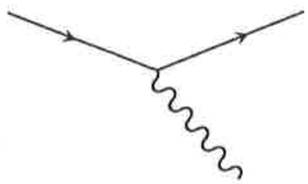
KEY

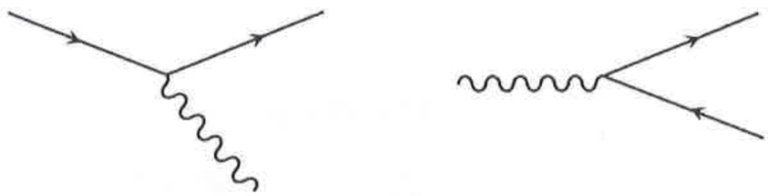
Feynman diagrams represent particle interactions. The diagrams obey a few basic rules.

1. You can draw two kinds of lines, a solid straight line with an arrow or a wiggly line:

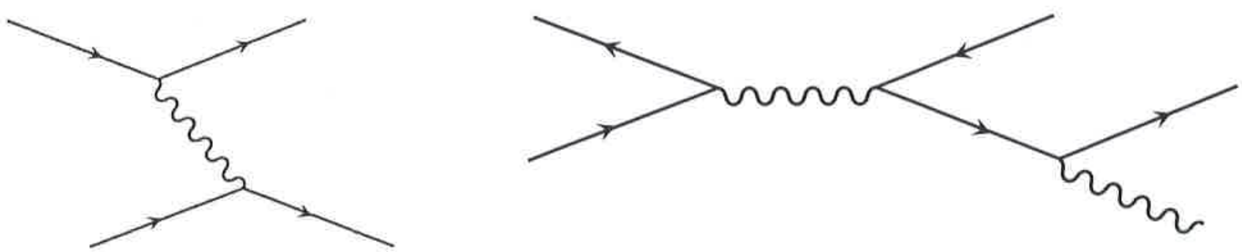
2. An intersection is called a vertex. Every vertex must have two arrows and one wiggly line:



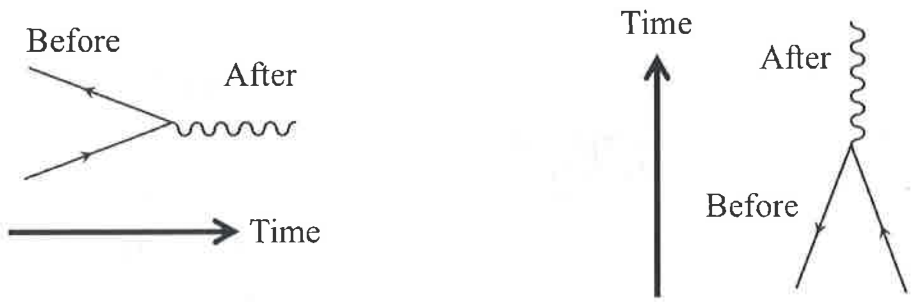
3. At each vertex, one of the two arrows must point in and the other arrow must point out.



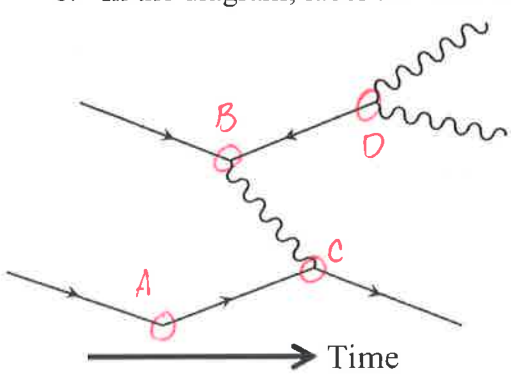
4. We will build up to diagrams with 2-3 vertices.



5. The diagrams are usually read from left to right. Though, they are sometimes read from bottom to top. This is indicated by a "time axis." Each vertex has a "before" side and an "after side."



6. In the diagram, label the vertices (A, B, C, D) *in the time order* that they occur. Identify all flaws.



A - No force carrier (~~~)

B - 2 arrows in

C - OK

D - 2 force carriers, no arrow in

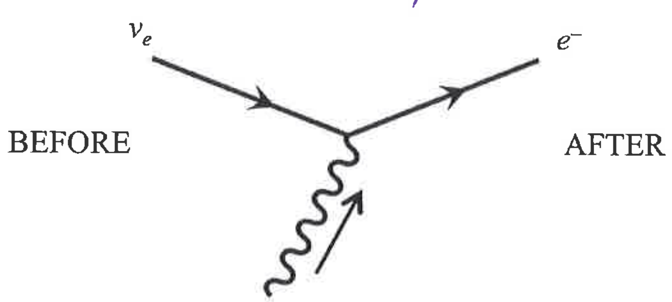
As particles in the Standard Model interact, certain quantities are always conserved.

- Conservation of charge: the total charge Q is conserved. (We'll use Q for charge, q for quark.)
- Cons'n. of lepton number: the total lepton count is conserved (antileptons count as negative).
- Cons'n. of baryon number: total baryon count is conserved (q count as positive; $\bar{q}$ count as negative).

Feynman diagrams represent interactions by distinguishing incoming particles from outgoing particles.

- Solid lines represent free particles.
  - Solid arrows that point *forward with time* are *matter particles*.
  - Solid arrows that point *backward against time* are *antimatter particles*.
- Wavy lines represent exchange particles.

Example 1 Part of β^- decay



incoming exchange particle
carries negative charge

A) State the total charge entering the vertex.

?

B) State the total charge exiting the vertex.

e^- : charge -1

C) State the lepton number entering the vertex.

ν_e : 1

D) State the lepton number exiting the vertex.

e^- : 1

E) State the quark/baryon number entering the vertex.

0

F) State the quark/baryon number exiting the vertex.

0

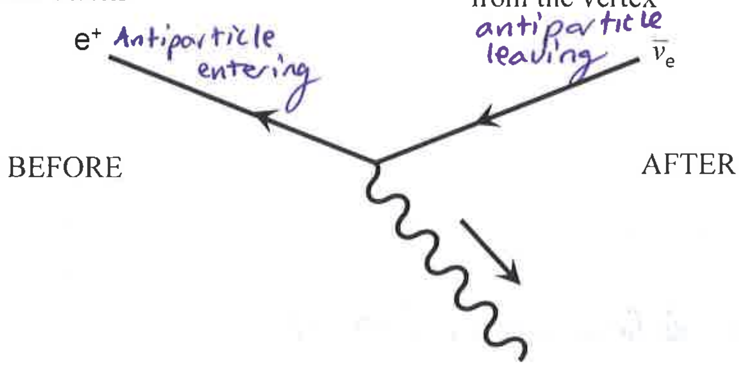
G) Identify (i) the exchange particle and (ii) the force involved.

must be W^- Boson, so weak interaction

Example 2

positron entering the vertex

antineutrino emerging from the vertex



A positron enters a vertex, emits an exchange particle and emerges as an antineutrino

A) State the total charge entering the vertex.

e^+: $+1$

B) State the total charge exiting the vertex.

?

C) State the lepton number entering the vertex.

e^+ : -1

D) State the lepton number exiting the vertex.

$\bar{\nu}_e$: -1

E) State the quark/baryon number entering the vertex.

0

F) State the quark/baryon number exiting the vertex.

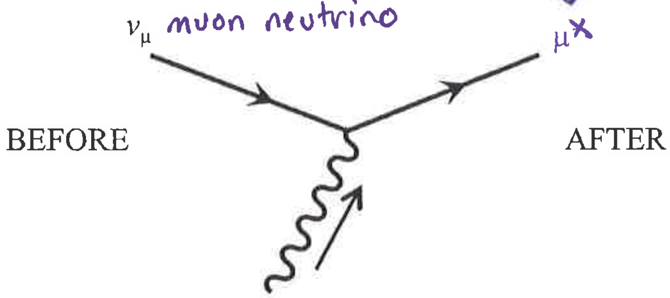
0

G) Identify (i) the exchange particle and (ii) the force involved.

W^+ Boson, so weak interaction

mistake, must be μ^-
(based on direction of arrow)

3) Inspect the Feynman diagram below.



incoming exchange particle

A) Using conservation of charge, determine the charge of the exchange particle.

must be -1

B) Identify (i) the exchange particle and (ii) the force involved in this interaction.

must be W^- Boson, so weak

C) Show that lepton number is the same entering the vertex as exiting the vertex.

$\nu_\mu : 1$ $\mu^- : 1$
$W^- : 0$

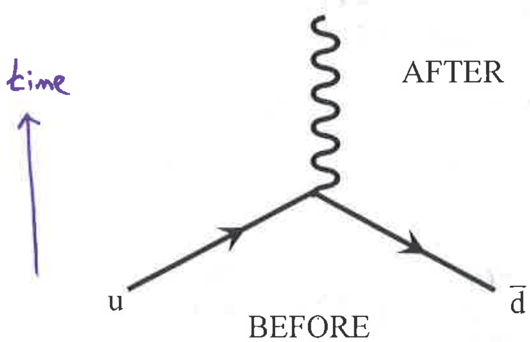
D) Show that the baryon number is the same entering the vertex as exiting the vertex.

$\nu_\mu : 0$ $\mu^- : 0$
$W^- : 0$

E) Describe the diagrammed interaction in words. Use the term "absorb."

A muon neutrino absorbs a W^- Boson and becoms a muon

4) Inspect the Feynman diagram below.



A) Using conservation of charge, determine the electric charge of the exchange particle.

electric charge: $u : +2/3$
$\bar{d} : +1/3$ so after, must be $+1$

B) This interaction is mediated by the weak nuclear force. Identify the exchange particle.

W^+ Boson

C) Explain why (B) could not be answered without being told that the weak force is involved.

only weak describes change in quark flavor

D) Show that lepton number is the same entering the vertex as exiting the vertex.

0 before, 0 after

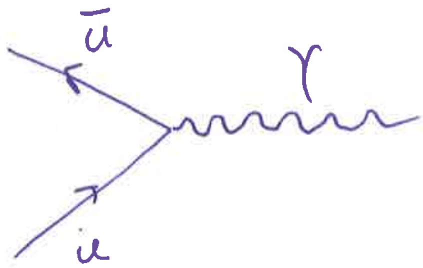
E) Show that the baryon number is the same entering the vertex as exiting the vertex.

$u : 1/3$ $W^+ : 0$
$\bar{d} : -1/3$

F) This is a more rare form of annihilation. Describe the interaction, in words.

an up quark and antidown quark annihilate to produce a W^+ Boson

Annihilation
When an up quark (u) and up antiquark (ū) collide, they **annihilate**, producing ~~two~~ one? *photons* in their place. Draw this Feynman diagram, using a horizontal time axis.



Pair Production
A *single photon* can spontaneously convert into a particle and its antimatter counterpart (e.g., $\gamma \rightarrow u + \bar{u}$). If this occurs out in empty space, the resulting matter-antimatter pair are "virtual" particles: they are never actually separate, and they immediately collide and annihilate, regenerating the single photon. But if this process occurs near a nucleus, the nucleus can repel the electrically positive particle and attract the electrically negative particle. This splits up the pair and imparts momentum to them both. Through this interaction with the nucleus, the matter-antimatter particles become **real** particles.

This process, wherein a photon interacts with a nucleus to spontaneously convert into a matter particle-antimatter particle pair, is called **pair production**.

(a) The mass of an electron is 9.11×10^{-31} kg. Calculate the minimum energy a photon must have to pair produce an electron and antielectron (a positron).

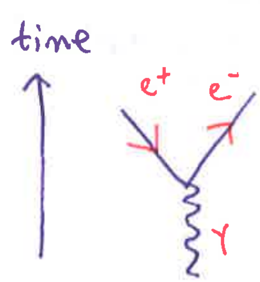
$$E = mc^2 = 9.1\times10^{-31}\,kg\,(3\times10^{8}\,m/s)^2 = 8.2\times10^{-14}\,J$$
$$= 0.51\,MeV/c^2$$

(b) Using your answer to (a), calculate the minimum frequency a photon must have to pair produce an electron and an antielectron (a positron).

must have $2\times 8.2\times10^{-4}\,J$

so $E = hf \rightarrow f = E/h = \frac{2\times8.2\times10^{-14}\,J}{6.63\times10^{-34}\,J\cdot s} = \boxed{1.2\times10^{20}\,Hz}$

(c) Draw a Feynman diagram for pair production of an electron and a positron. Use a vertical time axis.



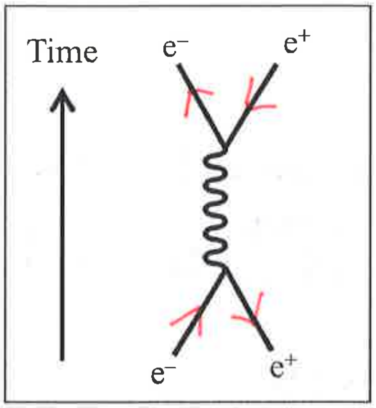
(d) Discuss the differences between annihilation and pair production.

photon → mass

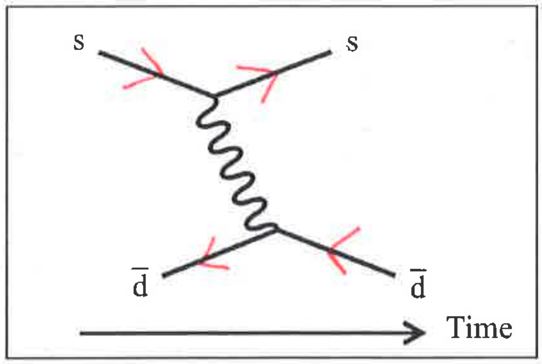
vs

mass → photon

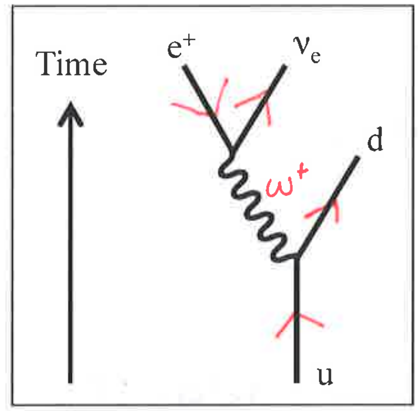
5) In each Feynman diagram below, add the correct directions to each solid line.



a positron and electron annihilate into a photon then pair produce back to a positron and electron



a strange quark emits a photon and remains strange; a down antiquark absorbs the photon & remains antidown; they are scattering off each other

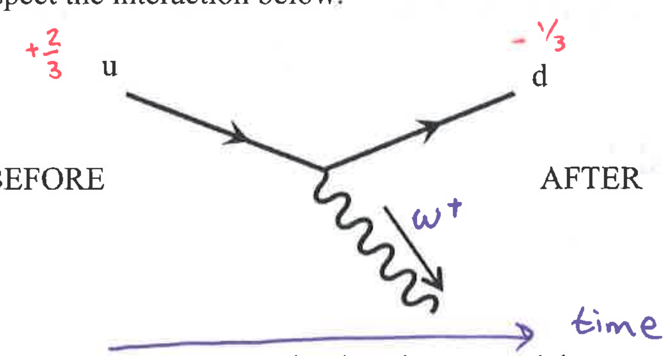


an up quark emits a W^+ boson & becomes a down quark; the W^+ boson becomes a positron and an electron neutrino

In the middle: how can you tell, from the diagram, that s emits the photon **before** $\bar{d}$ absorbs the photon?

Because, on the time axis, the strange quark's vertex occurs before the down antiquark's vertex.

6) Inspect the interaction below.



emitted exchange particle carries away positive charge

A) Identify the exchange particle. How do you know what it is?

W^+ charge before is $+\frac{2}{3}$ so charge after must be $+\frac{2}{3}$

B) State force involved. $+1 + -\frac{1}{3} = +\frac{2}{3}$ ✓

weak

C) Show that the total baryon number is conserved before & after the first vertex.

before $+\frac{1}{3}$

after $-\frac{1}{3}$

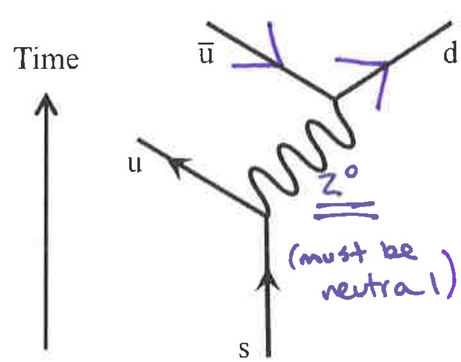
D) State the lepton number before and after the interaction.

before: 0 after: 0

E) Describe the interaction with words.

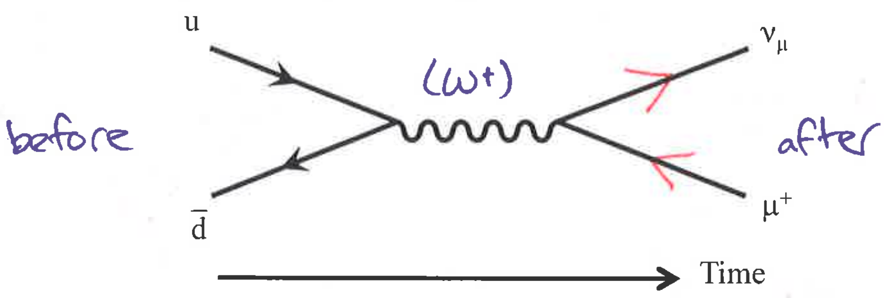
an up quark decays into a down quark and a W^+ Boson

7) Inspect the Feynman diagram shown to the right. (a) Add directions to the solid lines where omitted. (b) On the diagram, identify the exchange particle. The **weak force** is the only force by which a strange quark can decay. Otherwise, the total number of strange particles is conserved (where s = +1; $\bar{s}$ = −1).
(c) Describe the diagrammed interaction in words.



A strange quark decays into an up quark and a Z^0 Boson, which decays into u & $\bar{u}$

8) Inspect the Feynman diagram below.



A) This interaction is mediated by the weak nuclear force. Identify the exchange particle, and explain your reasoning.

Conservation of electric charge.
Before: $(+\frac{2}{3} + \frac{1}{3})$ after $(+1)$

B) Show that (i) the total baryon number and (ii) the total lepton number are conserved at each vertex.

before: Baryon: $(+\frac{1}{3}$ & $-\frac{1}{3})$ after: Baryon (0)
lepton: (0) lepton $(+1$ & $-1)$

C) Add the appropriate directions to the solid lines on the right. The μ^+ particle is an antimuon and not a muon; how can you reason logically to this conclusion? (There are at least two ways.)

must have +1 charge
must have lepton # −1

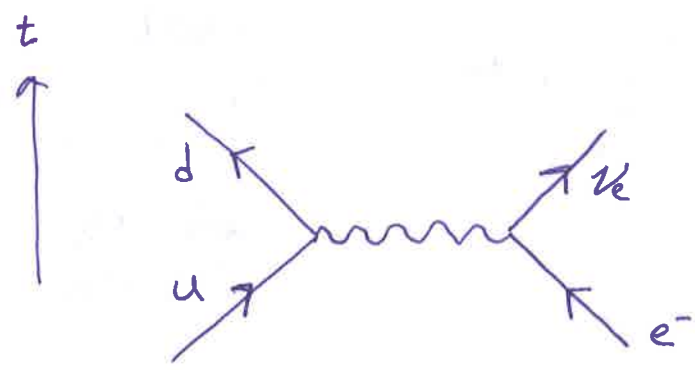
D) Describe the interaction in words.

an up quark and ~~at down~~ antidown annihilate to produce a W^+ Boson, which decays into a μ^+ & ν_μ.

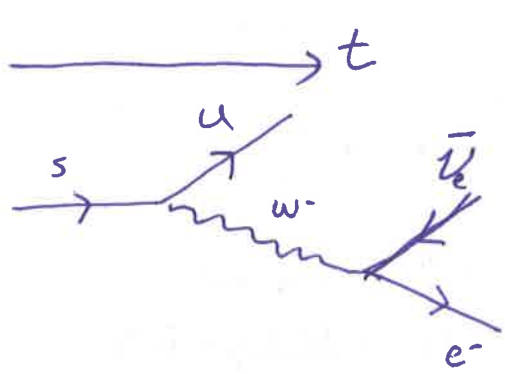
E) This interaction is written in the following way: $u + \bar{d} \rightarrow \nu_\mu +$ $\underline{\mu^+}$. Complete the interaction. Do we include the exchange particles when writing out an interaction in equation/reaction form?

No!

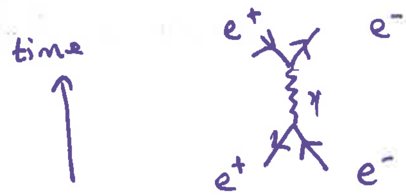
9) Draw a Feynman diagram for the following interaction: $u + e^- \rightarrow d + \nu_e$. Use a vertical time axis.



10) Draw a Feynman diagram for the following interaction: $s \rightarrow u + e^- + \bar{\nu}_e$. Use a horizontal time axis.

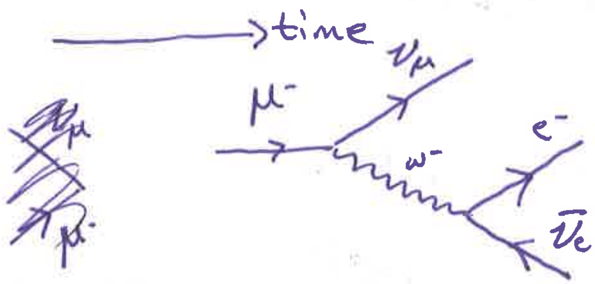


11) Draw a Feynman diagram for the following interaction: $e^+ + e^- \rightarrow e^+ + e^-$. Use a vertical time axis.



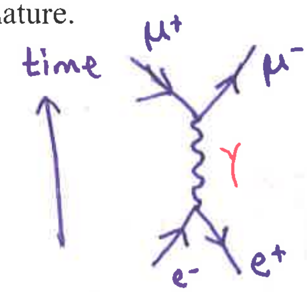
12) Draw a Feynman diagram for the following interaction: $e^- + e^- \rightarrow e^- + e^-$, where the two electrons repel each other electromagnetically Use a vertical time axis.

13) Draw a Feynman diagram for the following interaction: $\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$. Use a horizontal time axis.

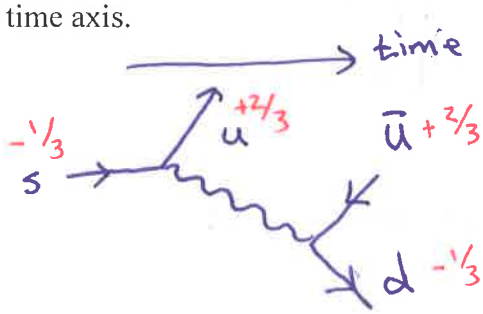


14) Draw a Feynman diagram for the following interaction: $e^- + e^+ \rightarrow \mu^- + \mu^+$. Use a vertical time axis. The interaction is electromagnetic in nature.

photon



15) Draw a Feynman diagram for the following interaction: $s \rightarrow u + \bar{u} + d$. Use a horizontal time axis.



must be with W⁻. Do you see why?

16) In beta minus decay, a neutron converts into a proton.

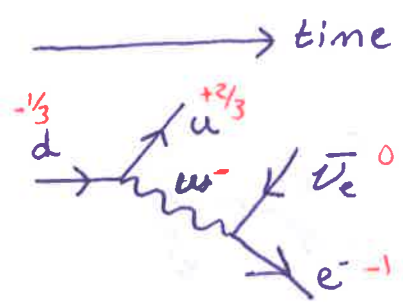
(a) State the quarks that make up a proton. State the quarks that make up a neutron.

proton: uud   neutron: udd

(b) Write out the complete reaction, in terms of quarks, for a beta minus decay.

$$d \longrightarrow u + \bar{\nu}_e + e^-$$

(c) Draw a Feynman diagram, in terms of quarks, for a beta minus decay:



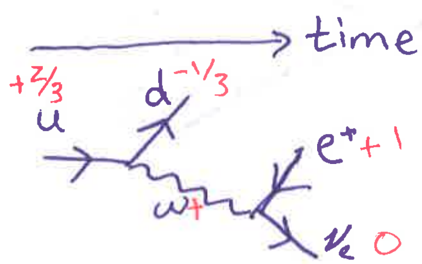
- electric charge marked
- are other #'s balanced too?

17) In beta plus decay, a proton converts into a neutron.

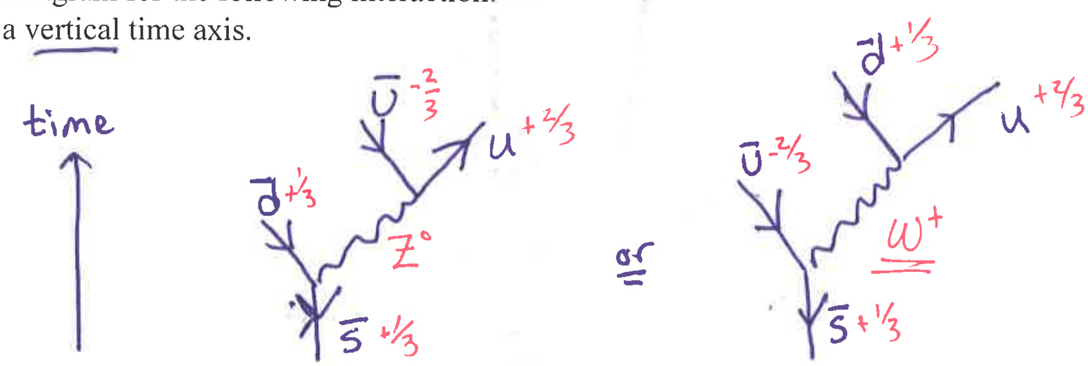
(a) Write out the complete reaction, in terms of quarks, for a beta plus decay.

$$u \longrightarrow d + \nu_e + e^+$$

(b) Draw a Feynman diagram, in terms of quarks, for a beta plus decay:



18) (a) Draw a Feynman diagram for the following interaction:
$\bar{s} \rightarrow \bar{u} + u + \bar{d}$. Use a vertical time axis.



(b) Without balancing the charge, how can you tell that the interaction involves the weak nuclear force?

strangeness (flavor) not conserved!