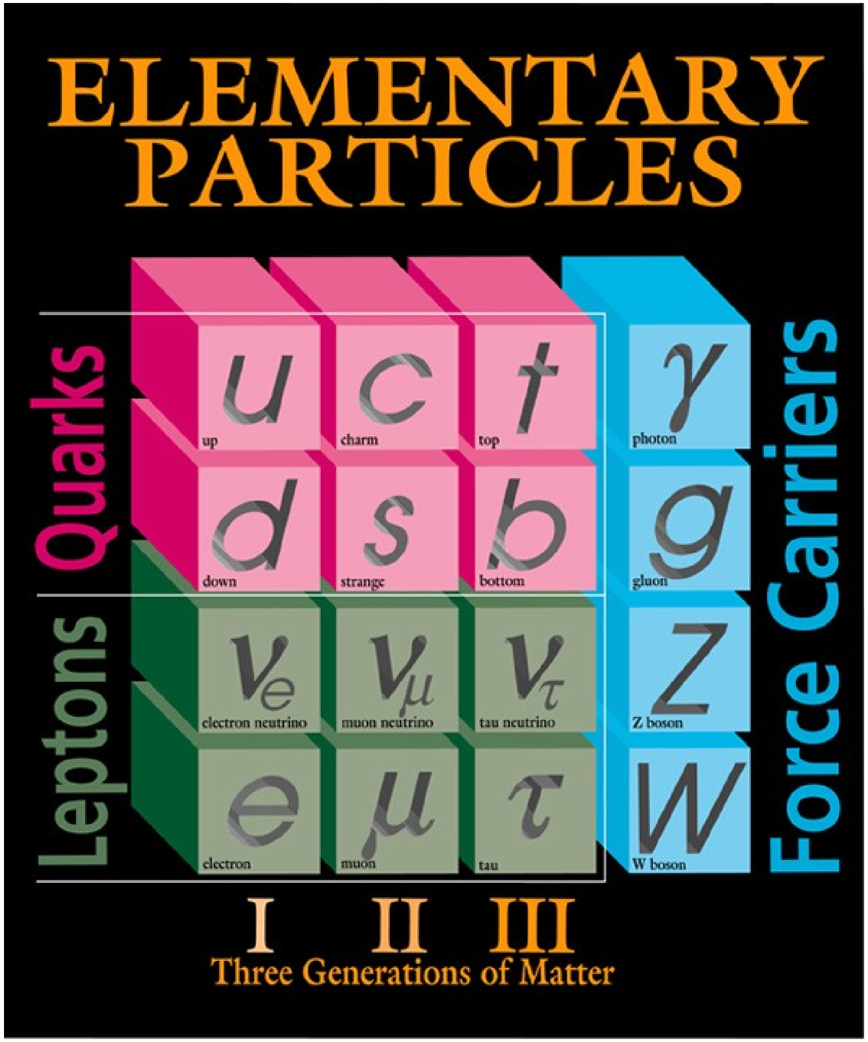
Elementary particles, forces and Feynman diagrams



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Particles & Forces

	quarks	**Charged leptons (e, μ, τ)**	**Neutral leptons (ν)**
Strong	**Y**	**N**	**N**
Electro-Magnetic	**Y**	**Y**	**N**
Weak	**Y**	**Y**	**Y**

Quarks carry strong, weak & EM charge !!!!!

The electromagnetic force

The Photon (γ)

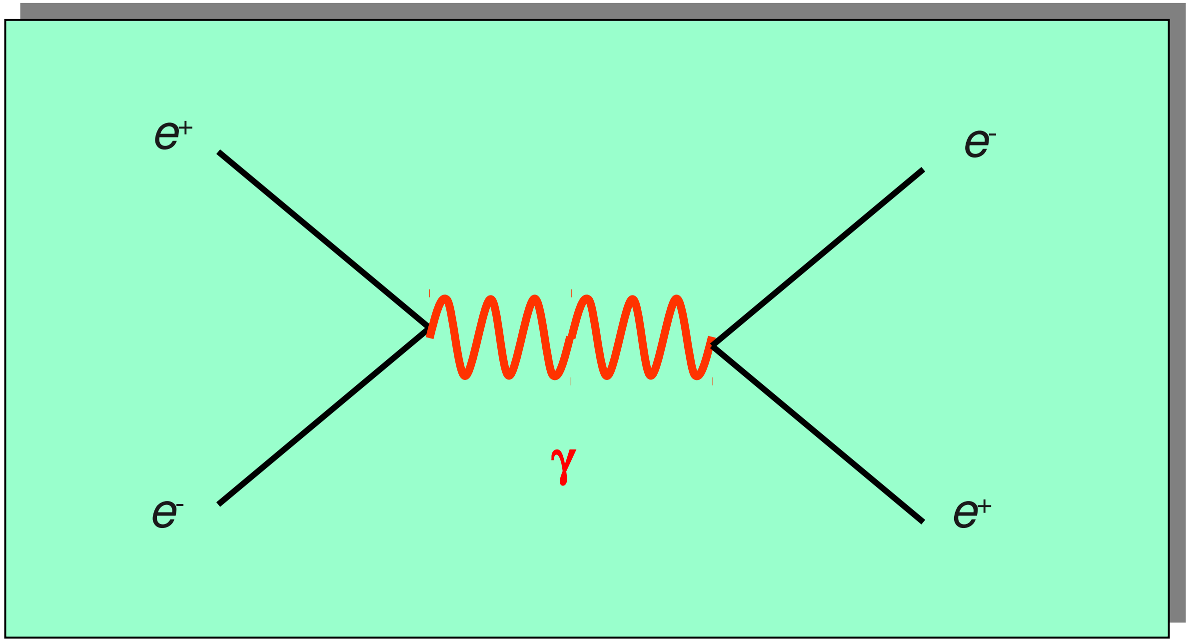
Property	Value
Mass	0
Charge	0

- The photon is the “mediator” of the electromagnetic interaction

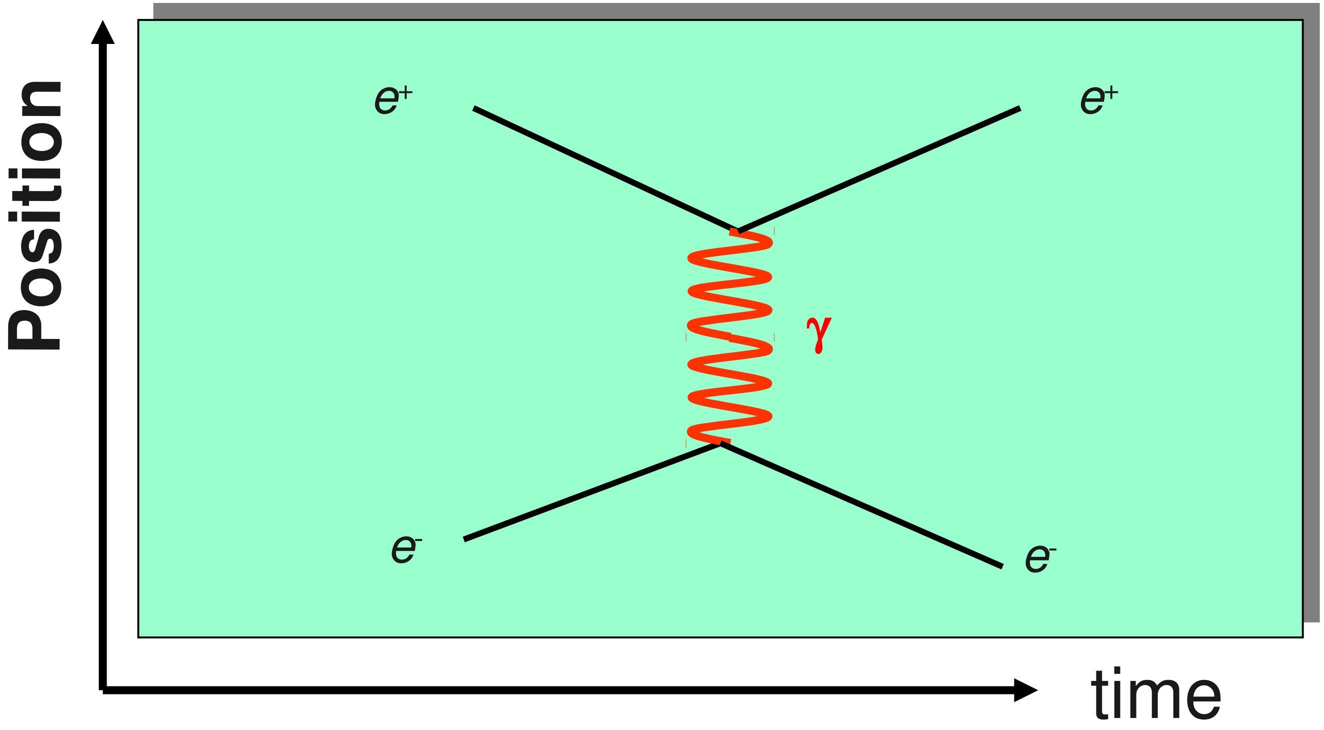
- The photon can only interact with objects which have electric charge

Feynman Diagrams (Electron Scattering)

Electron-Positron Annihilation

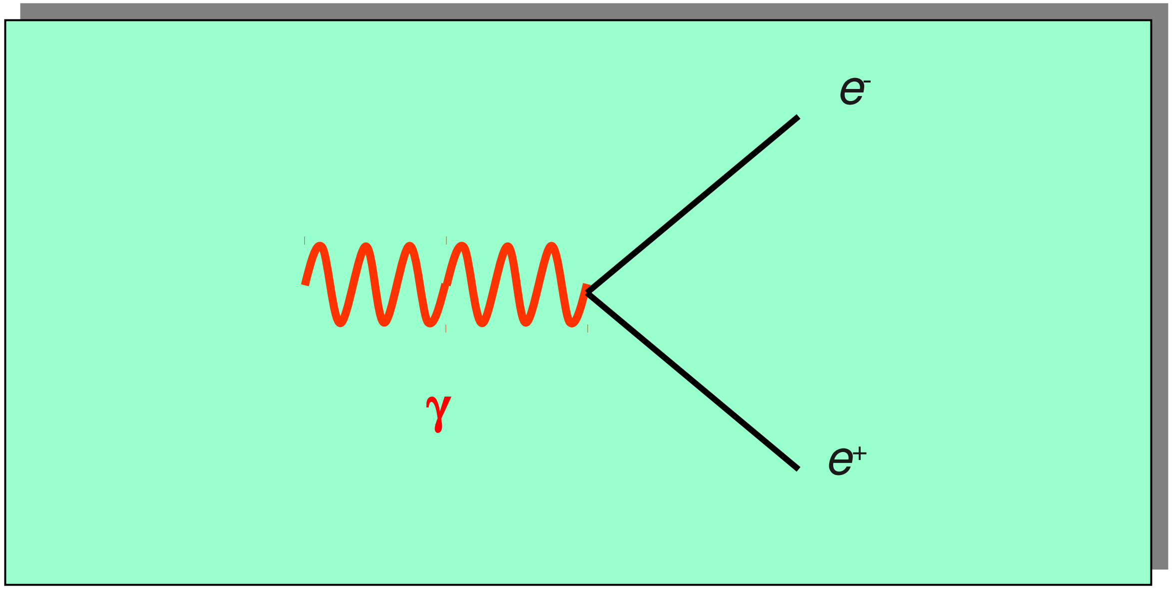


Compton Scattering

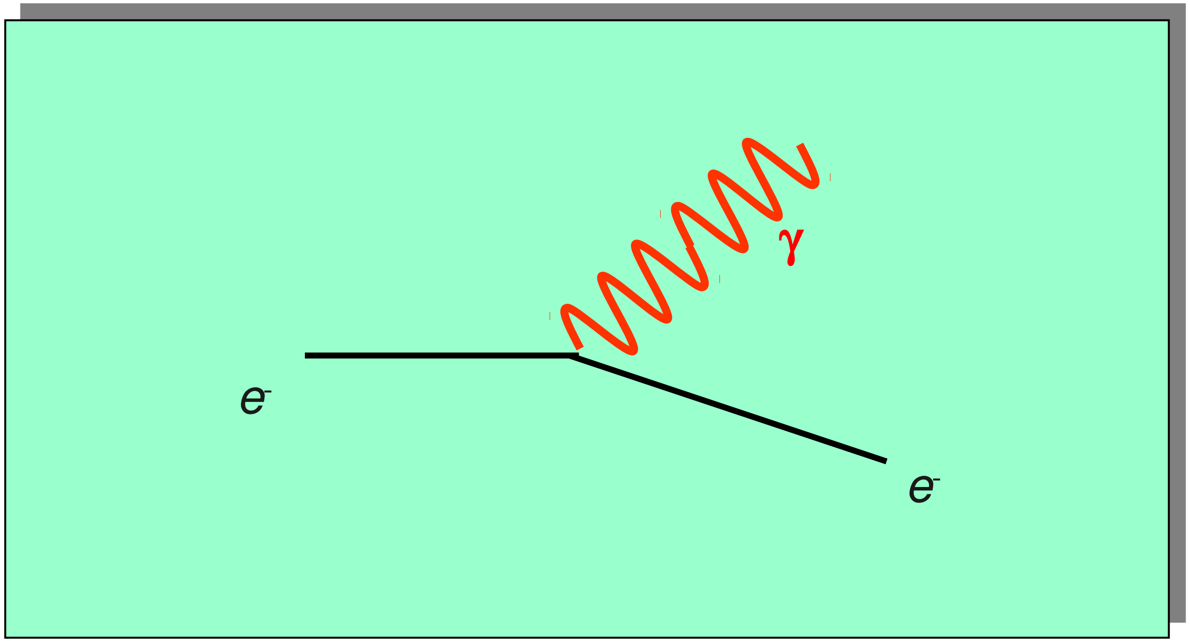


Photon Conversion and Emission

Photon Conversion



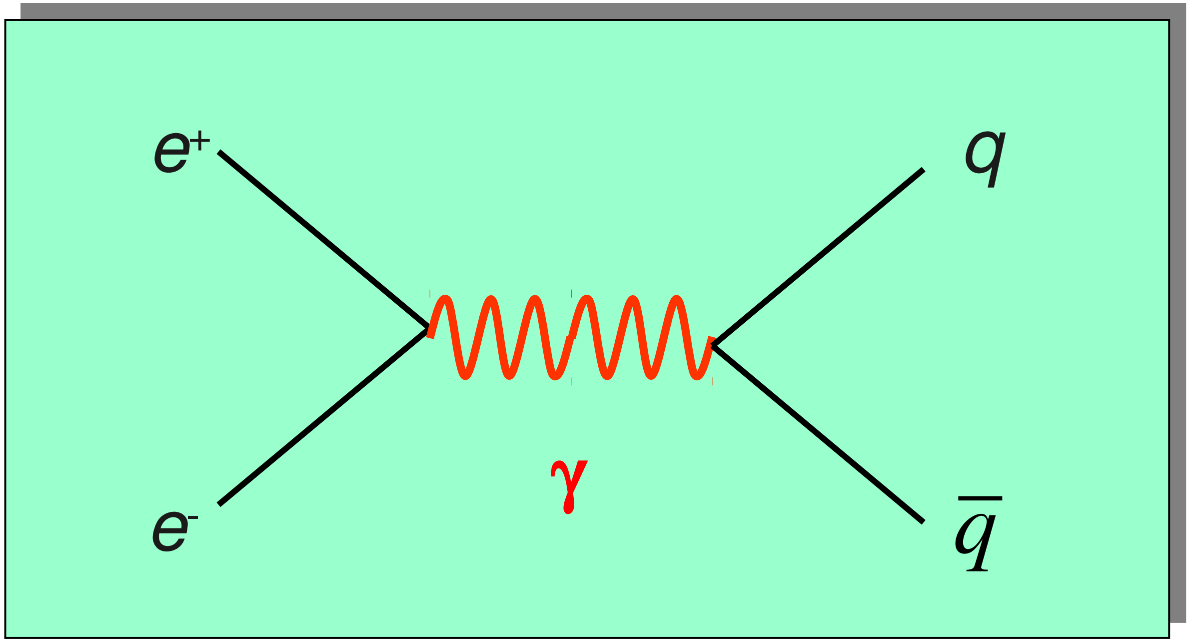
Photon Emission



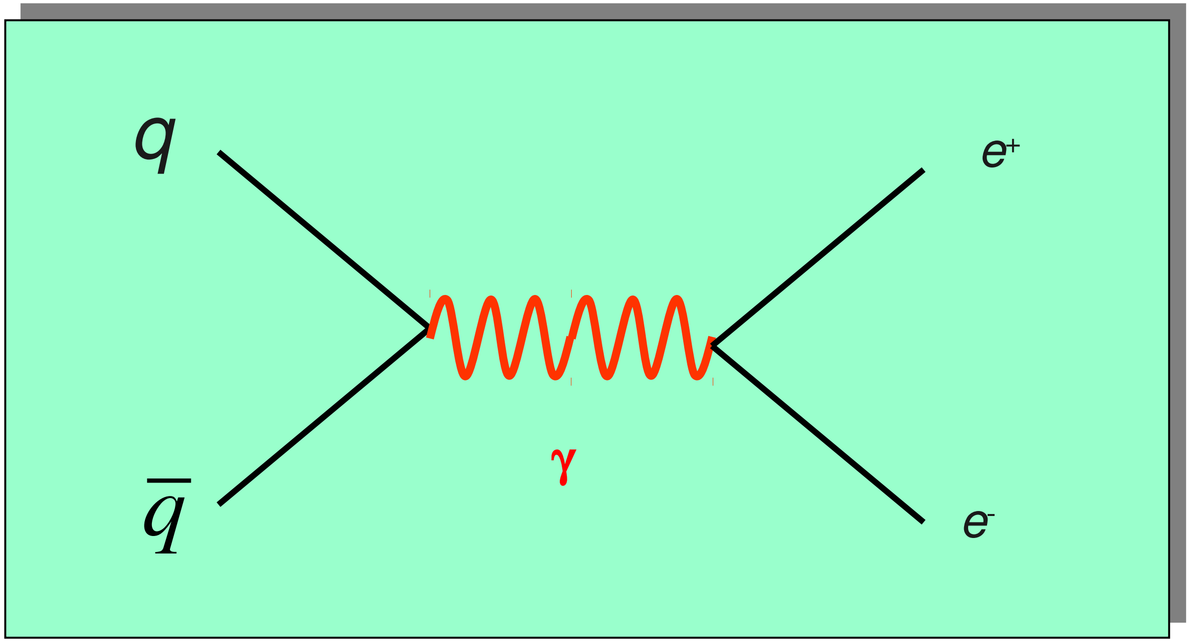
More Feynman Diagrams

Quark Pair Production

- "***q***" can be any quark, as long as there is enough energy to create 2 of 'em!



Quark Antiquark Annihilation



Summary of EM Interactions

1. The **Photon** is the **mediator** of the **EM Interaction.**
   - This means that EM interactions occur via photons.

2. The **photon** is **massless** and has **no electrical charge.**

3. Photon can **convert** into pairs of **oppositely-charged, like-type leptons or quarks**.
   $\gamma \rightarrow e^+e^-, \ \mu^+\mu^-, \ \tau^+\tau^-$
   $\gamma \rightarrow u\bar{u}, \ d\bar{d}, \ s\bar{s}, \ c\bar{c}, \ b\bar{b}, \ t\bar{t}$

4. Feynman diagrams are a pictorial method for expressing a type of interaction.

The weak force

The weak force

- Like the Electromagnetic & Strong forces, the Weak force is also mediated by “force carriers”.
- For the weak force, there are actually 3 force carriers:

W^+ W^- Z^0

These “weak force” carriers carry electric charge also !

This “weak force” carrier is electrically neutral

The “charge” of the weak interaction is called “weak charge”

The weak force

Both quarks & leptons carry weak charge

➔ Both quarks & leptons “couple to” the W and Z force carriers

➔ Since the W’s have a charge of +1 and –1 they cause a “charge-changing” interaction. That is when they are emitted or absorbed, to conserve charge, the “emitting” or “absorbing” particle changes charge by +1 or –1 unit.

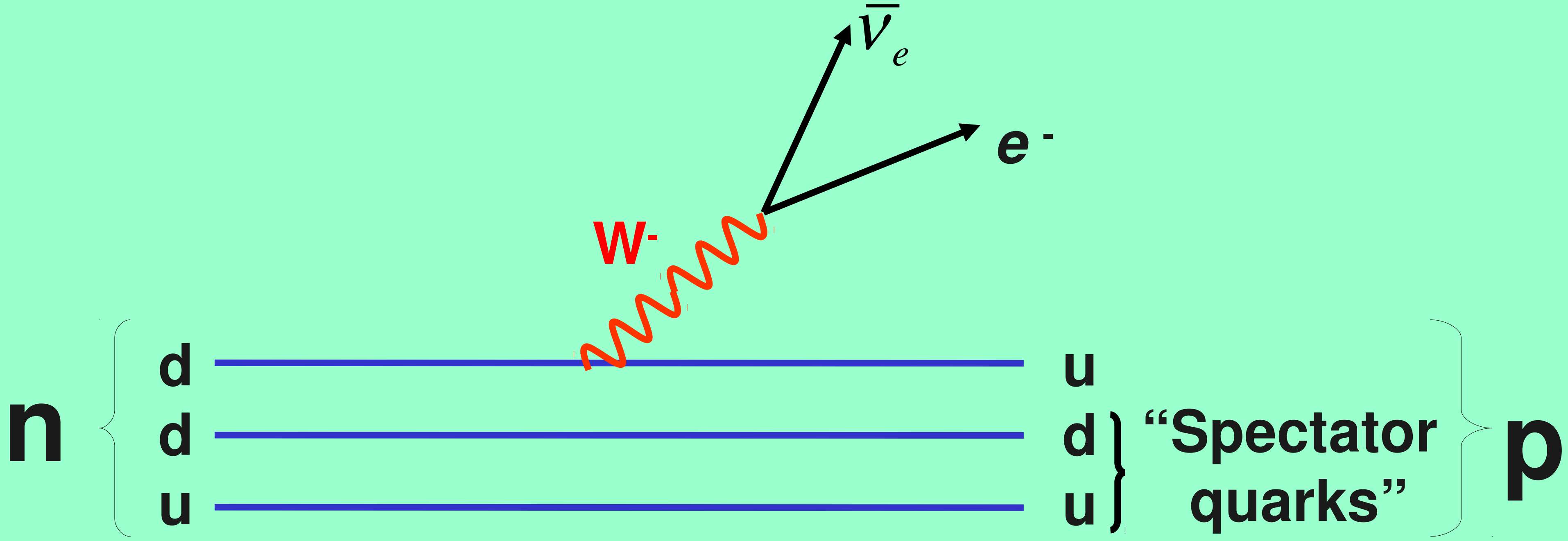
➔ The emitting or absorbing particle changes into a different particle. Alternately, when the W decays, it decays into 2 particles which:

- Carry weak charge
- The sum of their charges equals the charge of the W

➔ I will mainly talk about the W in the context of decays…

Feynman diagram for weak decay

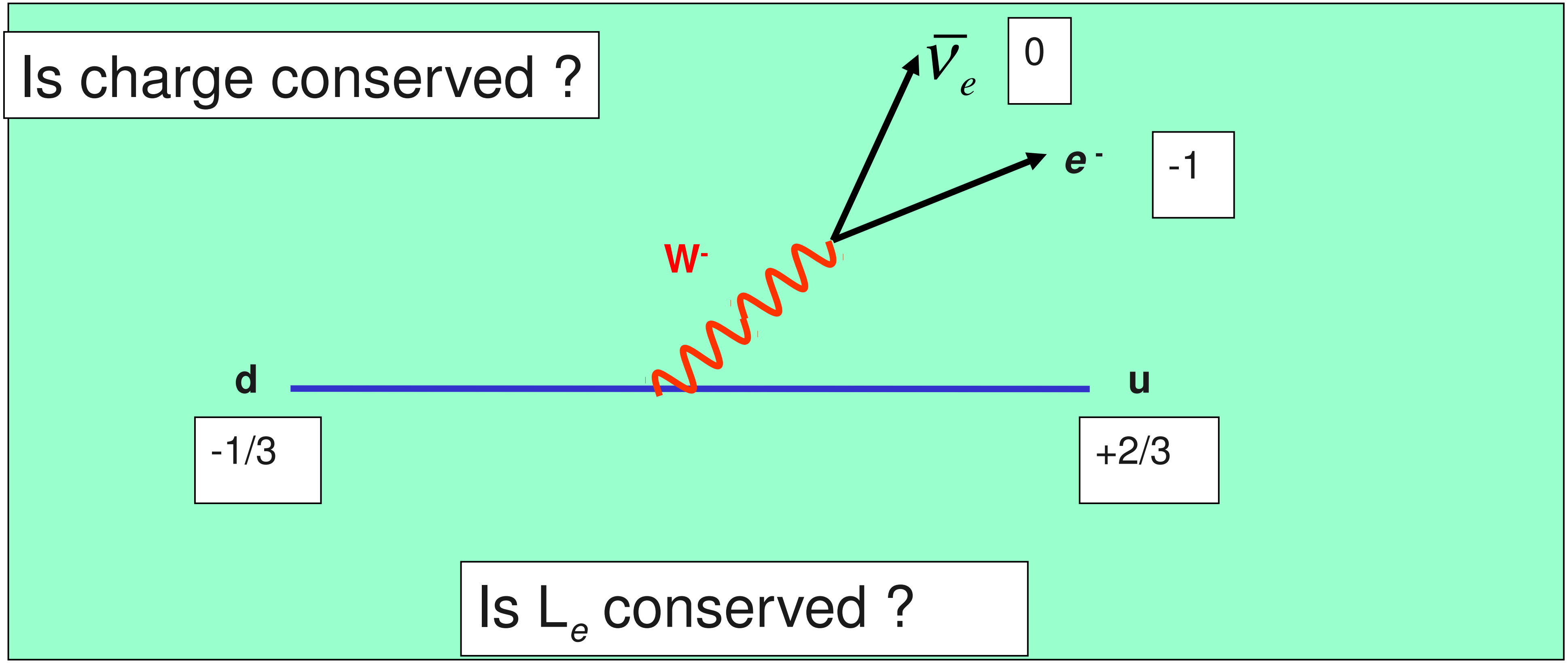
$$d \rightarrow u + e^- + \bar{\nu}_e$$



<u>Spectator quark(s):</u> Those quarks which do not directly participate in the interaction or decay.

Feynman diagram for weak decay *(continued)*

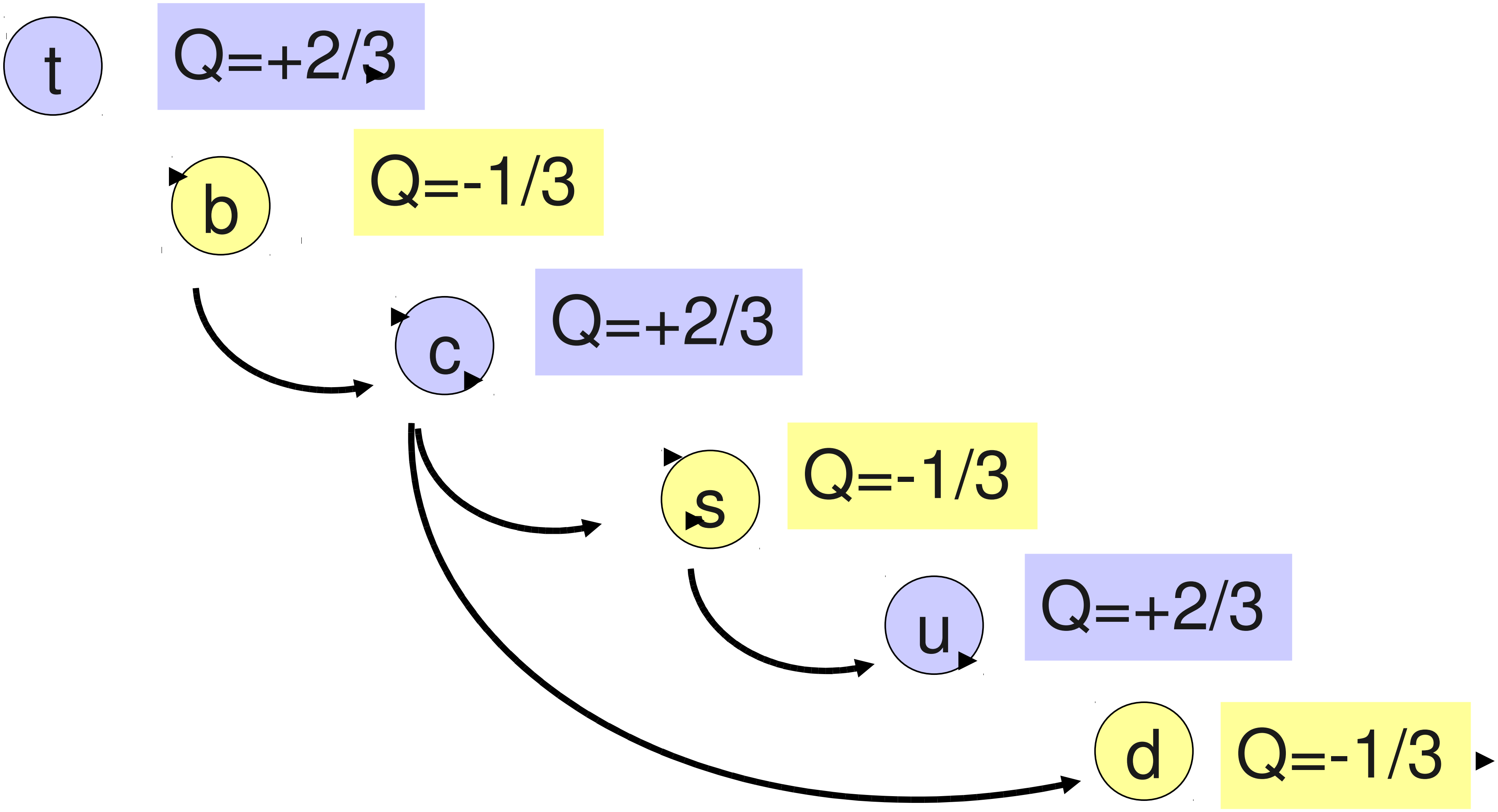
- Since the spectator quarks do not directly participate in the decay, we can just omit them…
- This yields the "quark-level" Feynman diagram!


Is charge conserved ?

Is L_e conserved ?

Decays of “heavy” quarks

The heavy quarks decay to the lighter ones by “cascading down”



t Q=+2/3

b Q=-1/3

c Q=+2/3

s Q=-1/3

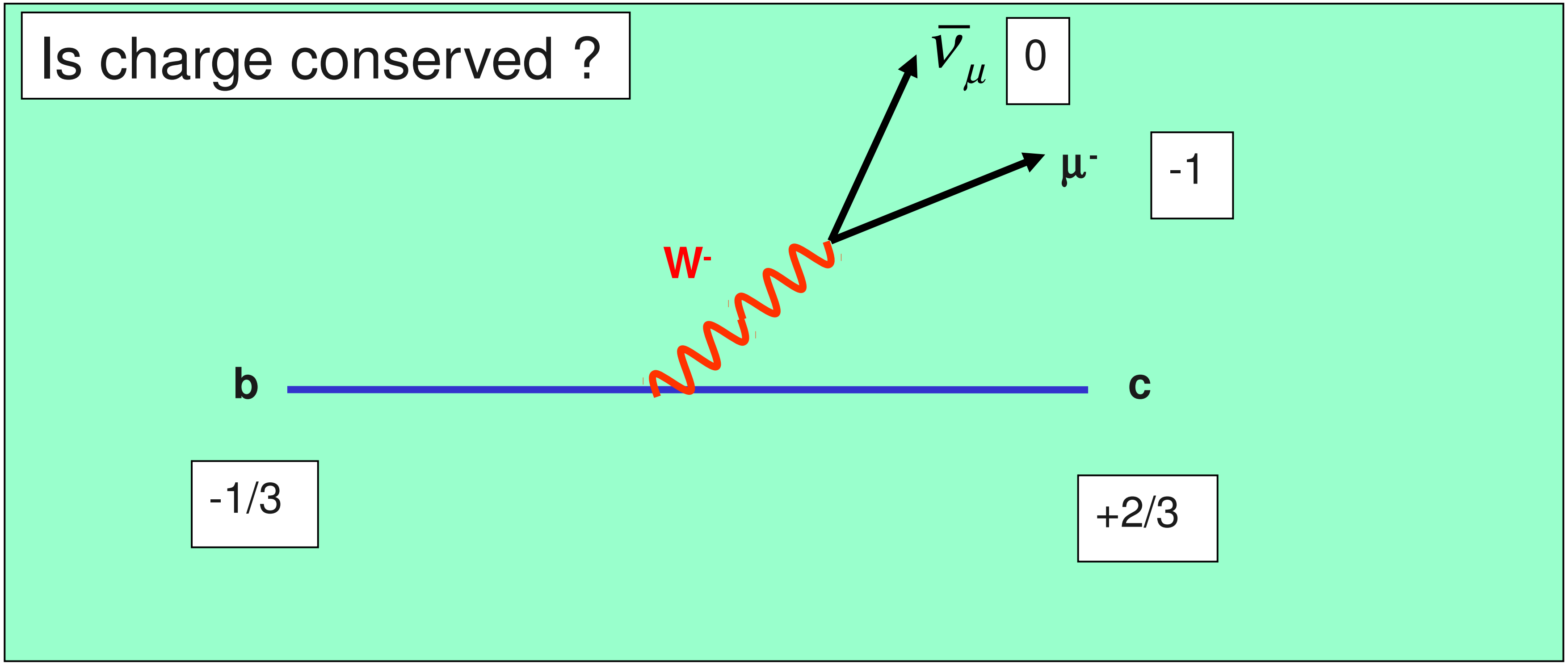
u Q=+2/3

d Q=-1/3

What about the decay of a b-quark?

$$b \rightarrow c + \mu^- + \bar{\nu}_\mu$$

Is charge conserved ?



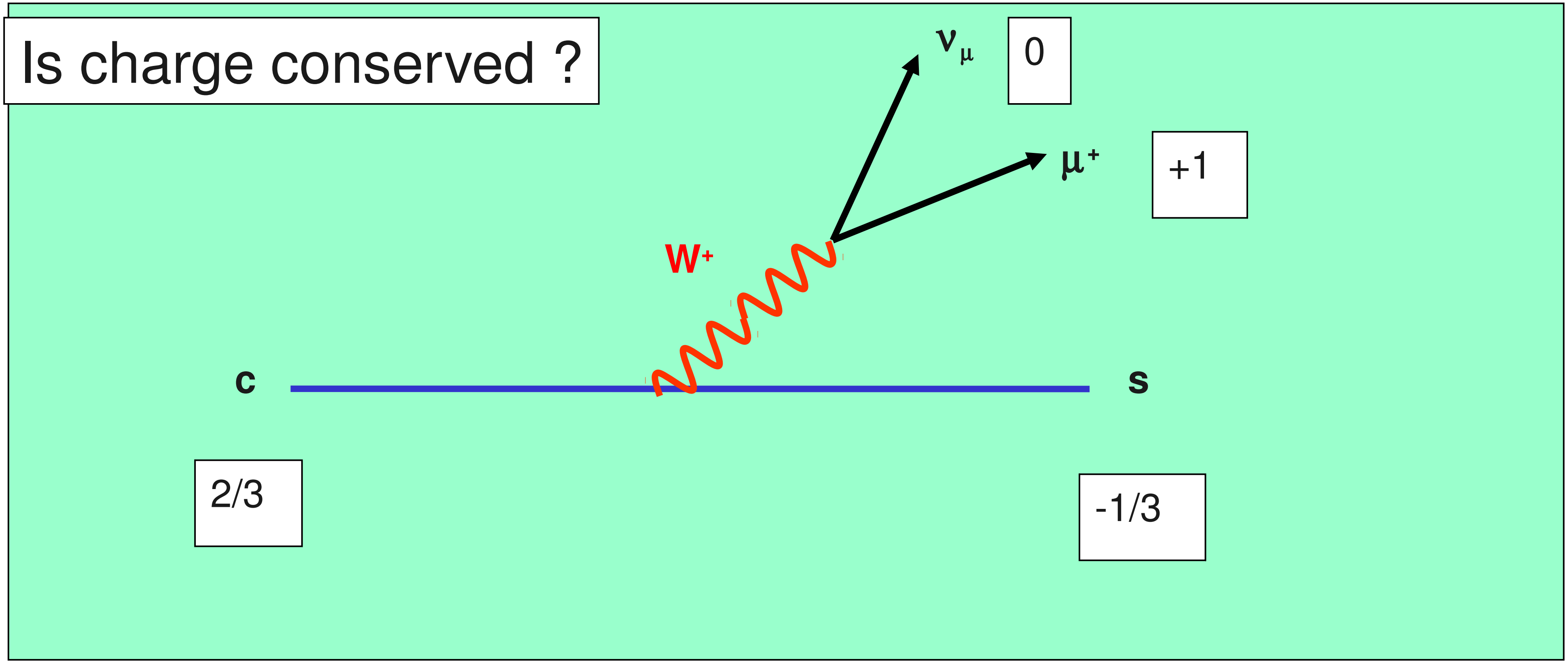
Notice: Here, the W^- decays to a μ^- and ν_μ

Is L_μ conserved ?

What about the decay of a c-quark?

$$c \rightarrow s + \mu^{+} + \nu_{\mu}$$

Is charge conserved ?



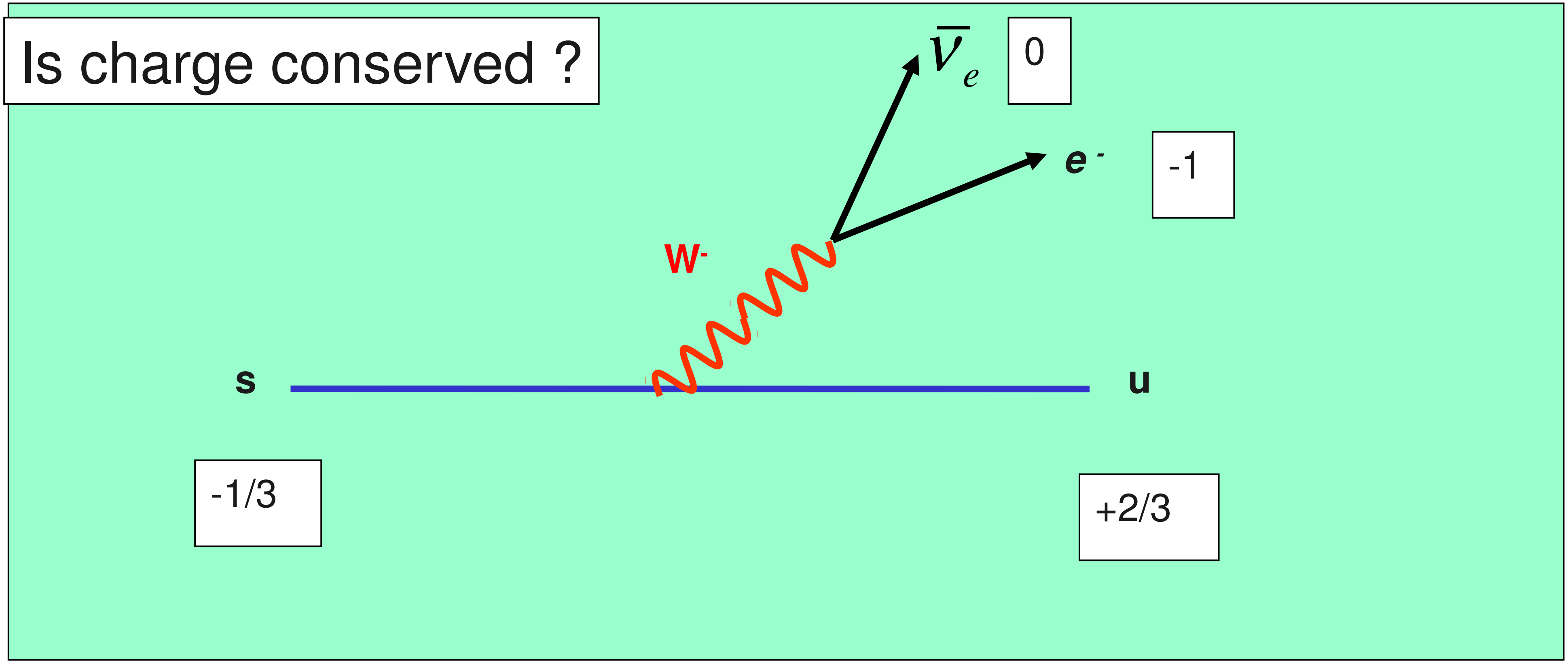
Notice: Here, I have the W^+ decaying to a μ^+ and ν_μ (could have been an e^+ and ν_e as well).

Is L_μ conserved ?

What about the decay of a b-quark?

$s \rightarrow u + e^{-} + \bar{\nu}_e$

Is charge conserved ?



Is L_e conserved ?

Decays of heavy quarks to u & d

- A quark can only decay to a lighter quark.
- The W charge has the same sign as the parent quark.

Quark	Charge	Mass [GeV/c^2]
top	+2/3	~175
bottom	-1/3	~4.5
charm	+2/3	~1.5
strange	-1/3	~0.2
up	+2/3	~0.005
down	-1/3	~0.010

t → b W^+(100%)

b → c W^- (~90%)
b → u W^- (~10%)

c → s W^+ (~95%)
c → d W^+ (~5%)

s → u W^- (~100%)

d → u W^+ (~100%)

"Leptonic" Decay of W

Once the W is produced, it must decay

$W^- \rightarrow e^- \overline{\nu}_e$

$W^+ \rightarrow e^+ \nu_e$

$W^- \rightarrow \mu^- \overline{\nu}_\mu$

$W^+ \rightarrow \mu^+ \nu_\mu$

$W^- \rightarrow \tau^- \overline{\nu}_\tau$

$W^+ \rightarrow \tau^+ \nu_\tau$

It's call "***leptonic decay***" because the ***W is decaying to leptons***!

The W ***can*** decay to leptons because ***leptons carry weak charge***

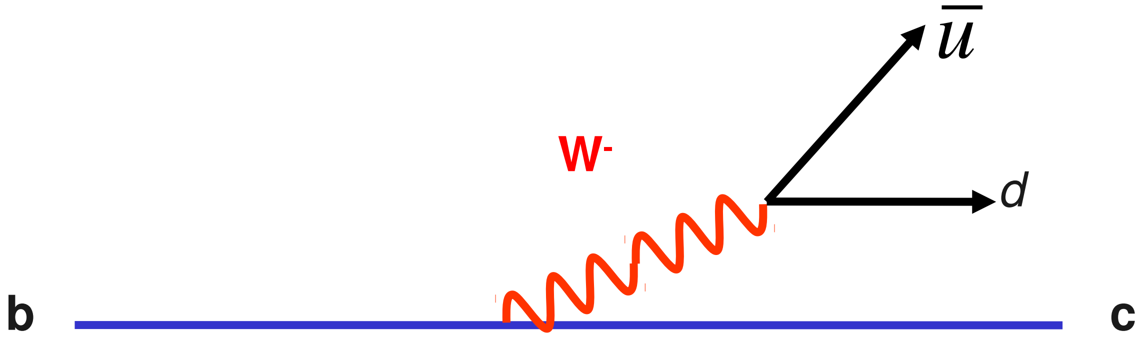
But so do quarks …

“Hadronic” Decay of W

Since quarks also carry weak charge, we can also get:

$$W^- \rightarrow \bar{u}\, d \qquad\qquad W^+ \rightarrow u\, \bar{d}$$

It’s call “***hadronic decay***” because the
W is decaying to quarks, which will form hadrons!

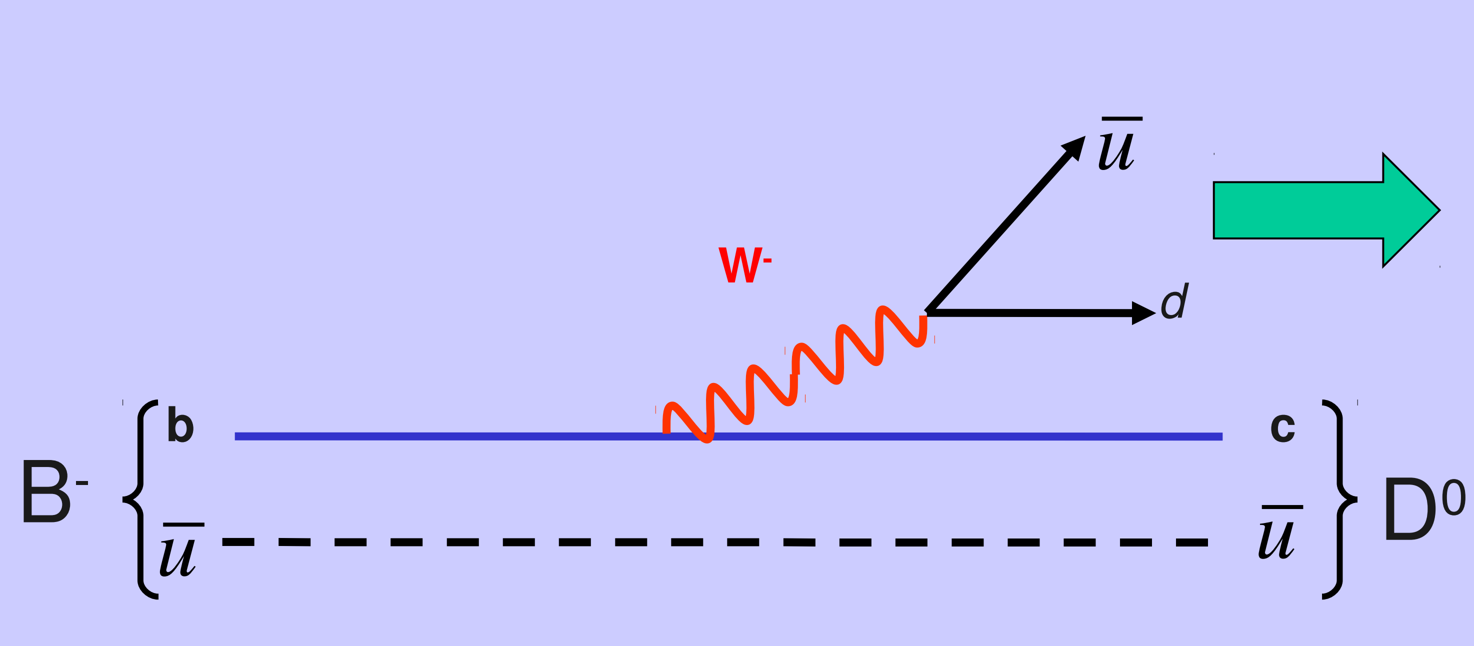


Check charge:
(-2/3 + -1/3 = -1)

But quarks are bound to one another by the strong force, and are not observed as “free” particle. That is, they are bound up inside hadrons…

What happens next ?

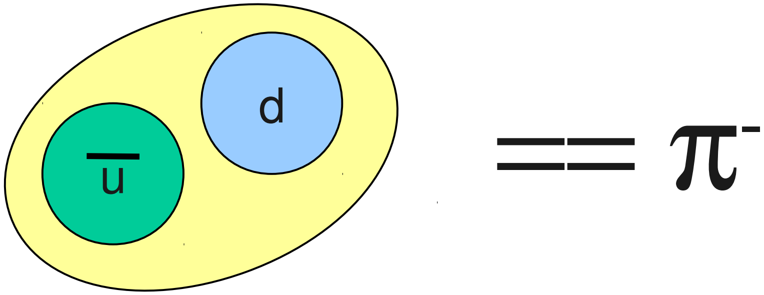
One possibility…



Can, in fact, form a π^-

B$^-$ Meson

D^0 Meson



$$\boxed{B^- \to D^0 \pi^-}$$

W Decays

Leptonic

$W^- \rightarrow e^- \overline{\nu}_e$

$W^- \rightarrow \mu^- \overline{\nu}_\mu$

$W^- \rightarrow \tau^- \overline{\nu}_\tau$

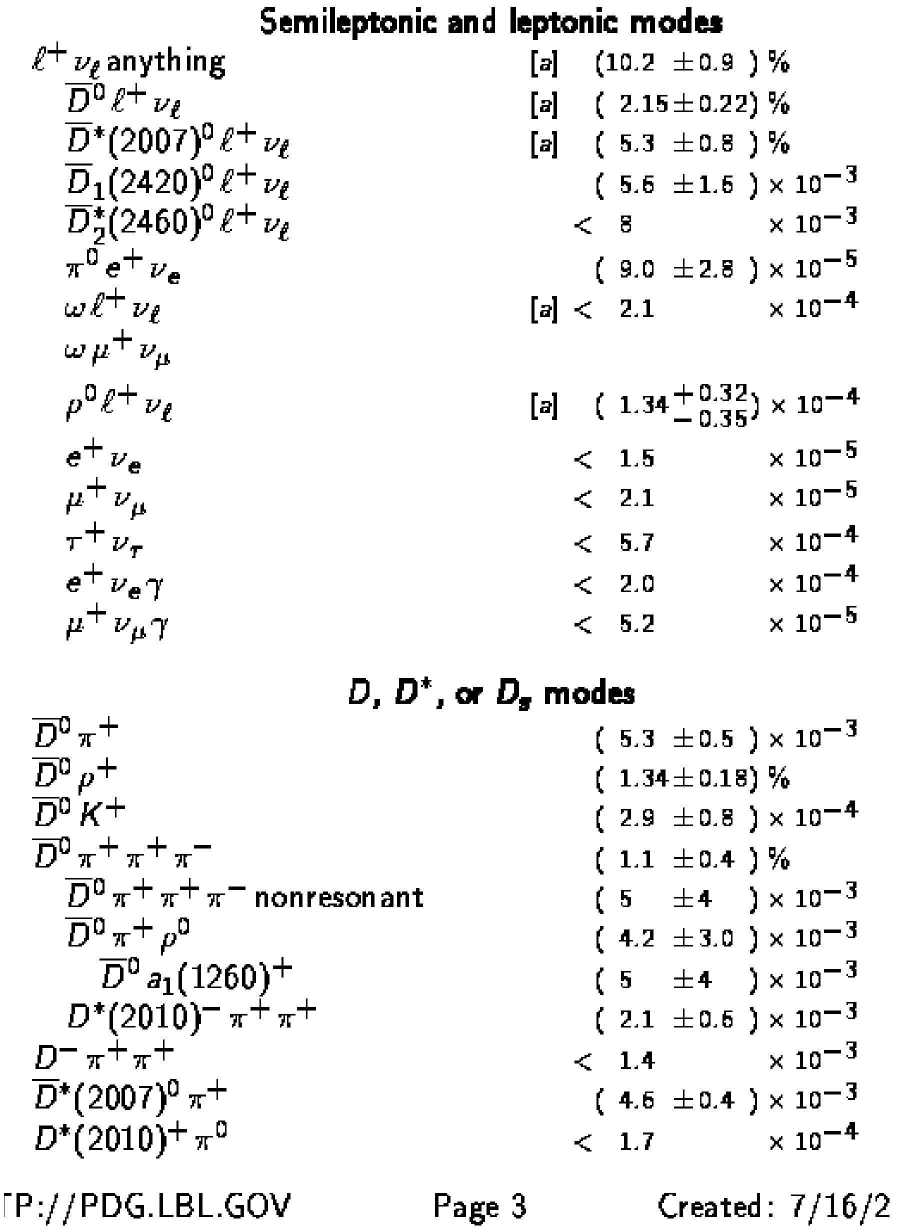
Hadronic

$W^- \rightarrow$ ***hadrons***

Can be 1 or more hadrons produced

W^+ follows in an analogous way… see previous slides

There are LOTS of ways the B⁺ can decay (here's a small fraction of em) !



Semileptonic and leptonic modes

$\ell^+ \nu_\ell$ anything	[a]	(10.2 ± 0.9) %
$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.15 ± 0.22) %
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(5.3 ± 0.8) %
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$		$(5.6 \pm 1.6) \times 10^{-3}$
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$		$< 8 \times 10^{-3}$
$\pi^0 e^+ \nu_e$		$(9.0 \pm 2.8) \times 10^{-5}$
$\omega \ell^+ \nu_\ell$	[a]	$< 2.1 \times 10^{-4}$
$\omega \mu^+ \nu_\mu$		
$\rho^0 \ell^+ \nu_\ell$	[a]	$(1.34^{+0.32}_{-0.35}) \times 10^{-4}$
$e^+ \nu_e$		$< 1.5 \times 10^{-5}$
$\mu^+ \nu_\mu$		$< 2.1 \times 10^{-5}$
$\tau^+ \nu_\tau$		$< 5.7 \times 10^{-4}$
$e^+ \nu_e \gamma$		$< 2.0 \times 10^{-4}$
$\mu^+ \nu_\mu \gamma$		$< 5.2 \times 10^{-5}$

D, D^*, or D_s modes

$\overline{D}^0 \pi^+$	$(5.3 \pm 0.5) \times 10^{-3}$
$\overline{D}^0 \rho^+$	(1.34 ± 0.18) %
$\overline{D}^0 K^+$	$(2.9 \pm 0.8) \times 10^{-4}$
$\overline{D}^0 \pi^+ \pi^+ \pi^-$	(1.1 ± 0.4) %
$\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant	$(5 \pm 4) \times 10^{-3}$
$\overline{D}^0 \pi^+ \rho^0$	$(4.2 \pm 3.0) \times 10^{-3}$
$\overline{D}^0 a_1(1260)^+$	$(5 \pm 4) \times 10^{-3}$
$D^*(2010)^- \pi^+ \pi^+$	$(2.1 \pm 0.6) \times 10^{-3}$
$D^- \pi^+ \pi^+$	$< 1.4 \times 10^{-3}$
$\overline{D}^*(2007)^0 \pi^+$	$(4.6 \pm 0.4) \times 10^{-3}$
$D^*(2010)^+ \pi^0$	$< 1.7 \times 10^{-4}$

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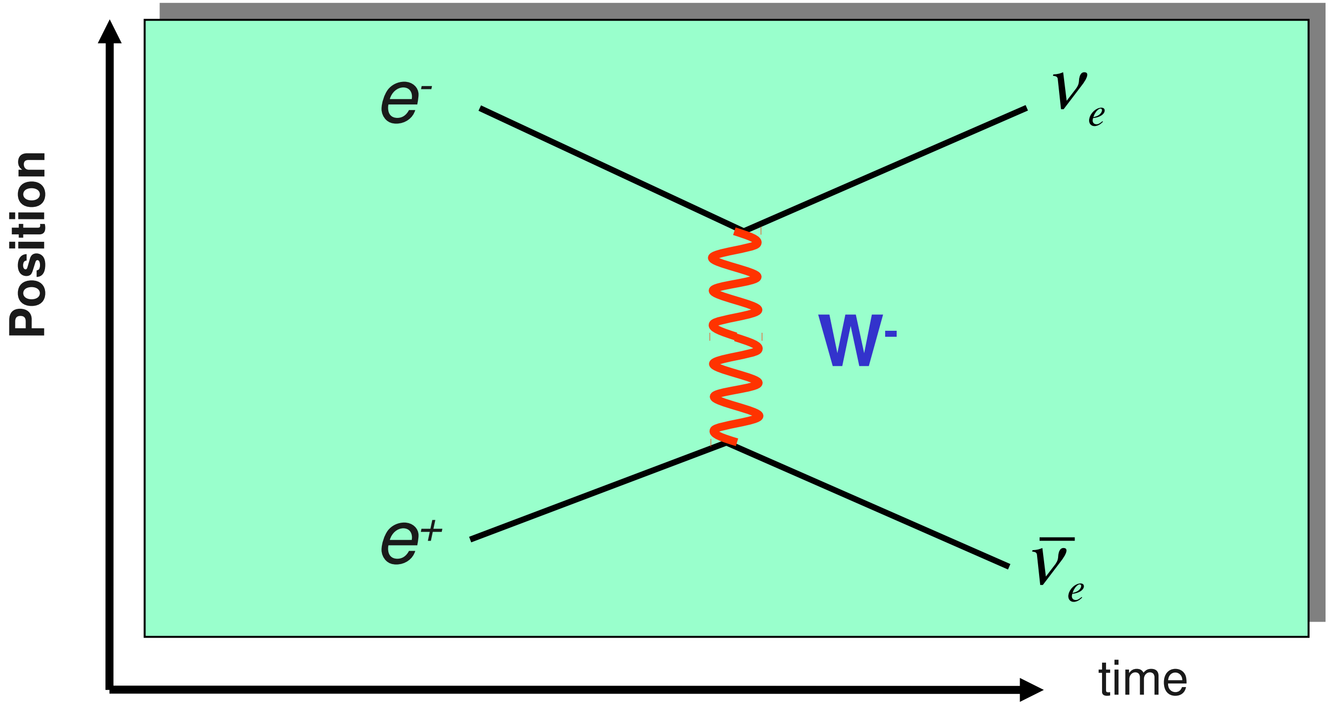
Observed decays where theW decays to a lepton and neutrino

Observed decays where theW decays to quarks ➔hadrons

Interactions involving W’s

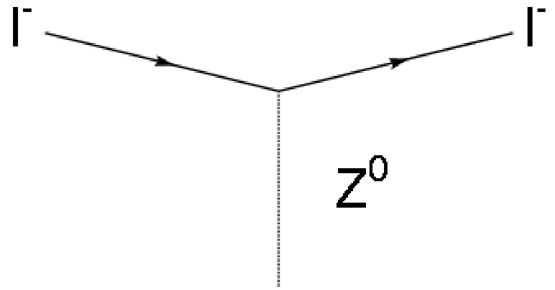
Here is one… Don’t worry about these types of interactions…
I want to emphasize the role of W’s in decays of quarks

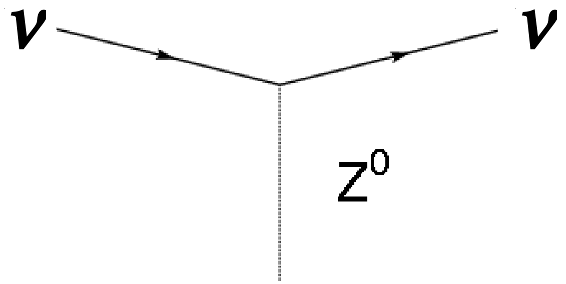
$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$$

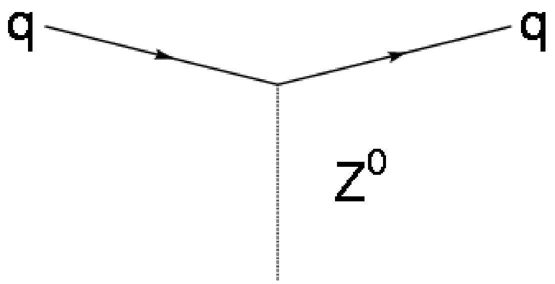


Check lepton number, charge conservation…

Weak Neutral-Current Interactions

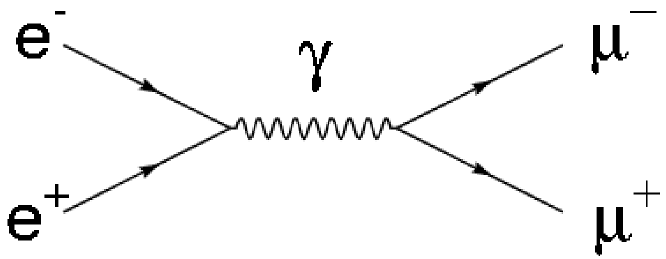


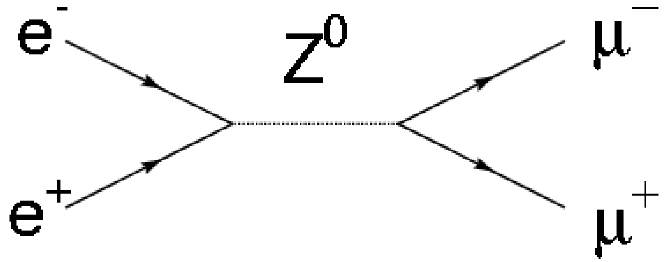




- In addition to the weak charged-current interaction, there is a weak neutral-current interaction mediated by the Z-boson whose mass is about 90 GeV/c^2.
- **The weak neutral-current interaction conserves flavor;** it does not change up into charm or strange; it does not change down into strange or bottom; etc.
- The weak neutral-current interaction is intimately related to both the weak charged-current interaction and to the electromagnetic interaction. The unified description of these interactions is known as the electro-weak interaction.

Electro-weak Interference





- The two amplitudes represented by these Feynman diagrams share initial and final states. Therefore, the amplitudes one calculates for these diagrams, following the Feynman rules, must be added together to determine the total transition rate.

- The propagator for photon exchange is proportional to

$$\frac{1}{q^2}$$

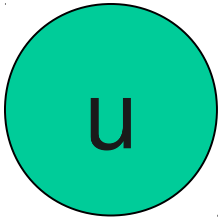
while that for Z exchange is proportional to

$$\frac{1}{q^2 - M_Z^2}$$

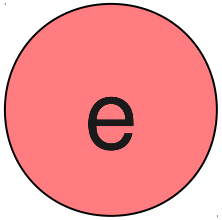
At low q^2 photon exchange is dominant; near $q^2=M_Z^2$, Z-boson exchange is dominant.

The strong force

‘Charge’



Electric charge
= +2/3



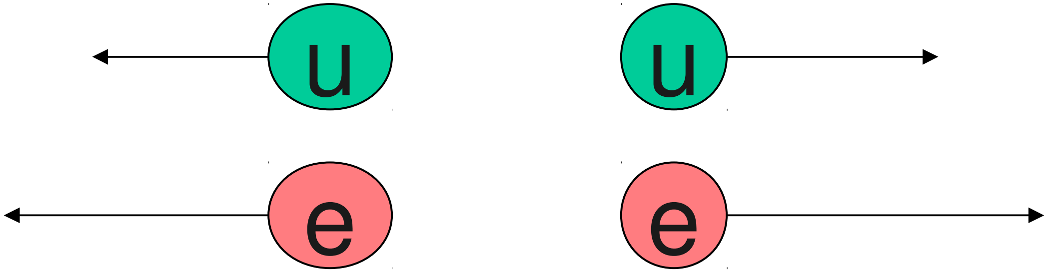
Electric charge
= -1

What does it really mean for a particle to have electric charge ?

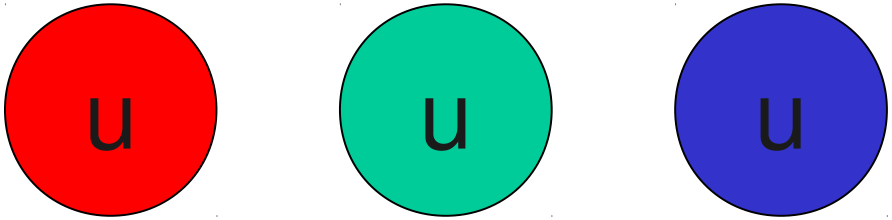
It means the particle has an attribute which allows it **to talk to (or ‘couple to’) the photon**, the mediator of the electromagnetic interaction.

The ‘strength’ of the interaction depends on the amount of charge.

Which of these might you expect experiences a larger electrical repulsion?



Strong Force & Color



We hypothesize that in addition to the attribute of ‘electric charge’, quarks have another attribute known as ‘color charge’, or just ‘color’ for short. The attribute’s name, color, is just by convention. It’s easy to visualize this attribute and how colors combine…(coming up)

The property of color allows quarks to talk to the mediator of the strong interaction, the gluon (g).

Unlike electric charge, we find (experimentally) that there are 3 values for color:

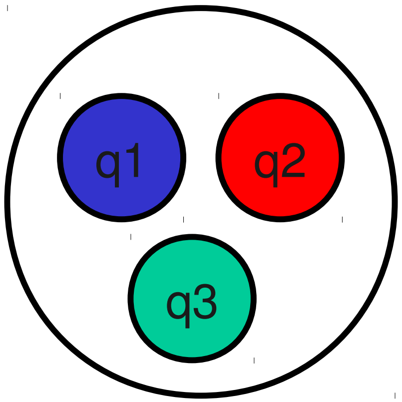
We assign these possible values of color to be: **red**, **green**, **blue**

Also, unlike Electromagnetism, we find that the carrier of the strong force carries ‘color charge’. Recall the photon is electrically neutral!

Comparison
Strong and EM force

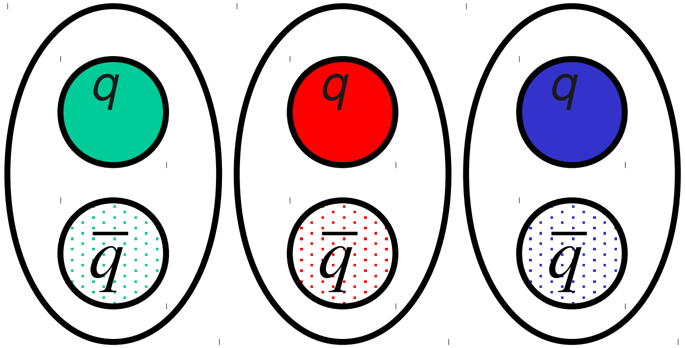
Property	EM	Strong
Force Carrier	Photon (γ)	Gluon (g)
Mass	0	0
Charge ?	None	Yes, color charge
Charge types	+, -	red, green, blue
Mediates interaction between:	All objects with electrical charge	All objects with color charge
Range	Infinite ($\sim 1/d^2$)	$\sim 10^{-14}$ [m] (inside hadrons)

Color of Hadrons



BARYONS

RED + BLUE + GREEN = “WHITE”
or “COLORLESS”



MESONS

GREEN + ANTIGREEN = “COLORLESS”
RED + ANTIRED = “COLORLESS”
BLUE + ANTIBLUE = “COLORLESS”

A meson can be any one of these combinations !

Hadrons observed in nature are colorless
(but there constituents are not)

Color Exchange

- Quarks interact by the exchange of a gluon.

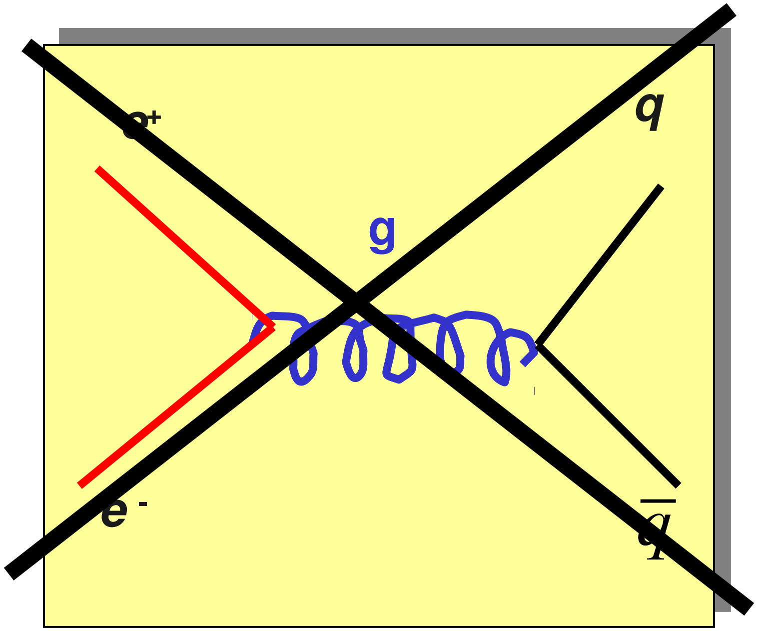
- Since gluons carry color charge, it is fair to say that the interaction between quarks results in the exchange of color (or color charge, if you prefer) !

Gluons – Important Points

- Gluons are the “force carrier” of the strong force.

- They only interact with object which have color, or color charge.

- Therefore, gluons cannot interact with leptons because leptons do not have color charge !



This cannot happen, because
the gluon does not interact with
objects unless they have color
charge!
Leptons do not have color charge !

Feynman Diagrams for the Strong Interaction

- As before, we can draw Feynman diagrams to represent the strong interactions between quarks.

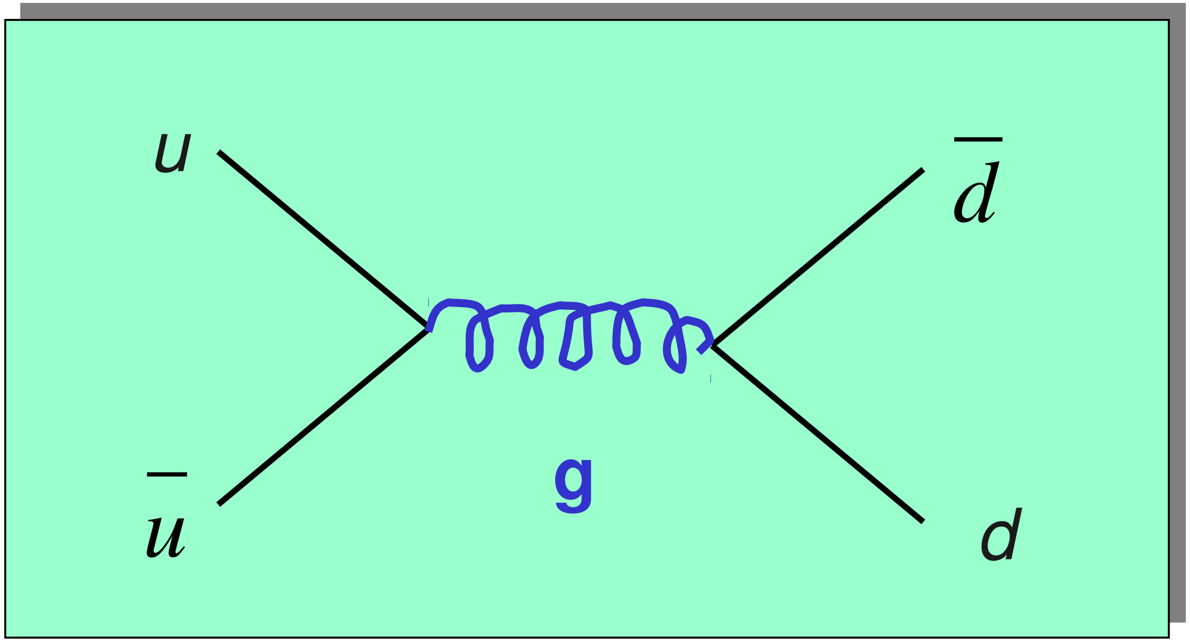
- The method is more or less analogous to the case of EM interactions.

- When drawing Feynman diagrams, we don't show the flow of color charge (oh goody). It's understood to be occurring though.

- Let's look at a few Feynman diagrams…

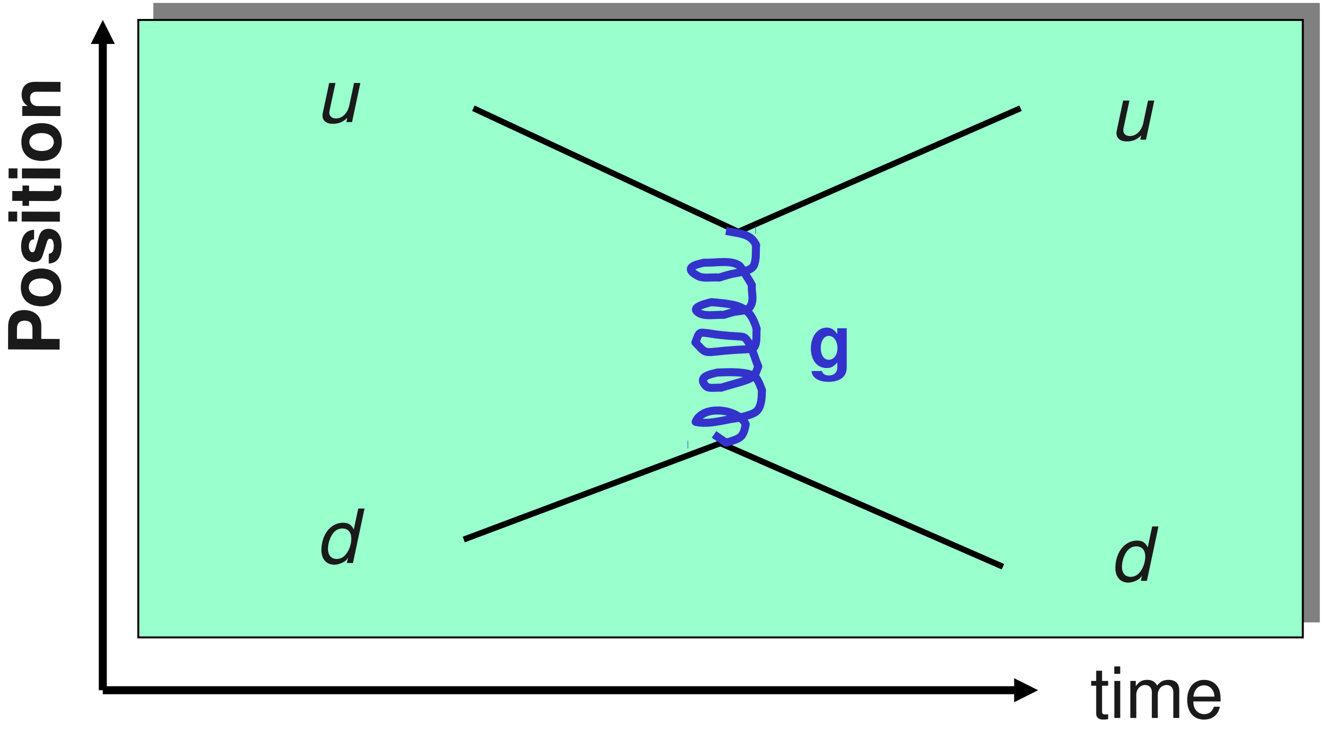
Feynman Diagrams (Quark Scattering)

Quark-antiquark
Annihilation



Quark-quark
Scattering

Could also be
Quark-antiquark
Scattering
or
Antiquark-antiquark
Scattering

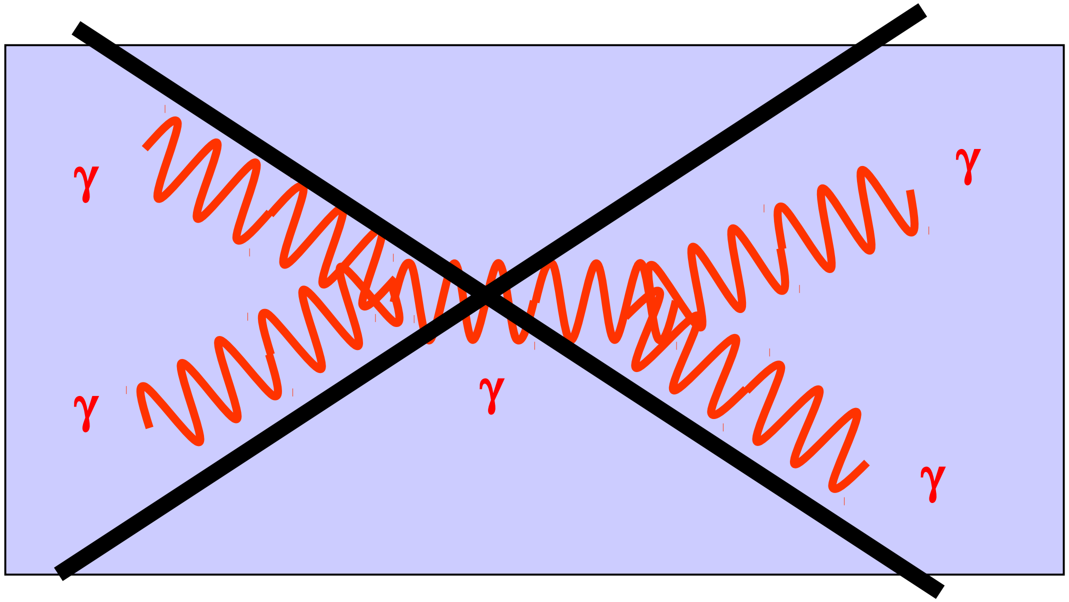


Flashback to EM Interactions

Recall that photons do not interact with each other.

Why?

Because photons only interact with objects which have electric charge, and photons do not have electric charge !



This can't happen because the photon only interacts with electrically charged objects !

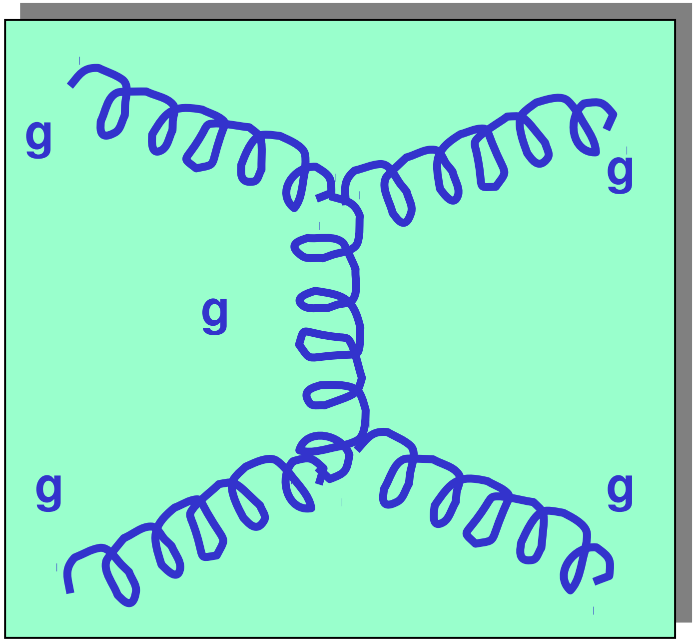
BUT GLUONS HAVE COLOR CHARGE !!!

Gluons carry the "charge" of the strong force, which is "color charge", or just "**color**" !

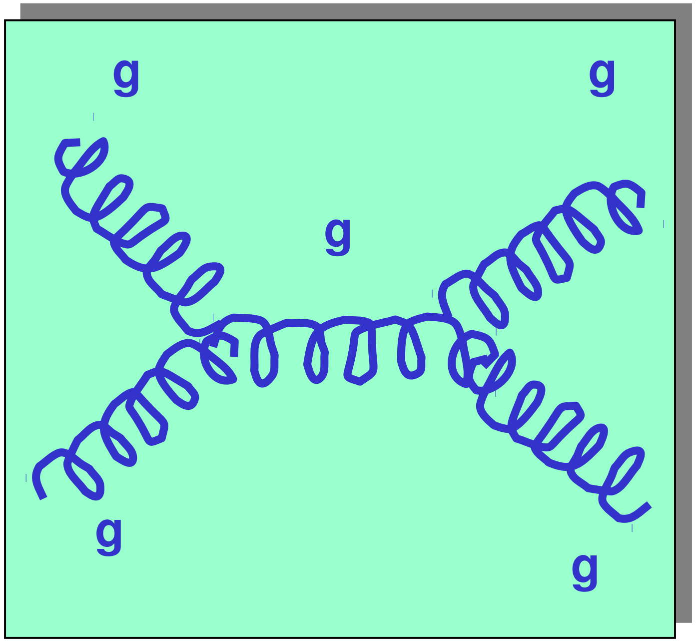
Ok, so here's where it gets hairy!

Since gluons carry "color charge", they can interact with each other !
(Photons can't do that)

Gluon-gluon Scattering



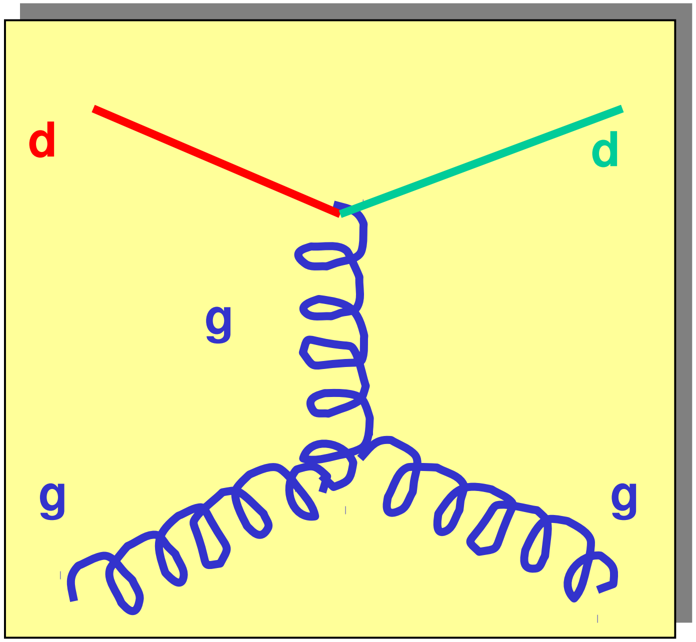
Gluon-gluon Fusion



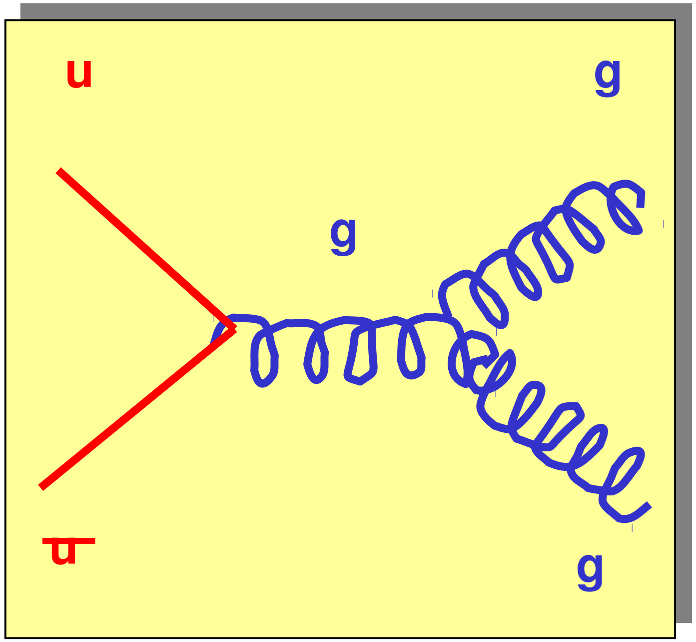
And quark-gluon interactions as well!

Since both quarks and gluons have color, they can interact with each other !!!

Quark-gluon Scattering



Quark-Antiquark Annihilation



Summary (I)

☐ The property which gives rise to the strong force is "color charge"

☐ There are 3 types of colors, RED, GREEN and BLUE.

☐ Quarks have color charge, and interact via the mediator of the strong force, the **gluon**.

☐ The gluon is **massless** like the photon, but differs dramatically in that:

- **It has color charge**
- It's force acts over a very **short range** (inside the nucleus)

Summary (II)

- ☐ Because **gluons carry color charge**, they can **interact among themselves**.

- ☐ **Quarks and gluons are confined inside hadrons** because of the nature of the strong force.

- ☐ Only ~50% of a proton’s energy is carried by the quarks. The remaining 50% is carried by gluons.

- ☐ We learn about the strong force by hadron-hadron scattering experiments.