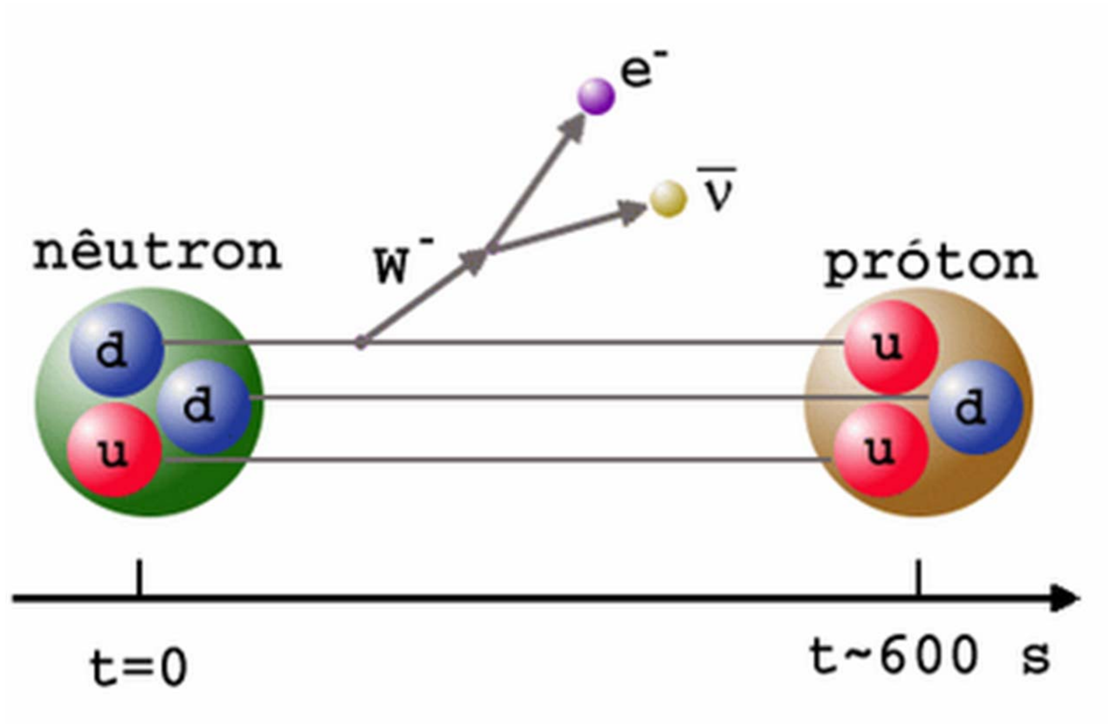


Syracuse Summer Institute
Weak Decays

Weak Interactions and Decays

- It's an experimental fact that particles decay.
- The first place one usually encounters this is in the context of radioactive nuclei.
- Why do some particles decay?

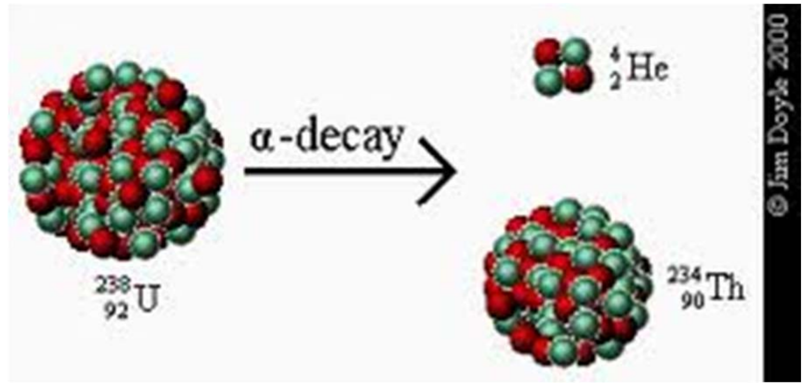
… because they can?

  – Remember, in QM, unless something is strictly forbidden from happening, it will occur with some probability!

Examples of radioactive decay

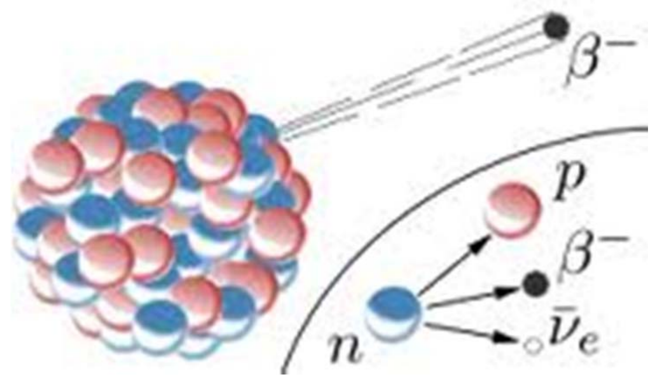
$$^{238}_{92}U \rightarrow\ ^{234}_{90}Th +\ ^{4}_{2}He$$

$$^{222}_{86}Rn \rightarrow\ ^{218}_{84}Po +\ ^{4}_{2}He$$

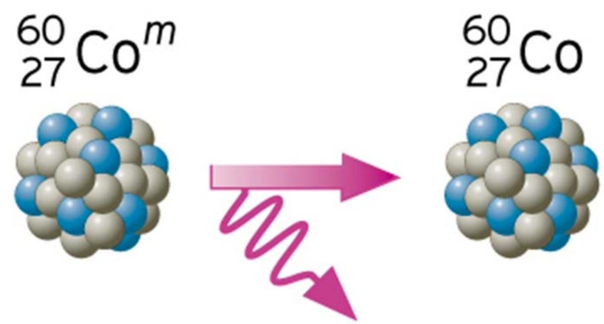


$$^{14}_{6}C \rightarrow\ ^{14}_{7}N + e^{-}\ \ (+\bar{\nu})$$

$$^{40}_{19}K \rightarrow\ ^{40}_{20}Ca + e^{-}\ \ (+\bar{\nu})$$



$$^{60}_{27}Co \rightarrow\ ^{60}_{27}Co + \gamma$$

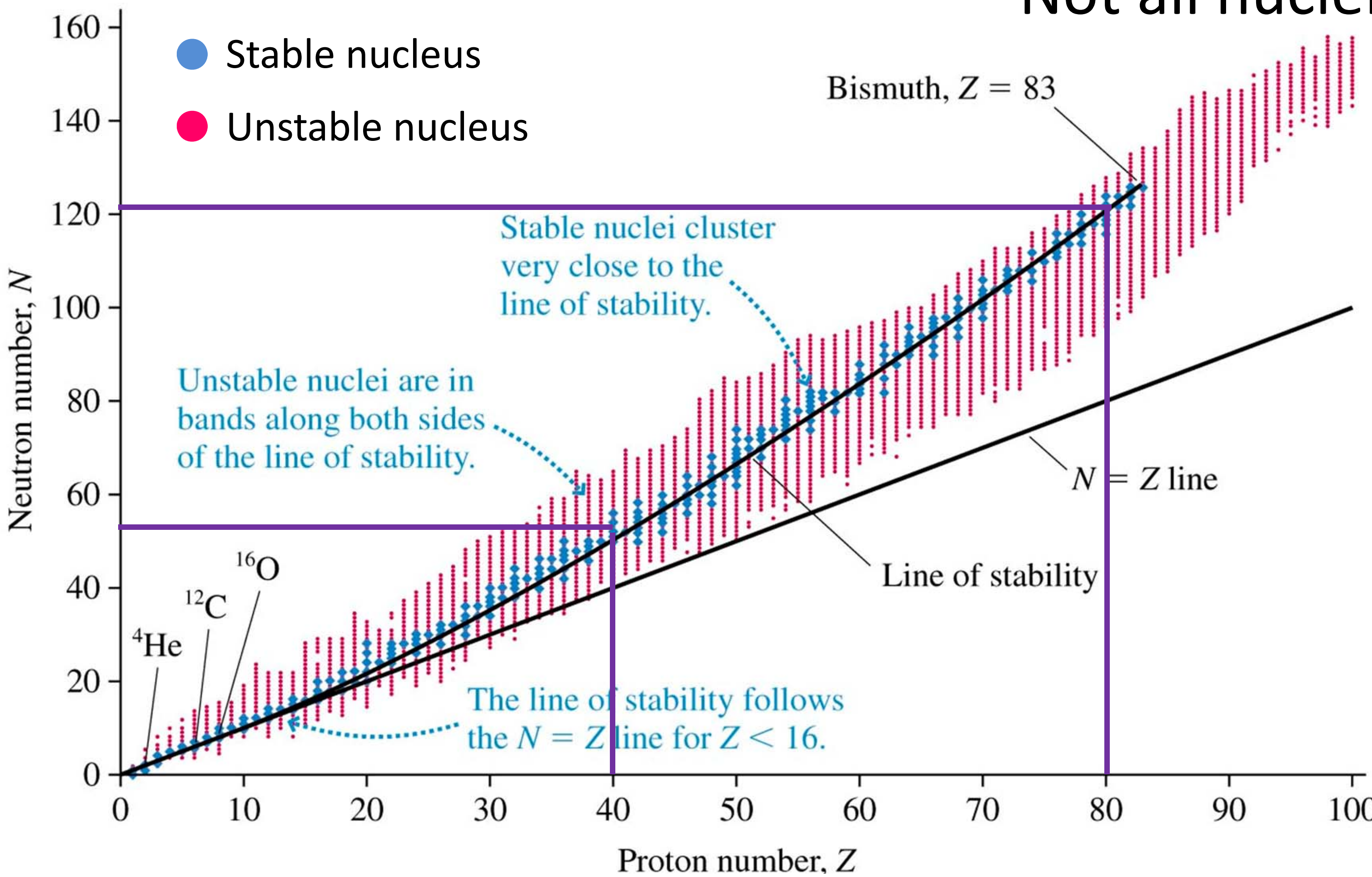


Radioactivity

- Some nuclei spontaneously disintegrate.
  - Heavy nuclei decay down to lighter ones
  - Other way violates energy conservation!
- Three main forms of radiation from nuclei:
  - **Alpha (α)**: 2p+2n = He nucleus (very stable structure)
    - Change of element
  - **Beta (β)** : electrons, $n \rightarrow p + e^- + \nu$
    - Change of element
  - **Gamma (γ):** a high energy photon, ~10's of MeV
    - Often referred to as "gamma rays"
    - Same element
  - **Beta+ (β^+):** $p \rightarrow n + e^+ + \nu$ (Can only happen in a nucleus)
- Why?
  - By doing so, the system goes to a lower energy state. This is what nature likes to do…

Nuclear Stability

Not all nuclei are stable



At Z=40,
N/Z ~ 1.2

At Z=80
N/Z ~ 1.5

- As Z increases, more neutrons are needed per proton to obtain a stable nucleus? Why's that?
- Once Z>83, no longer have ANY stable nuclei ?

Time constant or lifetime

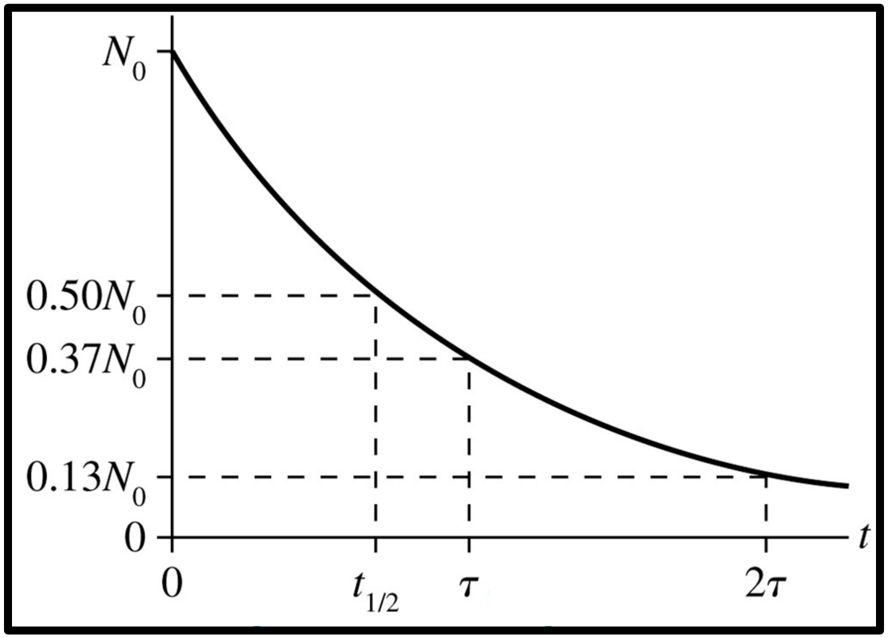
- For radioactive particles, it is found that the number that decay is proportional to the number you have:

$$dN = -kN$$

then, with a lil' ole calculus:

$$N = N_0 e^{-t/\tau}$$

(here $k = 1/\tau$)

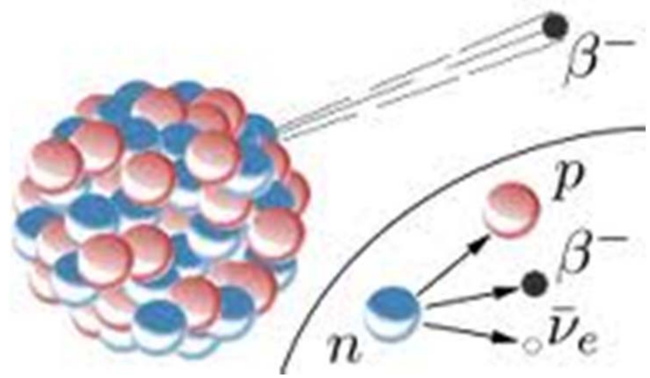


- **τ is called the lifetime or decay constant.**
  It can be viewed as either:
  (a) time for N to decrease to (1/e)xN = 0.37N (time constant)
  (b) Average decay time <t> from a collection of radioactive decays (lifetime)

Let's focus on "beta" decay

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} \ \ (+\overline{\nu}) $$

$$ {}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + e^{-} \ \ (+\overline{\nu}) $$



- The underlying process is: $n \rightarrow p + e^{-} + \overline{\nu}_e$
- Since M(n) = 939.56 MeV M(p) = 938.27 MeV/c2,
  M(e) = 0.51 MeV/c2
- M(n) > M(p) + M(e), not forbidden by energy conservation, but very close!
- Free neutron lifetime ~882 sec (~15 min) **VERY, VERY LONG** !
- HW: Why don't neutrons decay when harbored in stable nuclei?
  Why don't protons decay?

The Weak Force

- So far, we've encountered:
  - **EM force:** Responsible for all of chemistry, atomic binding, etc
  - **Strong force**: responsible for nuclear binding, quark-quark interactions, etc.
- We now encounter the **Weak Force**
  - Can lead to a **change in quark type and charge** ($W^{\pm}$).
  - There are also weak interactions that don't change quark type or charge (Z^0)
  - Neutrinos only "feel" the weak force.
  - The force carriers of the weak force have **LARGE mass**
    - $W^{\pm}$-boson: 80,000 MeV/c^2
    - Z^0 boson: ~91,000 MeV/c^2.
    - "Boson" refers to particles that have integral spin (here, Spin = 1).
  - The "charge" of the weak force is called "weak charge"
  - **Both quarks & leptons carry weak charge**!

Decays, in general

- In general, unstable particles will decay in any way that they are able to.
- In principle, particles can decay via the weak, EM or strong interaction.
- If all are accessible, the preference is:
  1) Strong
  2) Electromagnetic
  3) Weak
- This is because the strong force has the largest strength (coupling constant).
- Particles generally only decay weakly if they **cannot** decay via the strong or EM interaction.
- In some cases, particles can decay via more than one of the forces. E.g Decay of excited D^0 ($c\bar{u}$) meson

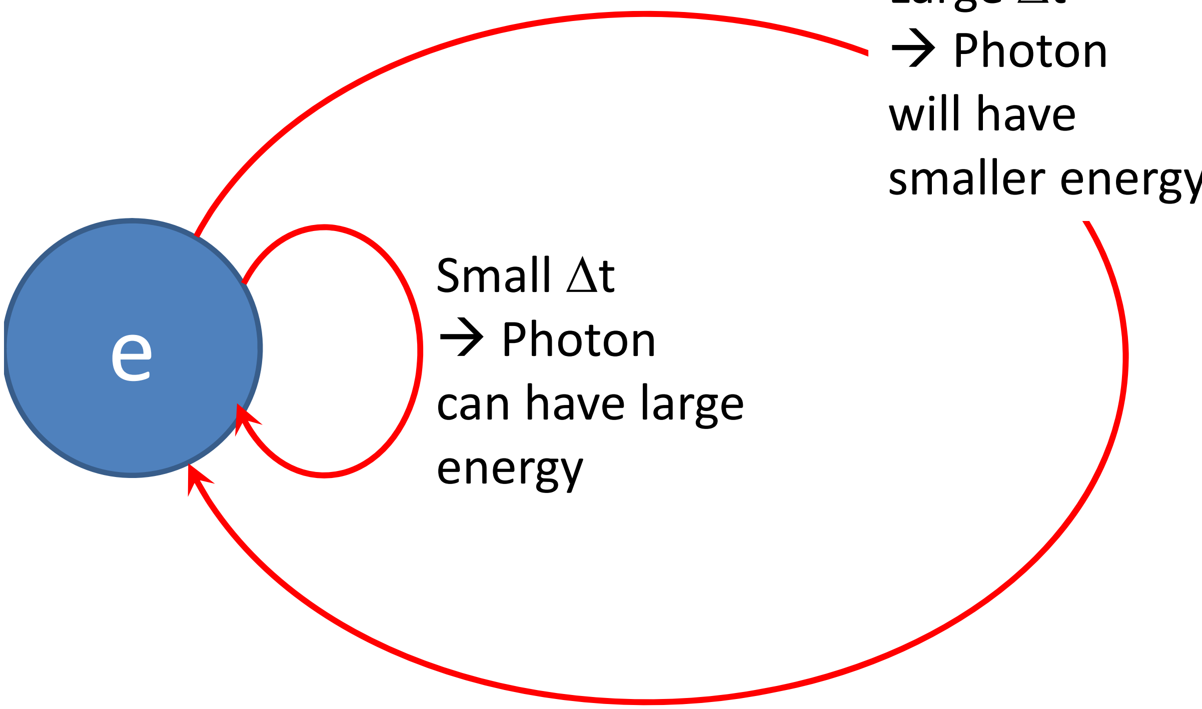
  $D^{*0} \rightarrow D^0\pi^0$ (62%, strong)

  $D^{*0} \rightarrow D^0\gamma$ (38%, EM)

Digression on range of forces

Virtual photons

- Quantum physics does not inhibit, say an electron, from emitting and re-absorbing a photon.
  - This will violate energy conservation ☹
  - But, as long as the “transit time” and energy of the photon satisfy: **$\Delta E \Delta t \geq \hbar$,** It’s OK!

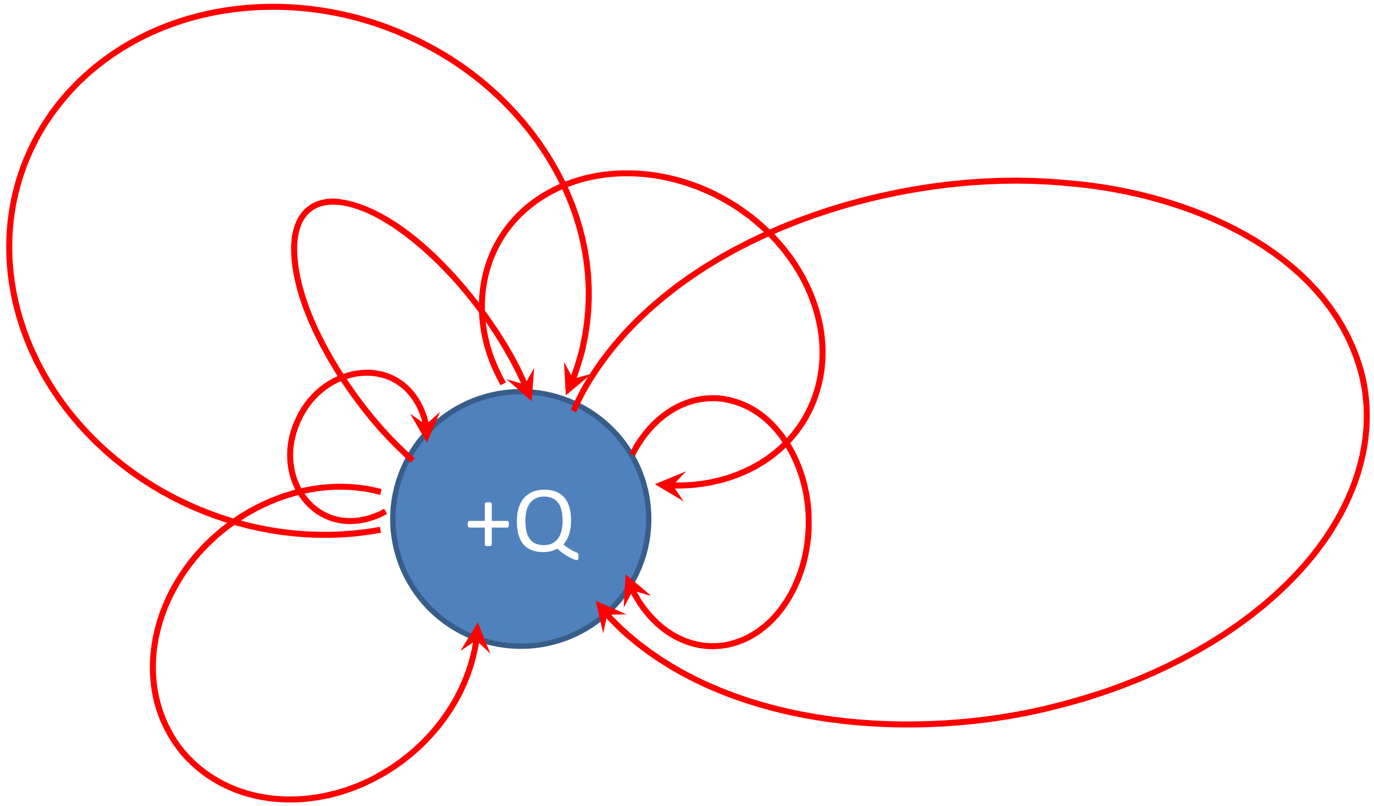


Key point

Because the photons at large distance carry smaller and smaller energy (& momentum) this accounts for the $1/r^2$ falloff of the EM force!

An even more complicated picture

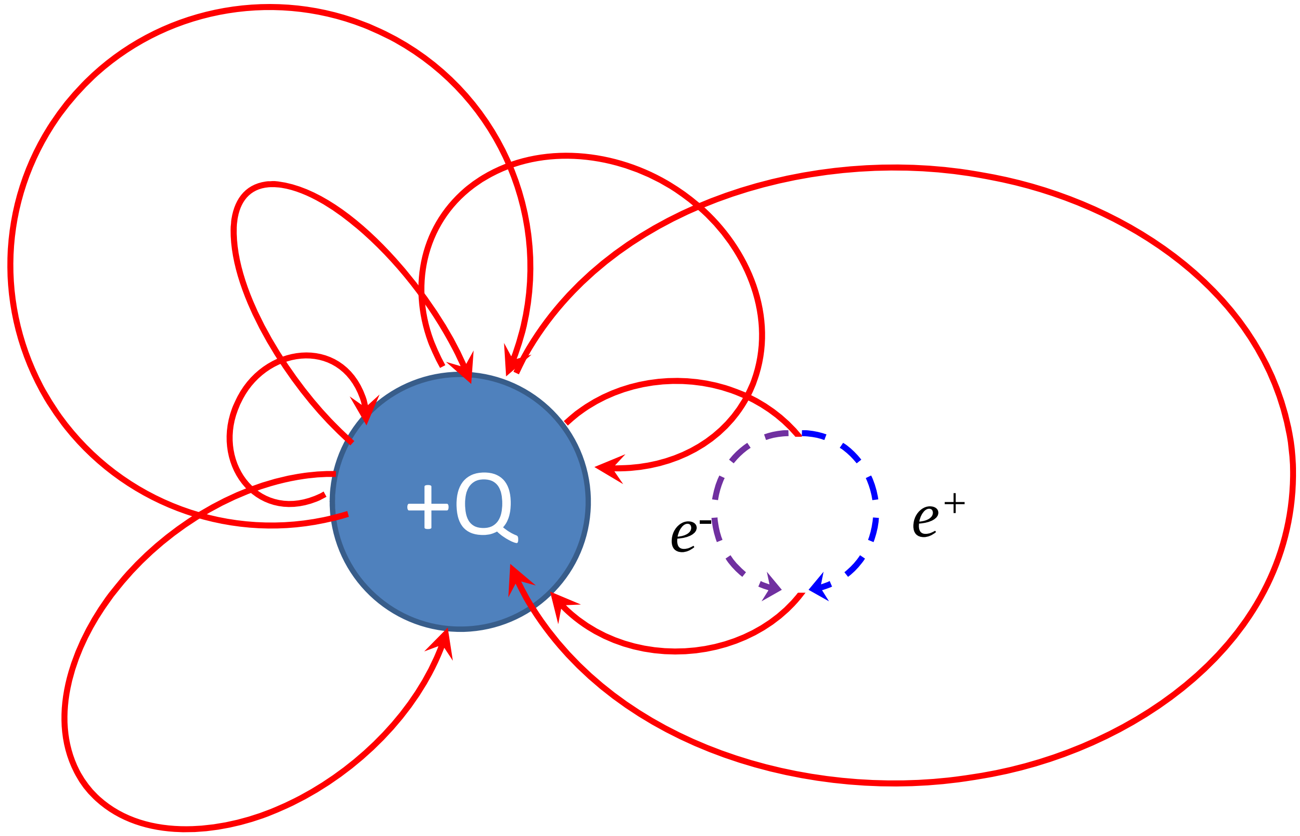
- A charged particle is **continually** emitting and re-absorbing photons



- **Real** photons have zero mass
- These photons generally won't have mass=0. Called **virtual** photons.
- The neat thing about **virtual particles** (in general) is that since they are emitted and re-absorbed, its **mass is not limited by energy conservation**!!!

It can get even more complicated

- Nothing prohibits a virtual photon from "transforming" into mass in the form of an e^+e^- pair.



- The effects of these virtual quantum loops are an integral part of QM.
- If you don't include them, QED would disagree with experimental data !
- If you include them, you get the right answer ☺

The W$^{\pm}$ Boson

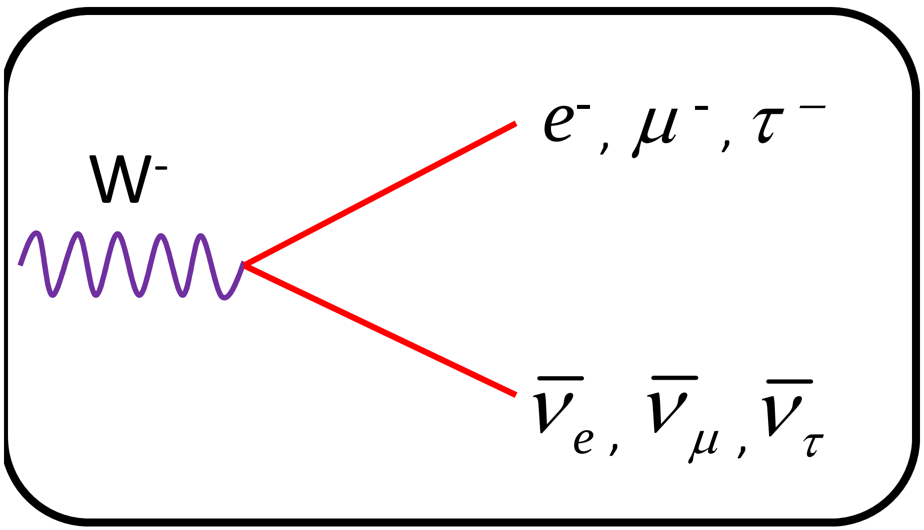
- The W boson is has very large mass (~90m$_p$). From the uncertainty principle:

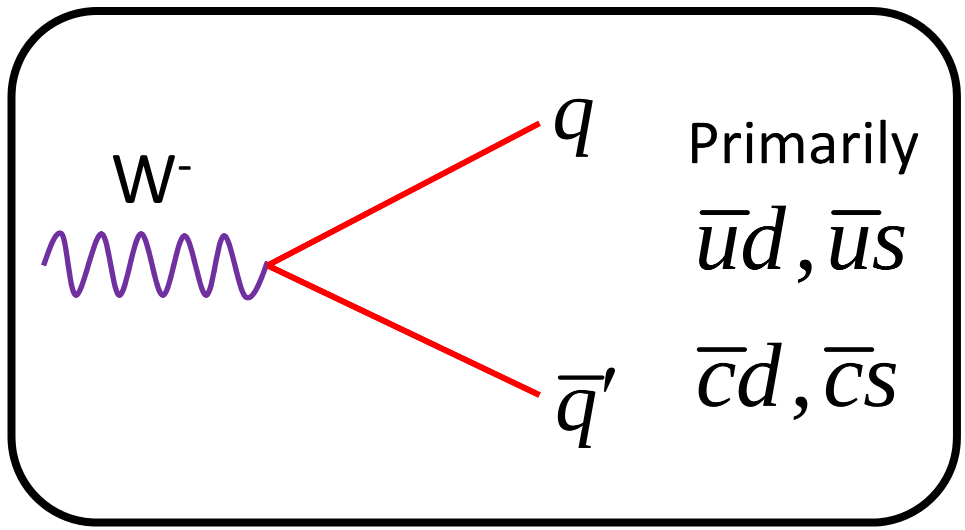
$$\Delta t \approx \hbar / \Delta E = \hbar / m_W c^2$$

$$d \sim c\Delta t = \hbar / m_W c$$

Very short range …
~ 0.001 of the proton radius

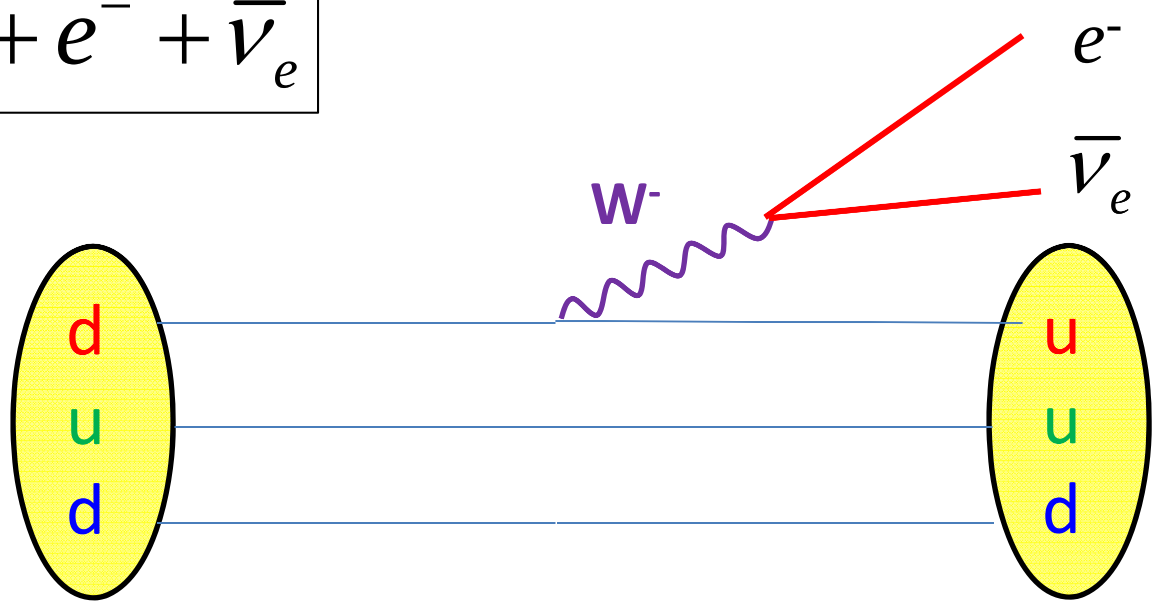
- Also, the W boson decays. Because both leptons and quarks have weak charge you can get:





Ok, now on to beta decay

$$n \rightarrow p + e^- + \overline{\nu}_e$$



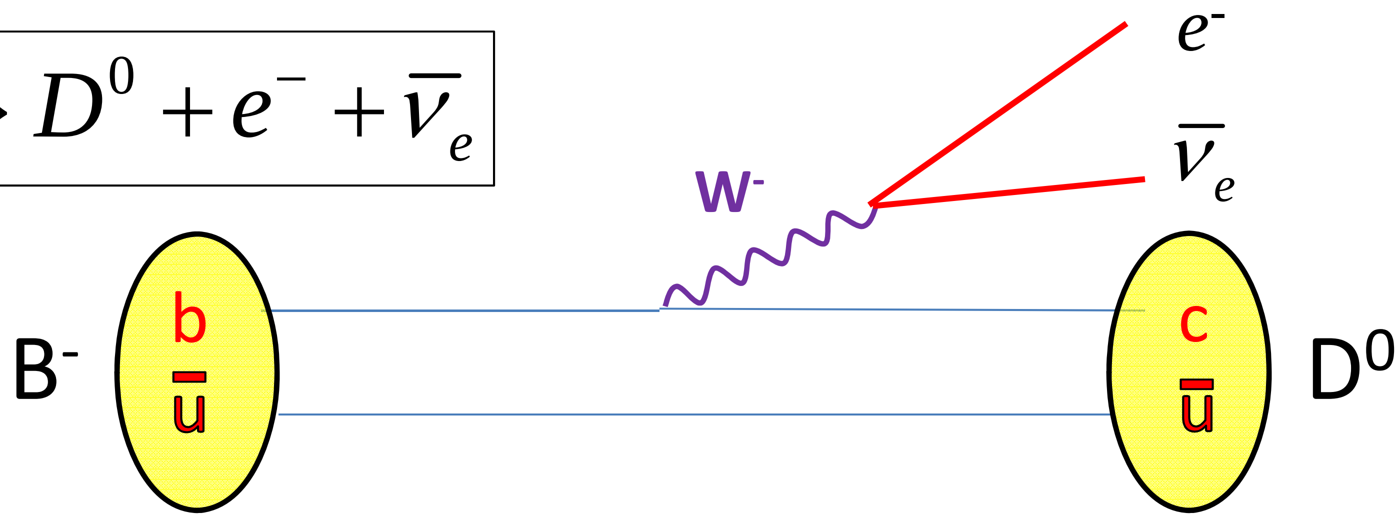
- Here , the d-quark emits a W^- and transforms into a u quark.
  - Easy to see that charge is conserved throughout.
  - The ud "just goes along for the ride" (spectator quarks)
  - The underlying quark-level process is:

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

- Many weak decay diagrams look very similar to this !

Let's look at a B meson decay

$$B^- \rightarrow D^0 + e^- + \overline{\nu}_e$$



- Here, the underlying quark-level process is:

$$b \rightarrow c + e^- + \overline{\nu}_e$$

- Particles containing b-quarks have relatively long lifetimes of ~1.5×10^{-12} s. This may not seem long, but:

$$dist = \gamma vt$$

using $E_B^{lab} = \gamma m_B c^2$:

$$\gamma = E_B^{lab}/m_B c^2 \approx 100\ GeV / 5\ GeV = \mathbf{20}$$

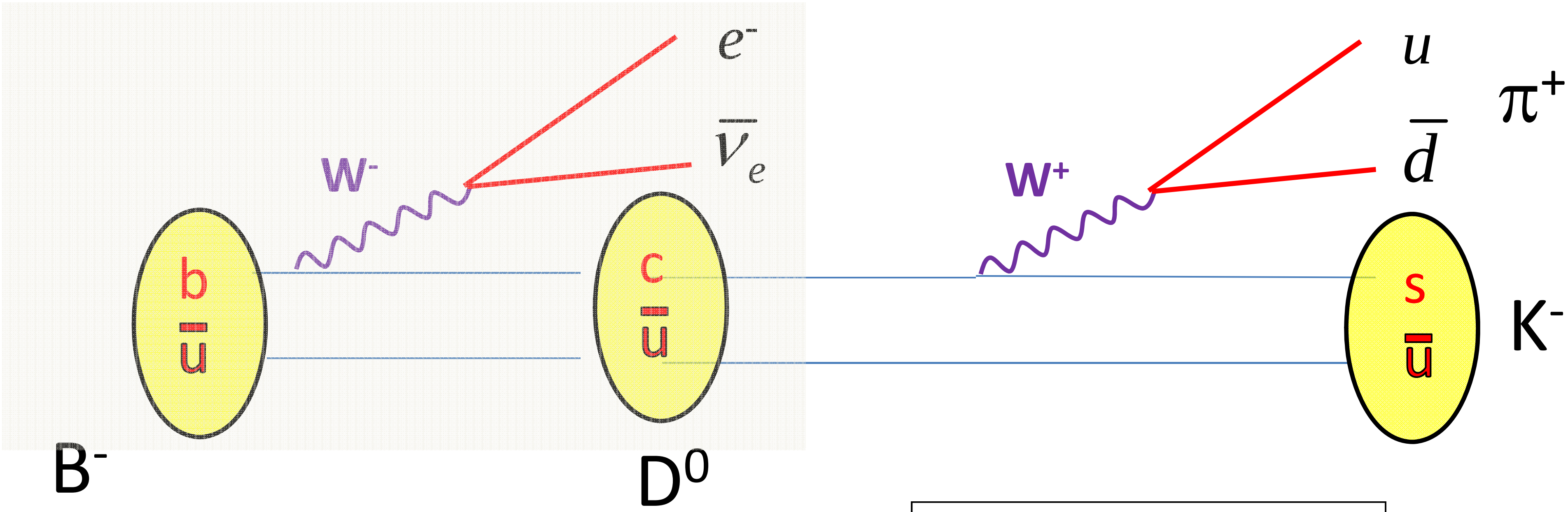
$$Since \quad \mathrm{v} \approx \mathrm{c}$$

$$\mathrm{dist} = 20 \times (3x10^8 m/s)(1.5x10^{-12} s)$$

$$= \boxed{9\ \mathrm{mm}}$$

- These distances are measureable with modern detectors.

Not quite the whole story …



$$B^- \to D^0 + e^- + \bar{\nu}_e$$

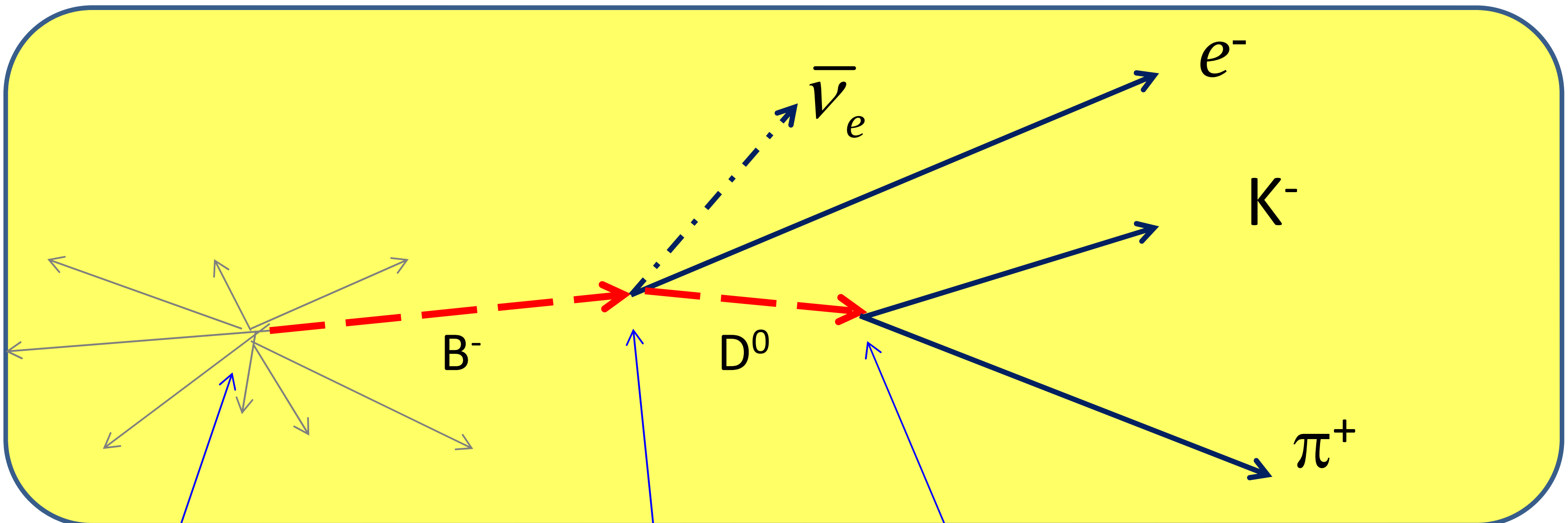
$$D^0 \to K^- \pi^+$$

- The D^0 particle is unstable as well. It has $\tau \approx 0.4\text{x}10^{-12}$ s. So, it travels (on average) about 3 mm before decaying.
- The K^- and π^+ have lifetimes ~10^4 times larger, so they mostly traverse the detectors and are detected before they decay!

So, the weak decay looks like

$$B^- \rightarrow D^0 + e^- + \bar{\nu}_e$$

$$D^0 \rightarrow K^- \pi^+$$



B^- produced here, say in pp collision

B^- decayed here. D^0, e^-, ν_e produced here.

D^0 decayed here. K^-, π^+ produced here.