratios of top decays

$$W_i = \frac{\Gamma_i/\Gamma}{\tau} \approx G_F(\Delta m)^5$$

$G_F \approx 1.17 \times 10^{-5}\, GeV^{-2}$
The branching ratio will be about the size of the mass difference in the process.

$m_t \approx 173\, GeV$, $m_b \approx 4\, GeV$, $m_c \approx 1\, GeV$, $m_s \approx 95\, MeV$, $m_\tau \approx 1776\, MeV \approx 2\, GeV$

$t \to b + c\bar{s}$

$$\Delta m = m_t - m_b - m_c - m_s \approx 168\, GeV$$

$t \to b + \tau^{+}\nu_\tau$ aproximate the neutrino to be massless.

$$\Delta m = m_t - m_b - m_{\tau^+} \approx 167\, GeV$$

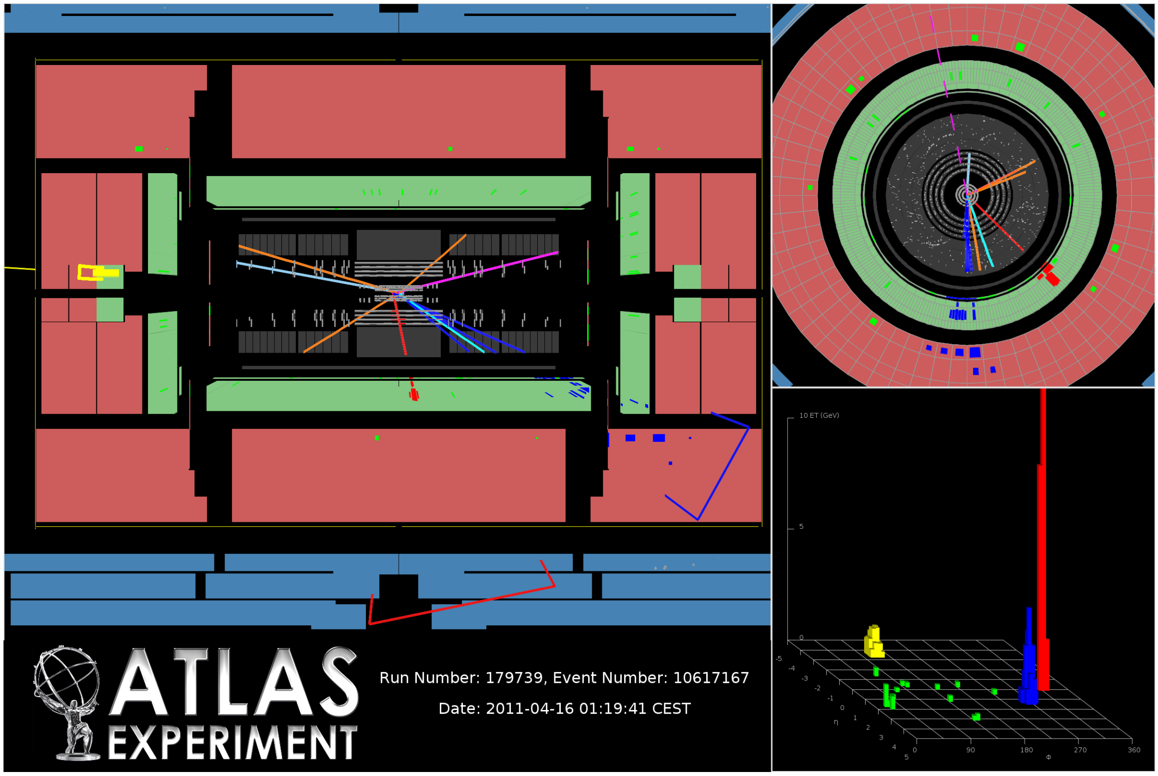


Figure 5: An event candidate for single top quark. Top decaying to electron (red line),two jets (blue and yellow), and several particles that can not be detected where the missingenergy is clumped together (pink line). Picture gotten from Atlas link

3 Gauge theories

3.1 Symmetries

The Standard Model is based on the symmetry group $SU(3) \otimes SU(2) \otimes U(1)$.

- QED is described in the $U(1)$ group giving rise to the photon as a mediating gauge boson.
- WI from $SU(2)$ which produces three bosons, $W^{\pm}$, W^0, the Z will come after combining $SU(2)_L \otimes U(1)_Y$ into electro weak theory. In electro weak theory it can be shown conservation of isospin.
- And finally the QCD comes from the $SU(3)_C$ where the 8 bosons are gluons, and it holds the conservation of the quantum number color.

The fermions are organized in three families as seen below.

$$\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix}, \quad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix}, \quad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$$

And each family can be divided into left handed doublets and right handed singlets $SU(2)_L$. There is the foce mediators g, W, Z, γ and the H boson which gives particles mass.

GUT In *GUT* the coupling constants will all be the same, meaning that all the forces will have equal strenght in their coupling. These are the conditions are considered to be available at very high energies, as in the start of our universe.

3.2 Gauge principle and QCD

The gauge principle is a requirement that the phase invariance should hold locally. These transformations give rise to mediator bosons.
Starting with the free Lagrangian

$$\mathcal{L}_0 = \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m_f) q_f \tag{10}$$

where $q_f^\alpha \equiv (q_f^1, q_f^2, q_f^3)$ has colour α and flavour f. This Lagrangian is invariant under global transformations in $SU(3)_C$ in colour space,

$$q_f^\alpha \to U_\beta^\alpha q_f^\beta, \quad U = \exp\left\{ i\frac{\lambda^a}{2}\theta_a \right\} \tag{11}$$

here U are the $SU(3)_C$ matrices, λ are the generators in the fundemental representation.
Now we require the Lagrangian to be also invariant under local $SU(3)_C$ transformations, which is done in the same way as QED, by changing the deriviatives to covariant objects.

$$D^\mu q_f \equiv \left[\partial^\mu + i g_s G^\mu(x)\right] q_f \tag{12}$$

Here the G_a^μ are the eight different bosons in QCD, also called gluons.
Since we want the transformation to be exactly like the transform of the colour-vector q_f, we get

$$(D^\mu)' \to U D^\mu U^\dagger \tag{13}$$

$$(G_a^\mu)' \to U G^\mu U^\dagger + \frac{i}{g_s}(\partial^\mu U) U^\dagger \tag{14}$$

Then under an infinitesimal $SU(3)_C$ transformation of the quarks and bosons

$$U \approx 1 + i \left(\frac{\lambda^a}{2}\right)_{\alpha\beta} \tag{15}$$

$$(q_f^\alpha)' \to q_f^\alpha + i \left(\frac{\lambda^a}{2}\right)_{\alpha\beta} \delta\theta_a q_f^\beta \tag{16}$$

$$(G_a^\mu)' \to \frac{1}{g_s}\partial^\mu(\delta\theta_a) - f^{abc}\delta\theta)_b G_c^\mu \tag{17}$$

We need to create field strengths of the gluon fields who transform homogeneously

$$(G^{\mu\nu})' = UG^{\mu\nu}U^\dagger$$

$$G^{\mu\nu}(x) \equiv \frac{\lambda^a}{2} G_a^{\mu\nu}(x) \tag{18}$$

$$G_a^{\mu\nu}(x) = \partial^\mu G_a^\nu - \partial_a^\nu - g_s f^{abc} G_b^\mu G_c^\nu \tag{19}$$

and taking the trace of the kinetic term og the gluon fields $\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}] = \frac{1}{2}G_a^{\mu\nu}G_{\mu\nu}^a$. All this results in the Lagrangian of QCD

$$\mathcal{L}_{QCD} \equiv -\frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a + \sum_f \bar{q}_f(i\gamma^\mu D_\mu - m_f)q_f \tag{20}$$

As with QED there is no invariant mass term for the gluon fields, making them massless spin-1 bosons. There is also self interacting terms due to the non-commutativity of the $SU(3)_C$ matrices, which do not occur in QED.