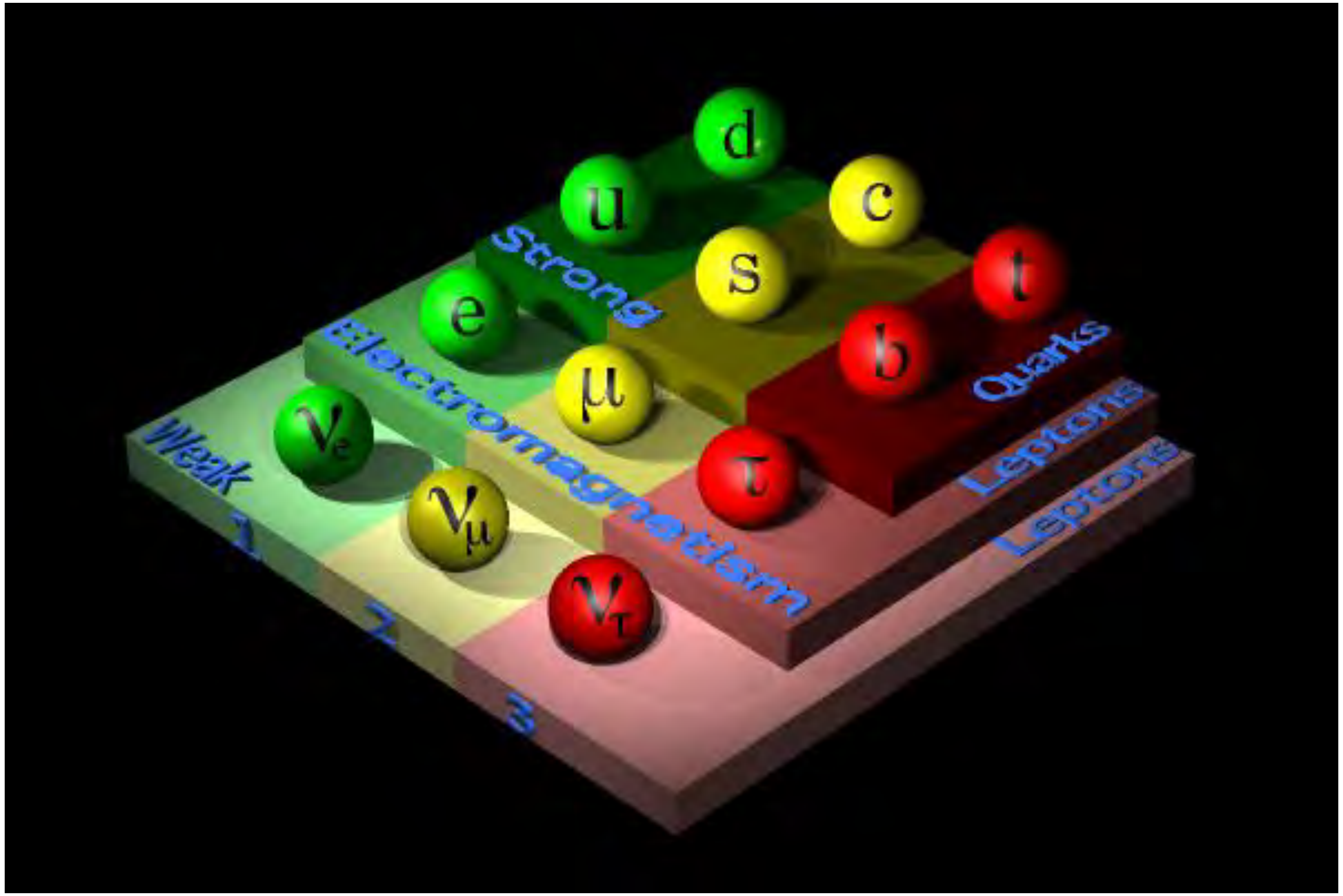
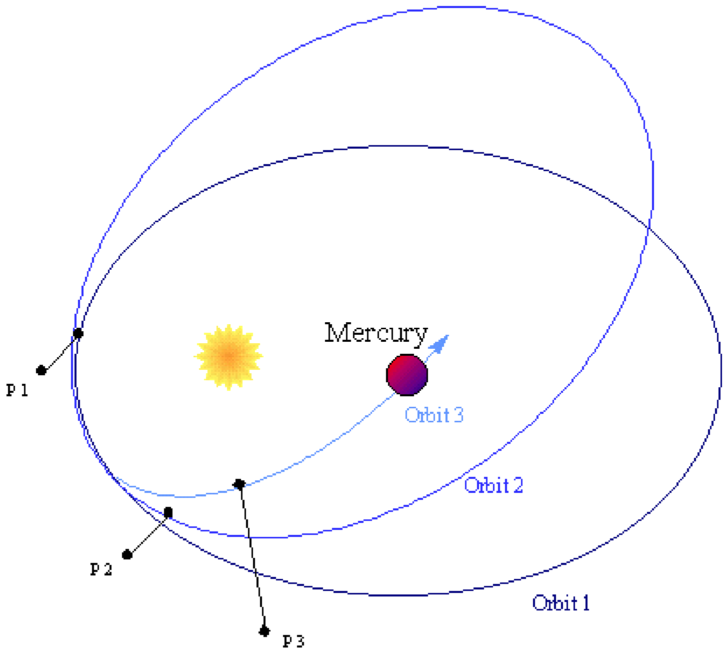
The Standard Model

Steve Blusk
Syracuse University



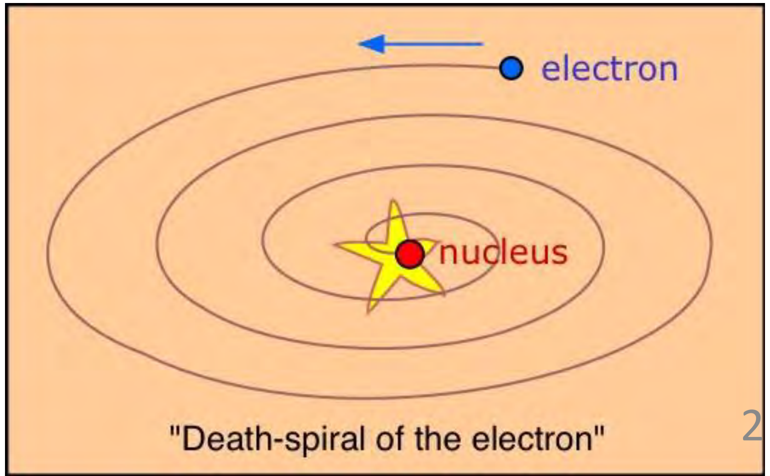
Science is an evolution

- ❑ Do the laws of nature lead to **a single fundamental theory of matter and forces** ?
- ❑ What do we mean by a **good theory**?
  - ❑ Accurate postdictions and predictions.
- ❑ Up to now, laws of physics are almost certainly **effective theories**.
  - ❑ Only guaranteed to be correct within the regime it is tested.



- ❑ **Example 1:**
  - ❑ **Precession of Mercury confronts Newton → General Relativity.**
- ❑ **Example 2:**
  - ❑ **The atom confronts classical theories → Quantum mechanics**

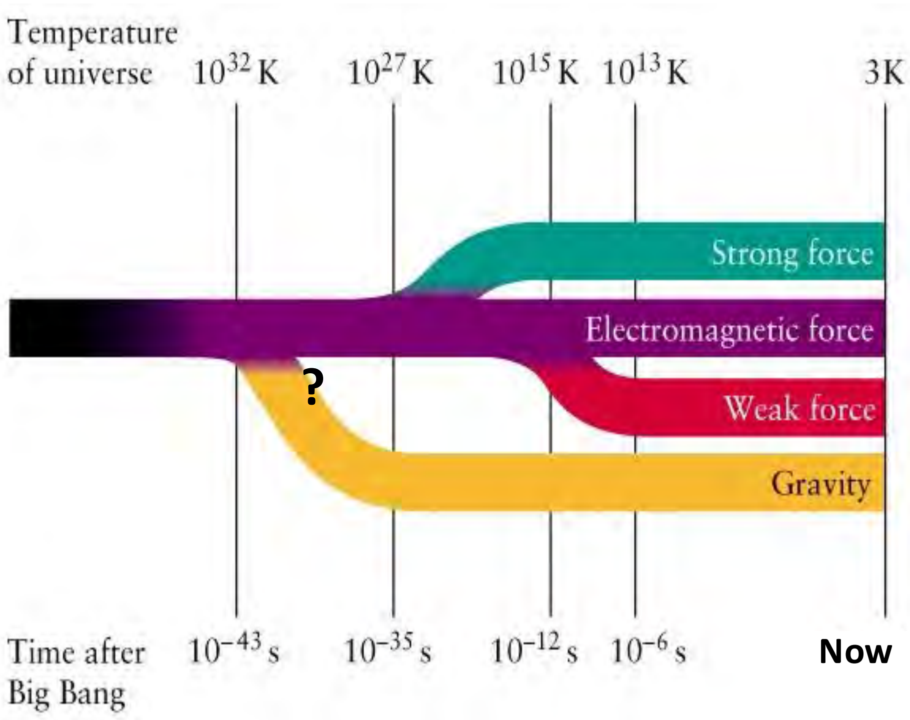
- ❑ **But, we have a problem:**
  - ❑ These 2 very successful theories are distinctly different theories.
  - ❑ **Which theory to use to describe the interior of a black hole, where both microscopic physics + intense gravity are in play?**



Physical Laws must be Unified

(presumably into a new theory)

Towards unification of the forces



- **In 1860's, Maxwell** unified electricity, magnetism and light into **Electromagnetism** (classical) [superseded by QED]

1831-1879

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

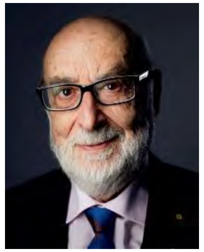
- **In 1967, Weinberg & Salam** unified the EM & **Weak forces** (**Electroweak [EW] force**).
  - Predicted $W^{\pm}$, Z^0 bosons discovered at CERN. **1979 Nobel prize to W&S**.

1933 -

1926-1996

- **In 1964: Higgs, Englert** postulated that fundamental particles acquire mass through their interaction with a new field, later called the **Higgs field**.
  - Higgs particle discovered at CERN **2012** → **2013 Nobels.**

1929 -

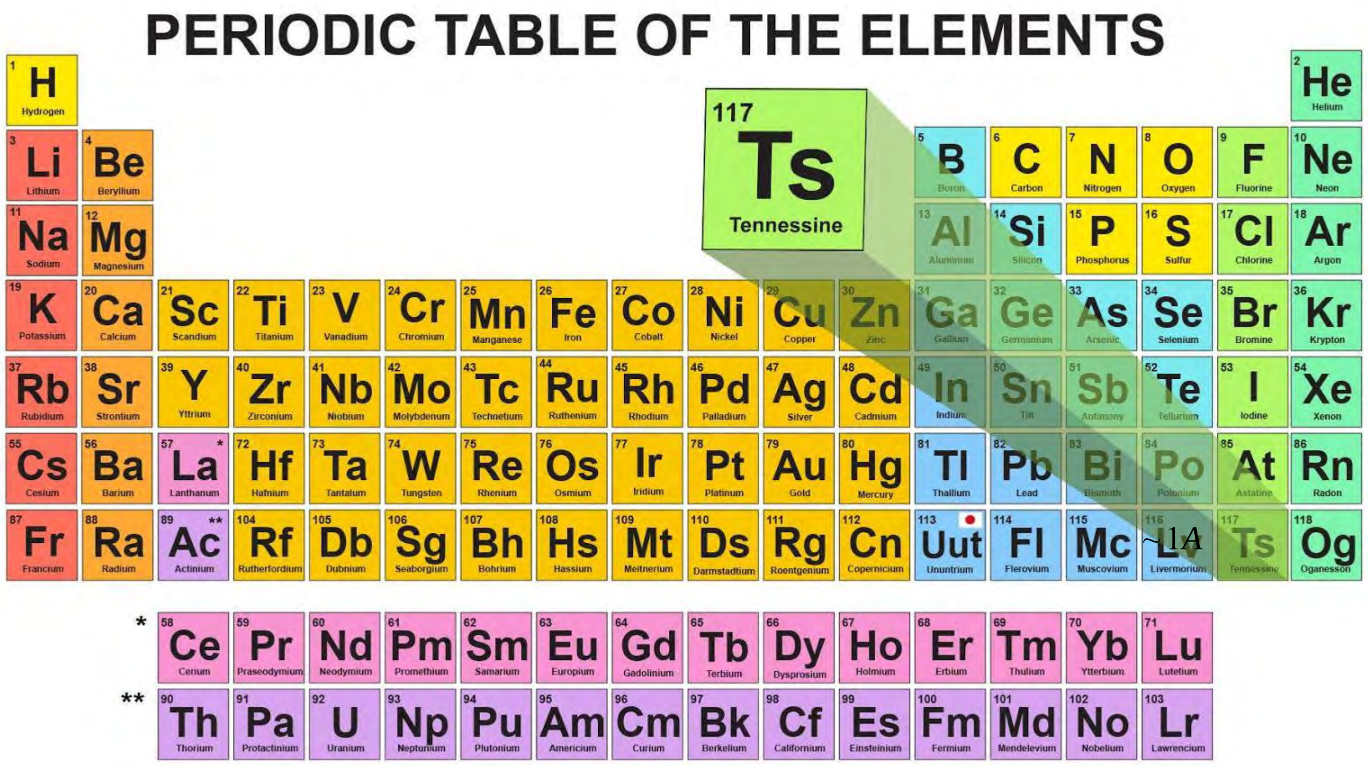


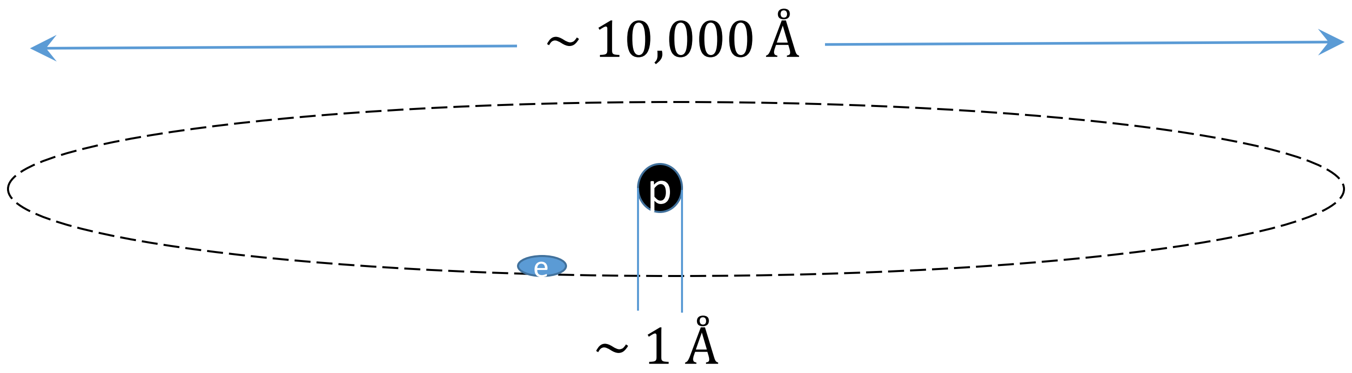
1932 -

So where are we now?

- **Two very successful, incompatible (effective) theories!** ☹
  - **Standard Model (Quantum theory):** Electroweak + Strong Force [not unified]
  - **General Relativity (Classical, not quantum):** Gravity (will not discuss today)

The search for order …

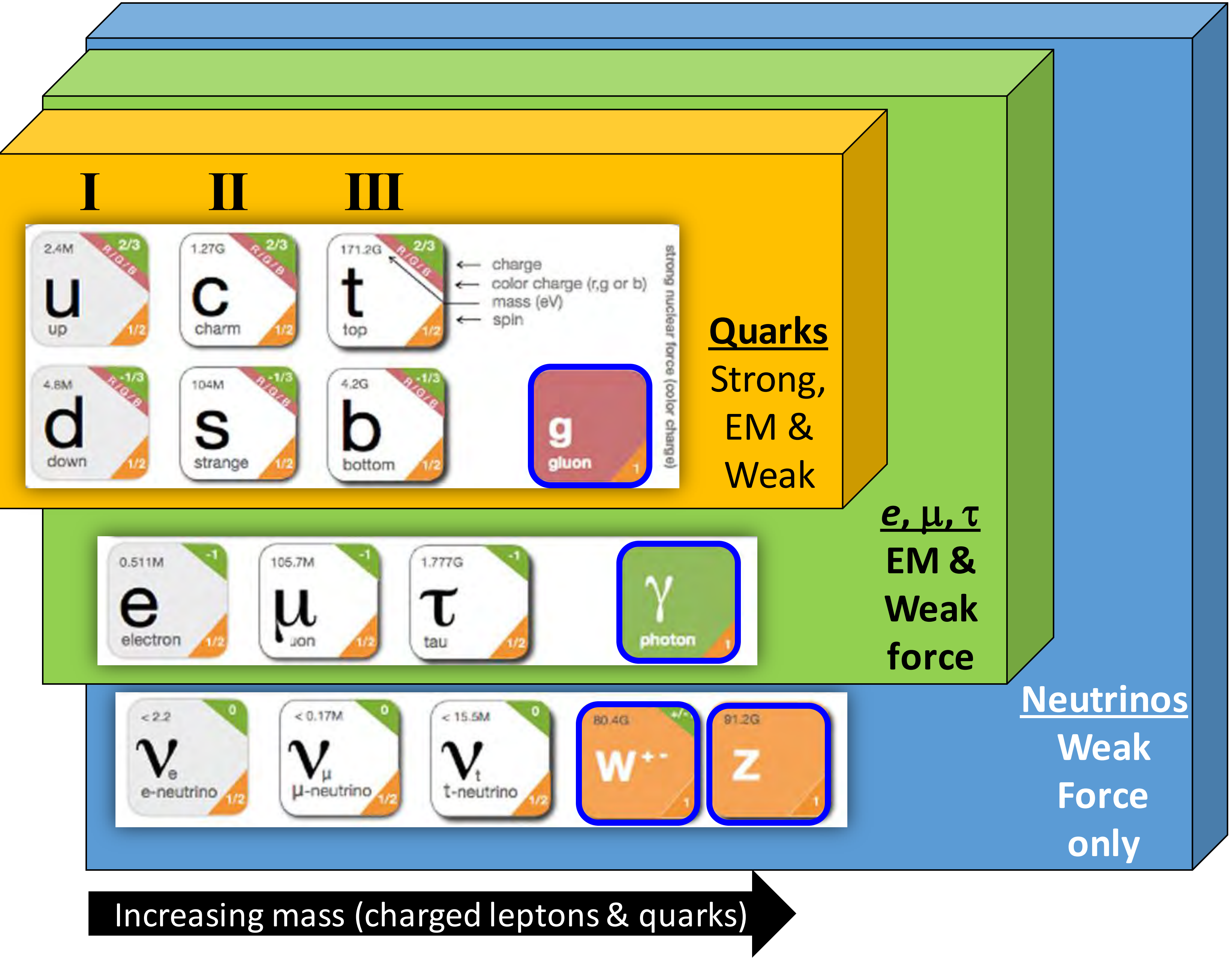




- As humans, we naturally seek some sort of "order"..
- Could the 100+ *different kinds of matter* really have a more simple understanding?

- Over time, we have peeled back the layers, and realized that all of this structure has 3 basic ingredients
  - **Nucleus**: Protons+ neutrons
  - **Electrons**
  - **EM force**.

A new order: The Standard Model



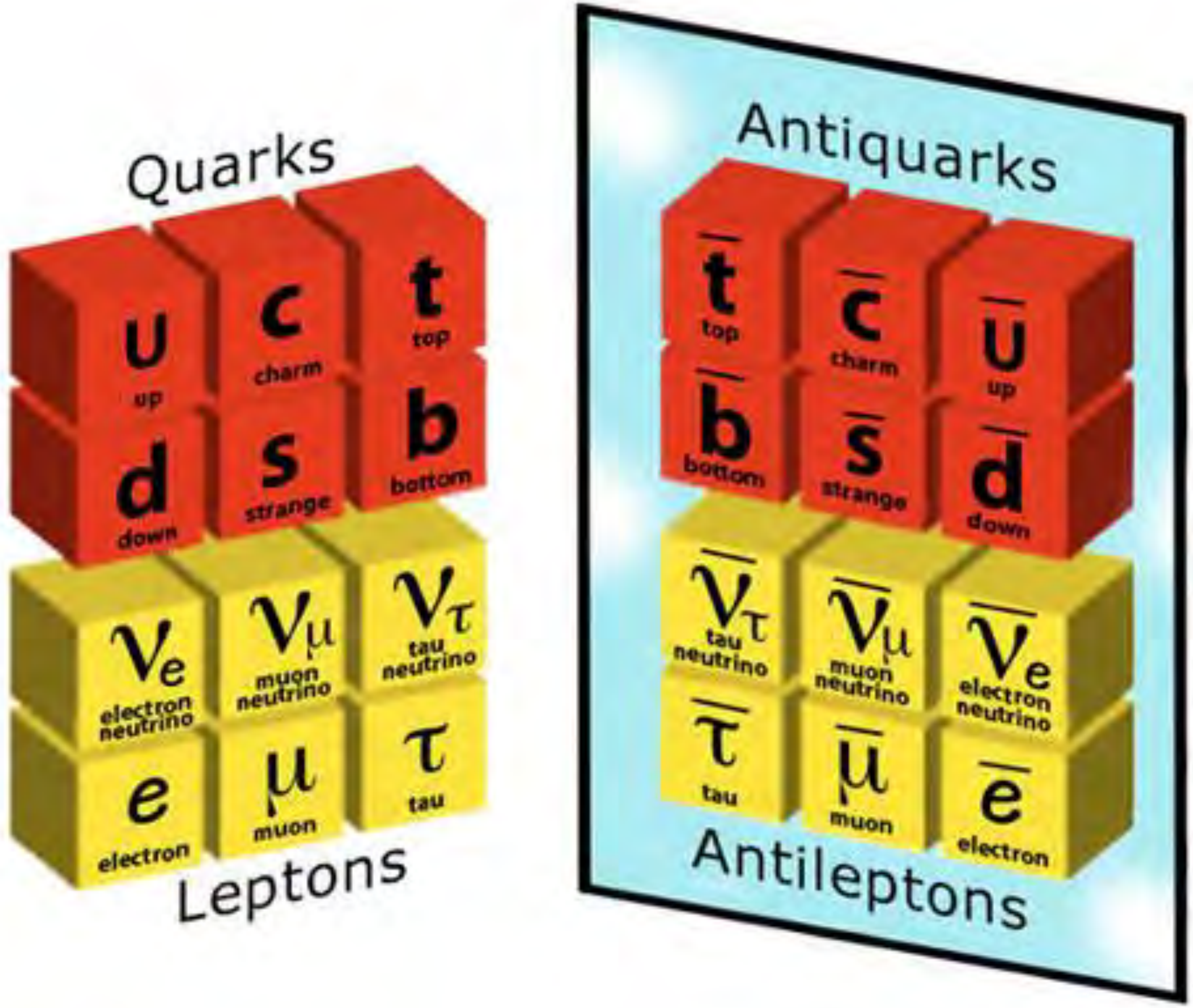
- **Matter particles consist of:**
  - 3 "families" of quarks.
    3 families of leptons
- Generally particle in families II, III are unstable and **decay** into family I (excluding neutrinos).

- Forces mediated by **force carriers**.
  - **Strong**: gluon (color charge)
  - **EM**: photon (electric charge)
  - **Weak:** $W^{\pm}$, Z^0 (weak charge)

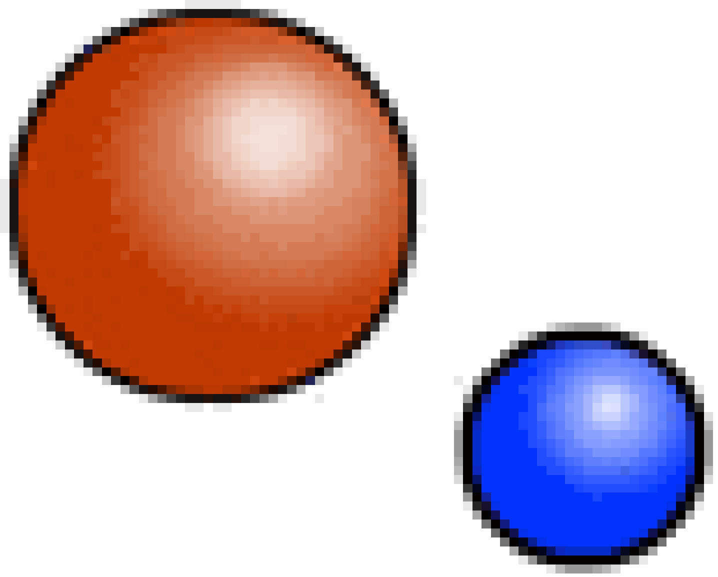
- **Force carriers** only interact with particles carrying the **correct charge**.
  - Quarks: Color, electric & weak
  - e^-, μ^-, τ^-: Electric, weak
  - Neutrinos: Weak

Antiparticles

- All of the matter particles have corresponding *antiparticles*.
- They have the **same mass** but **opposite charge** as their matter counterpart.
- Otherwise, very little difference between matter and antimatter!
- But, there must be some *fundamental difference*.. After all nature has clearly "preferred" matter over antimatter! **How? Why?**

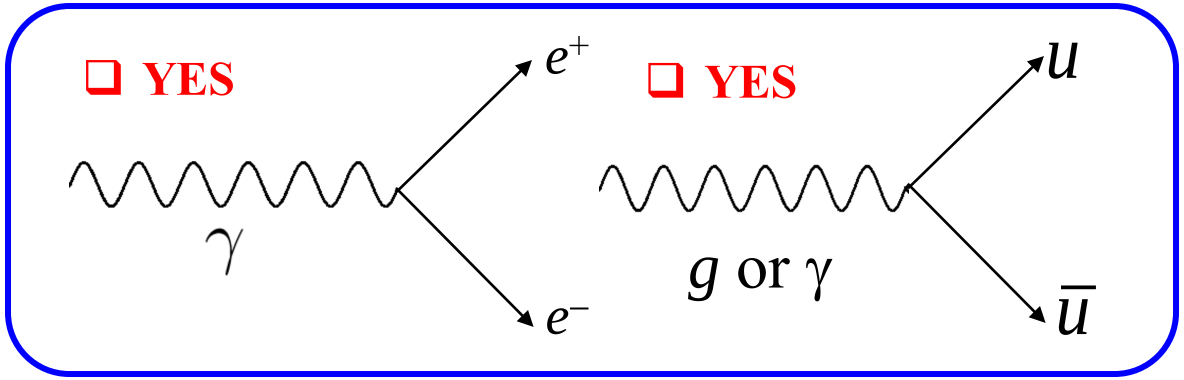


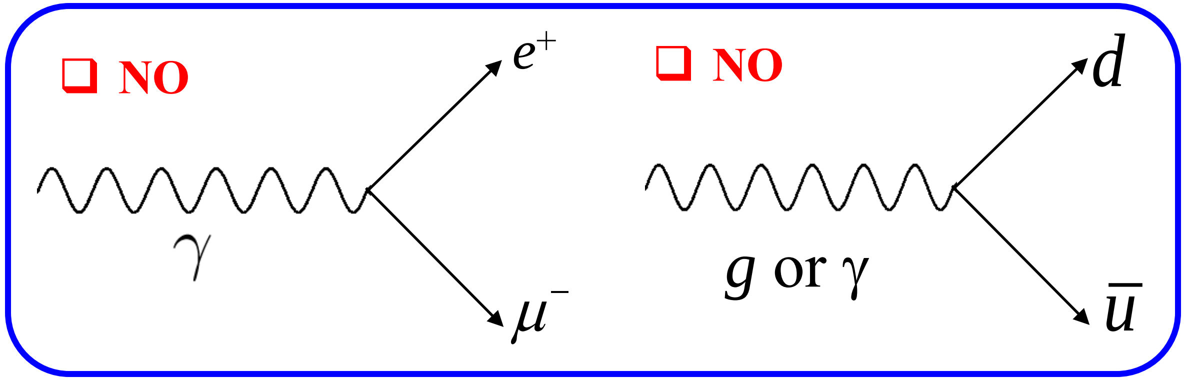
Modern view of fundamental forces



- **Force** == exchange of force carriers between particles carrying "*correct*" charge
- For an atom, photons are continuously exchanged between electrons and protons.

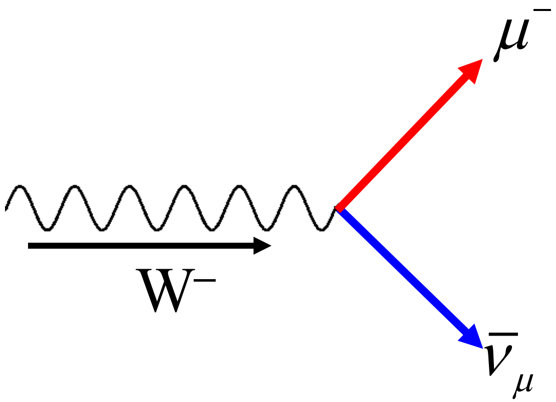
How do Strong, EM and Weak decays differ?



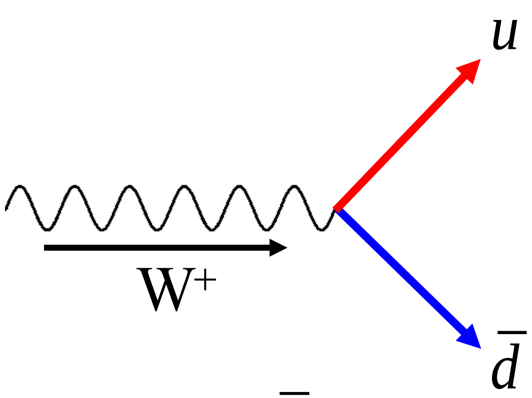


- Strong and EM forces can only produce $q\bar{q}$ or $\ell^+\ell^-$ of same type.
- However, the W^+ and W^- (**weak interaction**) are charged!

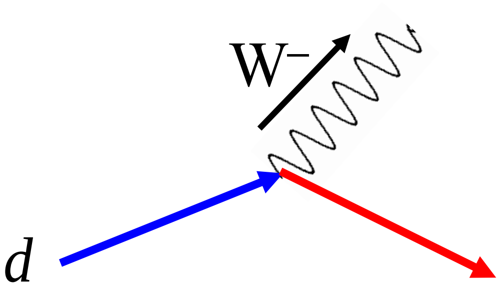
- Rotate the last figure CW, replace the incoming W^+ with an outgoing W^-, and outgoing $\bar{d}$ with an incoming d.
- $d \rightarrow u$ with emission of a W^-!



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



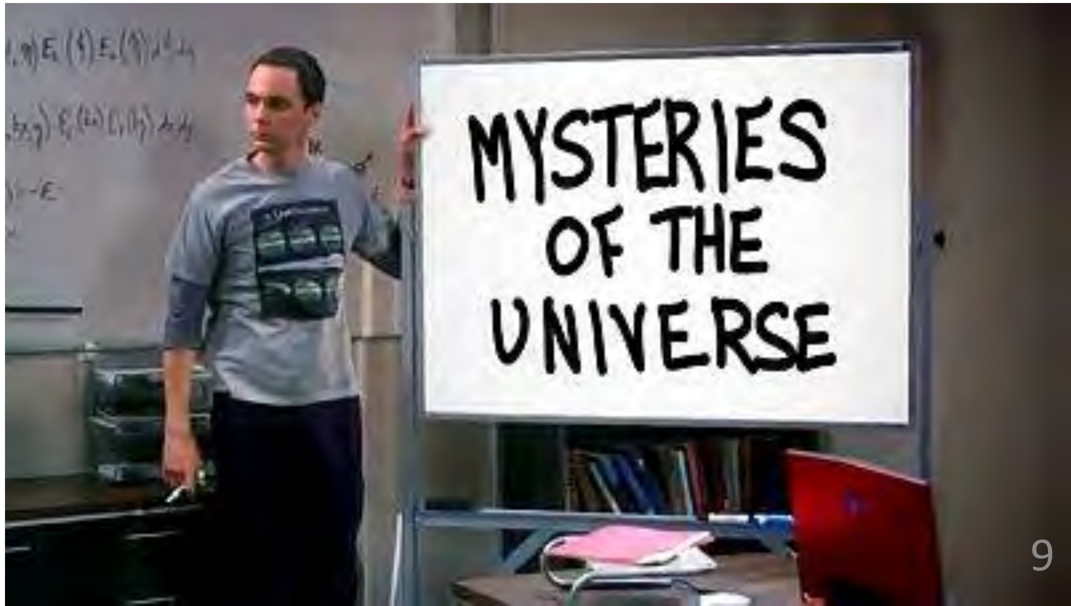
$W^+ \rightarrow u\bar{d}$



$d \rightarrow uW^-$

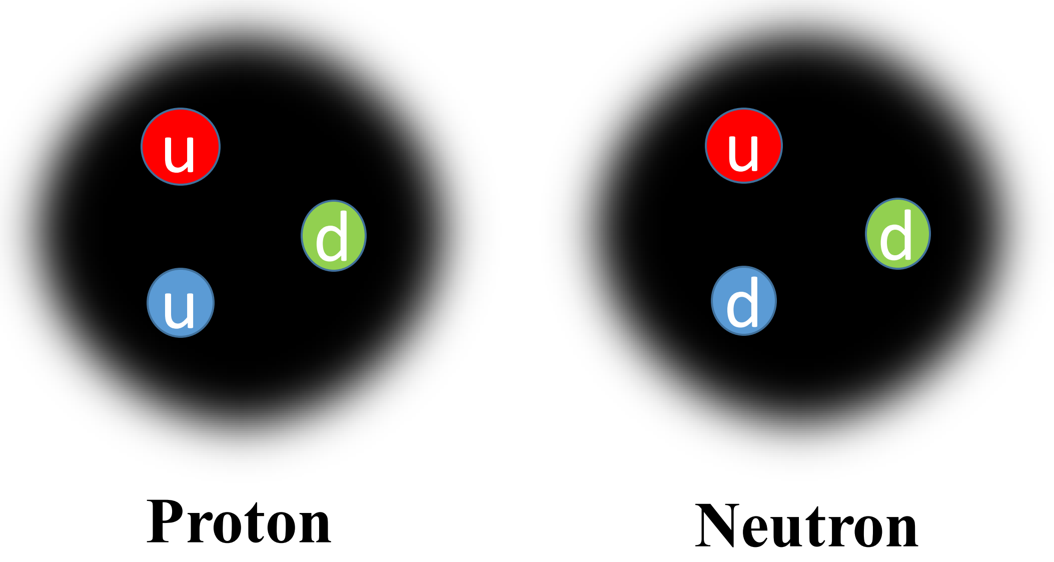
With this model, we can begin to ask, and answer, some basic questions that arise.

- And maybe even answer some of the

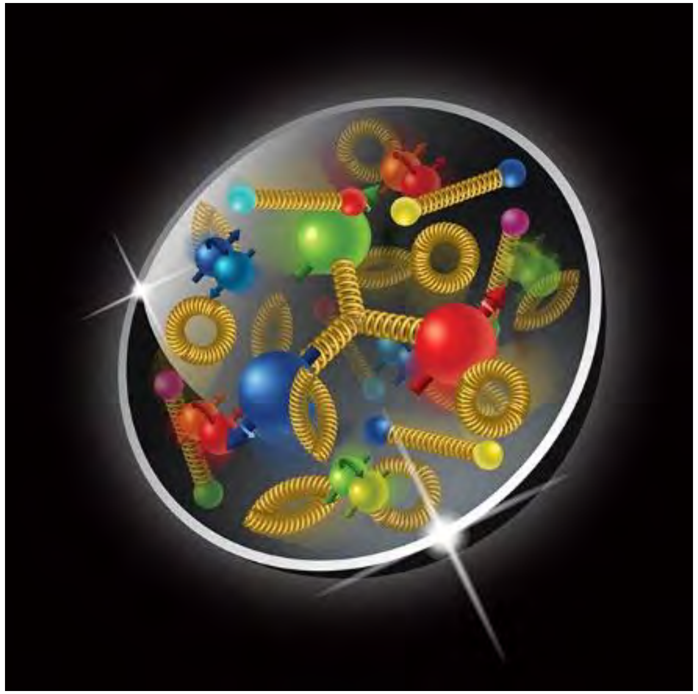


Q: How are protons and neutrons formed?

- Protons and neutrons belong to a general class of particles called "**baryons**".
- **Baryons are formed when any 3 quarks (except top) bind together due to the strong force.**



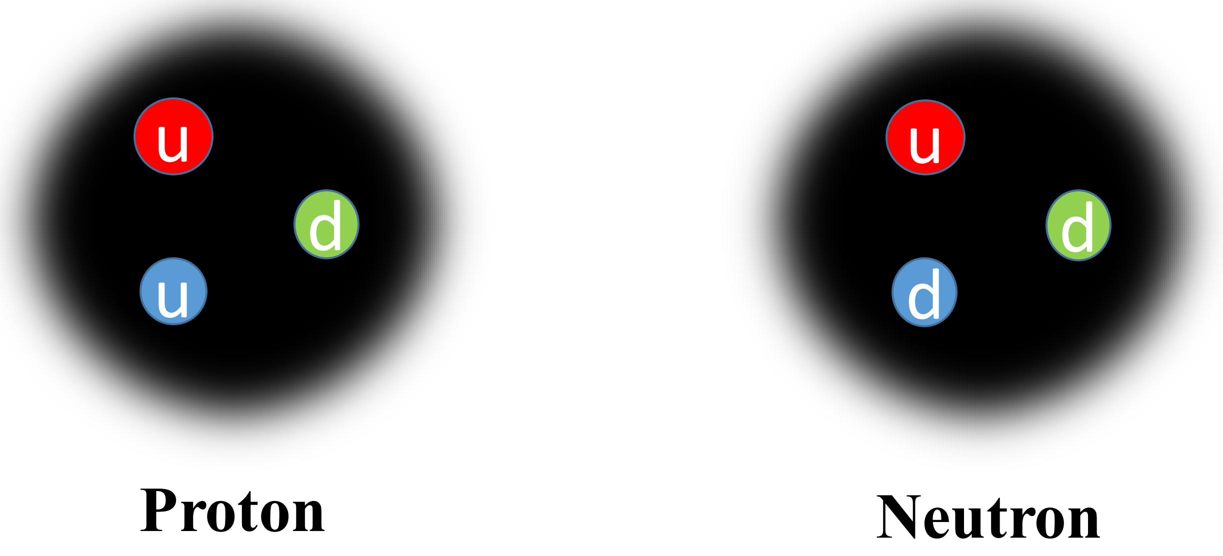
- Not to scale
- Quarks are at least 10,000x smaller than the proton.



- **Interestingly, the proton and neutron only differ by an up quark being replaced by a down quark!**

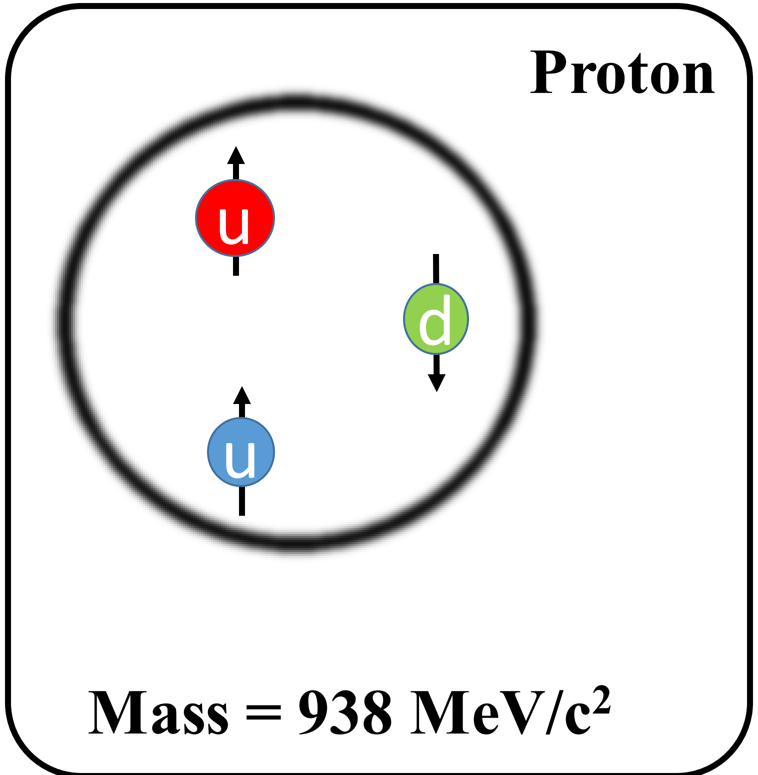
Q: Why did you draw the quarks as having 3 different colors?

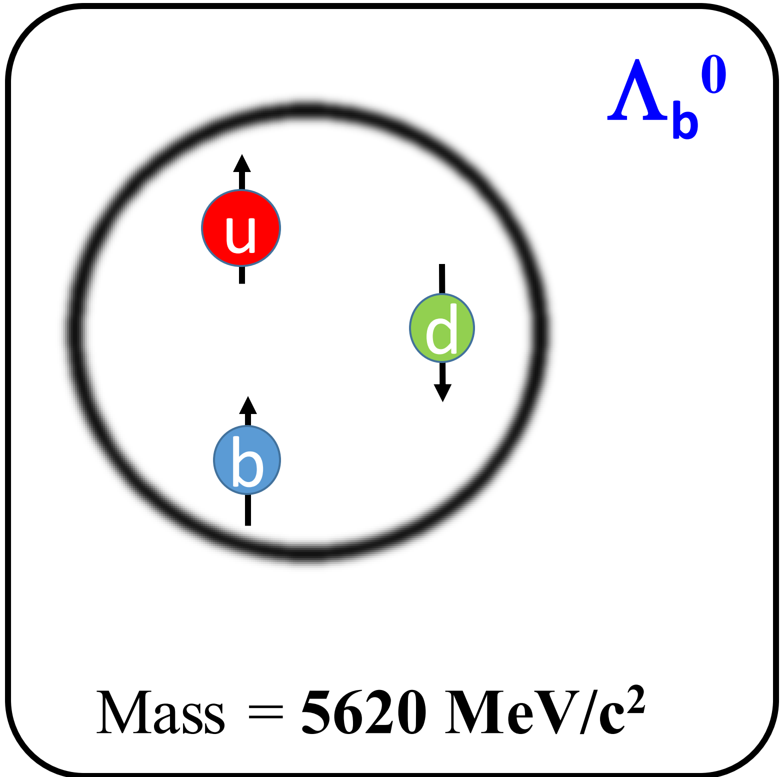
- We know that particles carry *intrinsic properties* (mass, electric charge, spin, …)
- **QCD** asserts that quarks also carry "**strong charge**".
  - The gluons only "see" the quark's **strong charge,** not their electric charge**.**
  - It is this strong charge that allows gluons to interact with the quarks.
  - Experiments strongly support **3 possible values** for this *strong charge*.
  - We use **color** as a way of thinking about the 3 charges (**red**, **green** & **blue**).
  - Within QCD, there is **strong attraction** when you have **one of each color**.
    Alternately, the theory says that composite particles are "color-neutral" (r+g+b = neutral).



Q: Are there baryons other than protons and neutrons?

- **Absolutely! Actually, there are a lot more!**
- So, how many possible baryons are there?
  - 5 x 5 x 5 = **125 possible baryons**.





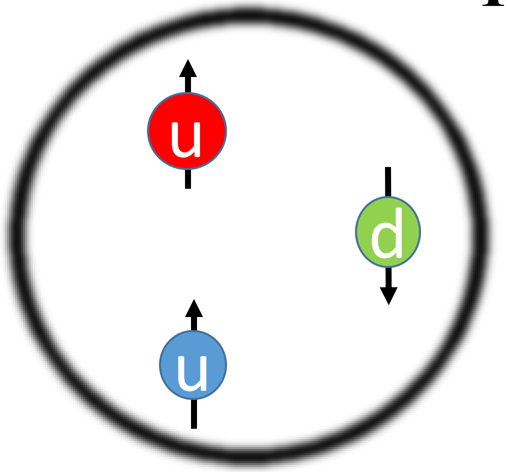
- Here, we have a beauty baryon (containing a b quark).
- It's mass is ~6x larger than that of a proton.

Q: Are there baryons other than protons and neutrons?

- **Absolutely!** **Actually, there are a lot more!**
- So, how many possible baryons are there?
  - 5 x 5 x 5 = **125 possible baryons**.

But there's more !!

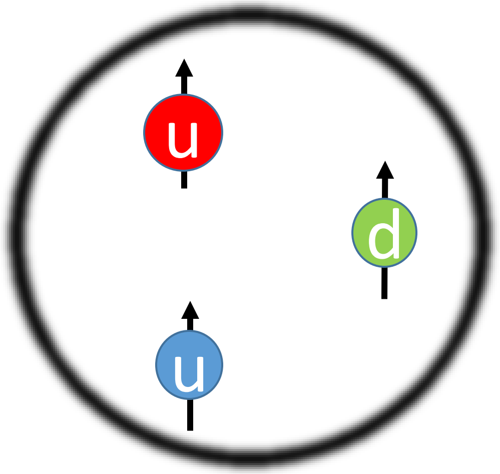
Proton



Spin: (½ + ½ - ½) = **½ ℏ**.

Mass = 938 MeV/c^2

Δ⁺



Spin: (½ + ½ + ½) = **3/2 ℏ**.

Mass = **1232 MeV/c^2**

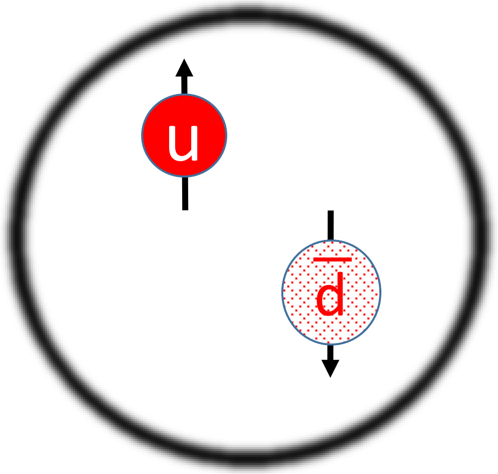
- Δ^+ also has (u u d)!
- But, Δ^+ is considered a **different particle** because mass, spin differ from the proton.
- Also, **Δ^+ baryon** is unstable and decays.
- **3 unstable brothers!**
  Δ^{++}(*uuu*), Δ^- (*ddd*), Δ^- (*udd*)

- **Each of the 125 baryons can have many "excited states", each one is its own particle!**

- **Baryons can only have ½ integer spin** (1/2, 3/2, 5/2 …) [**Fermions**]

Q: Can quarks combine in other ways (than sets of 3)?

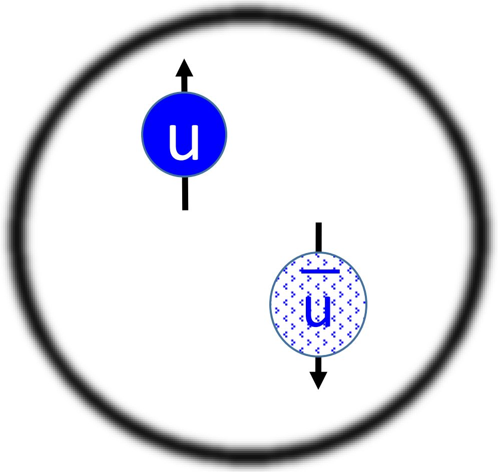
- ❑ **Absolutely!**
- ❑ A quark & antiquark can combine to form "**mesons**".
  - ❑ Lightest formed from **up** & **down** quarks.
  - ❑ Even # quarks → integer spin [**bosons**].
  - ❑ All mesons are unstable, and decay to lighter particles.



π^+

Spin: (½ - ½) = **0**

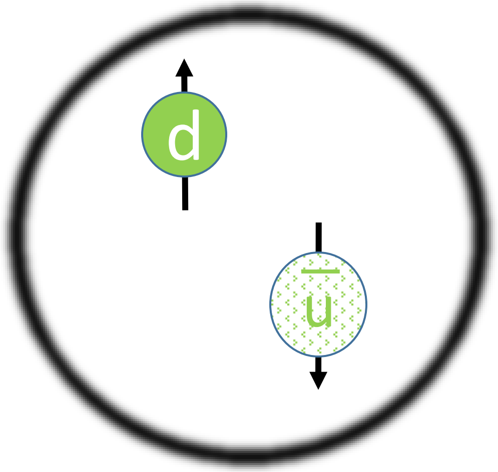
Mass = 139.6 MeV/c^2



π^0

Spin: (½ - ½) = **0**

Mass = 135 MeV/c^2



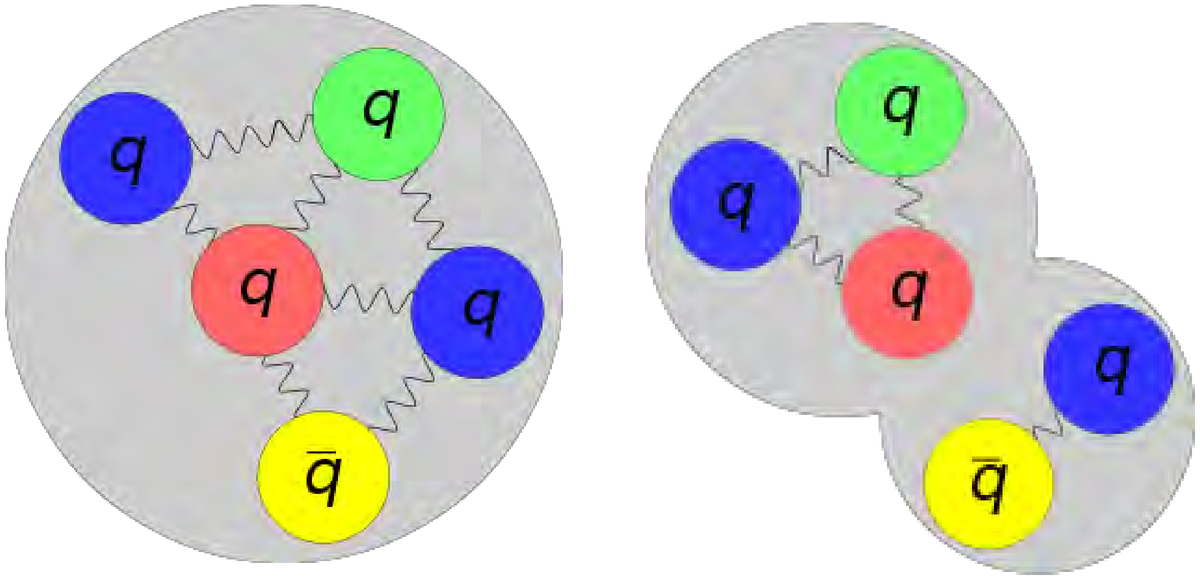
π^-

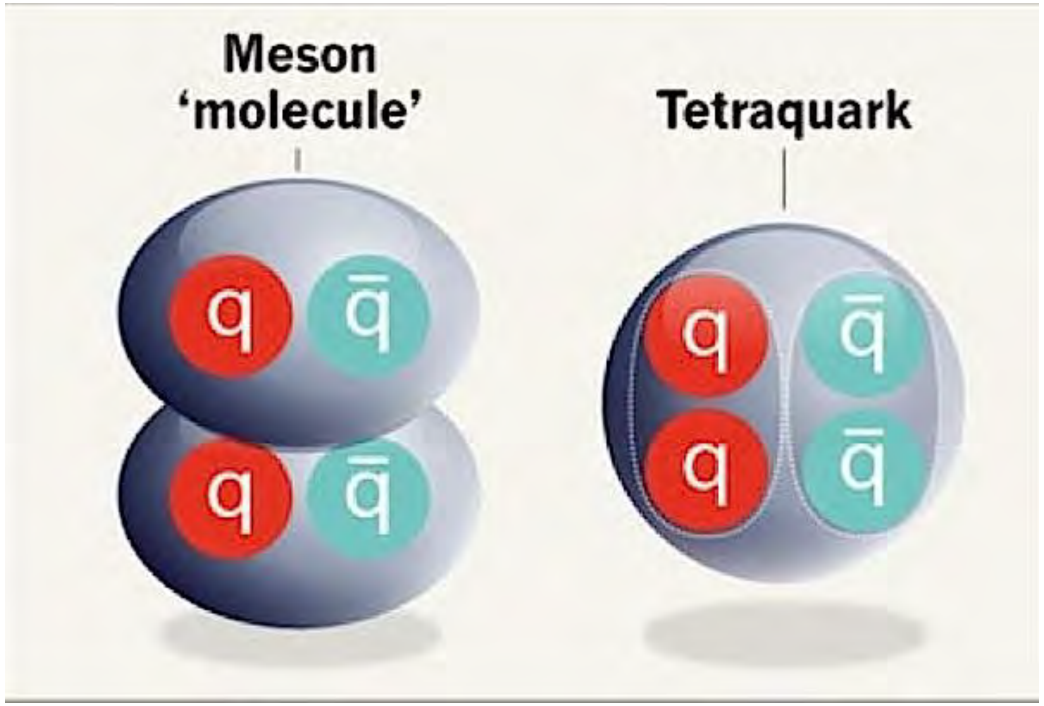
Spin: (½ - ½) = **0**

Mass = 139.6 MeV/c^2

Other funky states?

- ❑ The quark model permits other "color-neutral" combinations





- ❑ Pentaquarks: 4 quarks + 1 antiquark
- ❑ States with 2 quarks + 2 antiquarks

- ❑ Other combinations possible (e.g. 3 quarks + 3 antiquarks)
- ❑ No time to get into details here, but our group has done a lot on these states in the last few years.

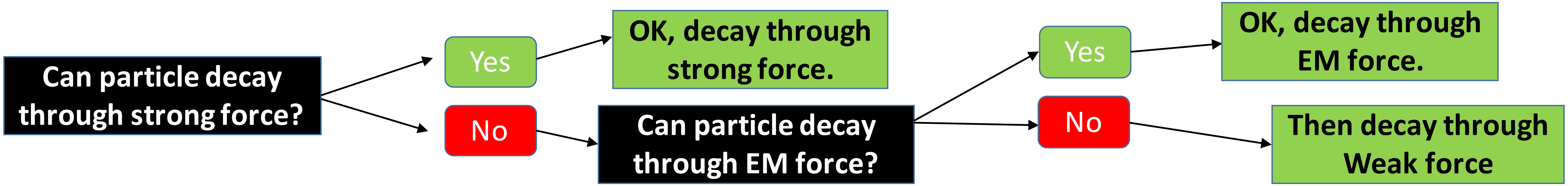
- OK, we've talked about how to make particles in the Standard Model.

- Let's spend a few minutes to learn how they interact.

- We'll focus on decay, since most particles in fact do decay.

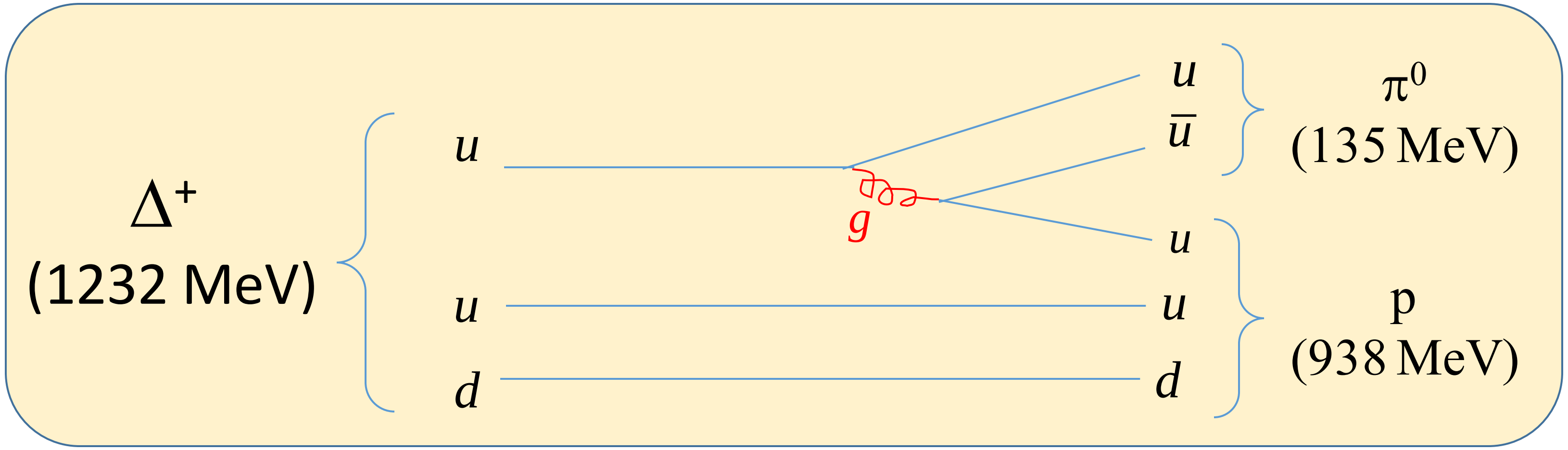
Q: How does the Δ^+ decay?

- In general, particles will decay by the "strongest possible force".



- There are rare exceptions, but this usually holds true.

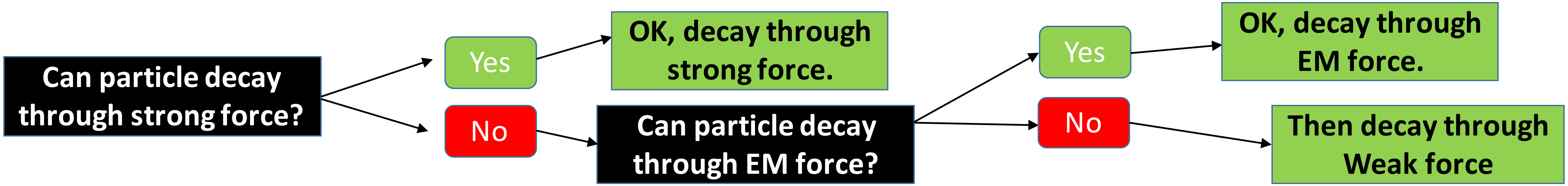
- Often use so-called **Feynman diagrams** to represent **interactions or decays**.
  The Δ^+ decay could be drawn as:



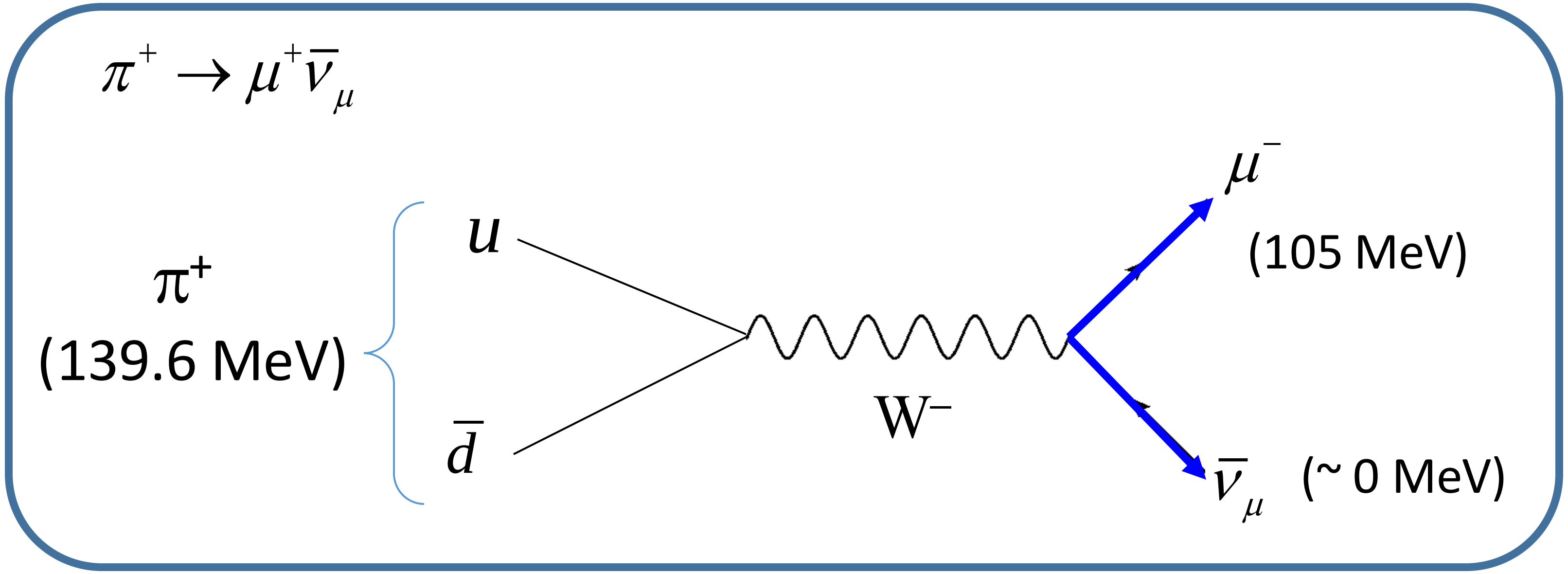
- Note: **energy is conserved, not mass !**

- We know it's a **strong decay** because it is mediated by a gluon (***g***).

Q: What about the π^+ ?

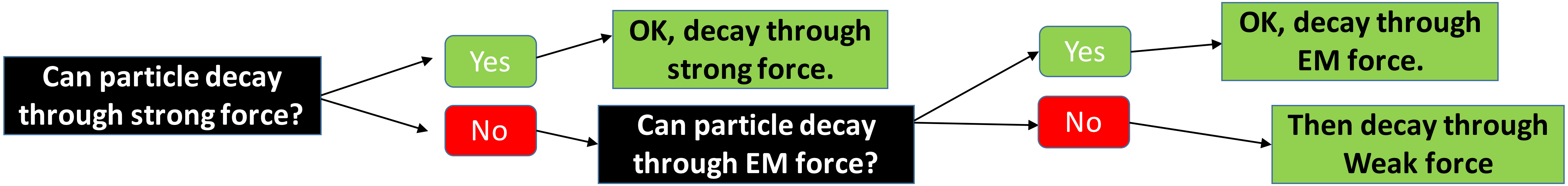


- ❑ Since the π^+ is the lightest meson, it cannot decay to other mesons. **No strong decay allowed**!
- ❑ Since the photon cannot make it's + charge "disappear", **EM decay not allowed**.
- ❑ Only thing left is weak decay!

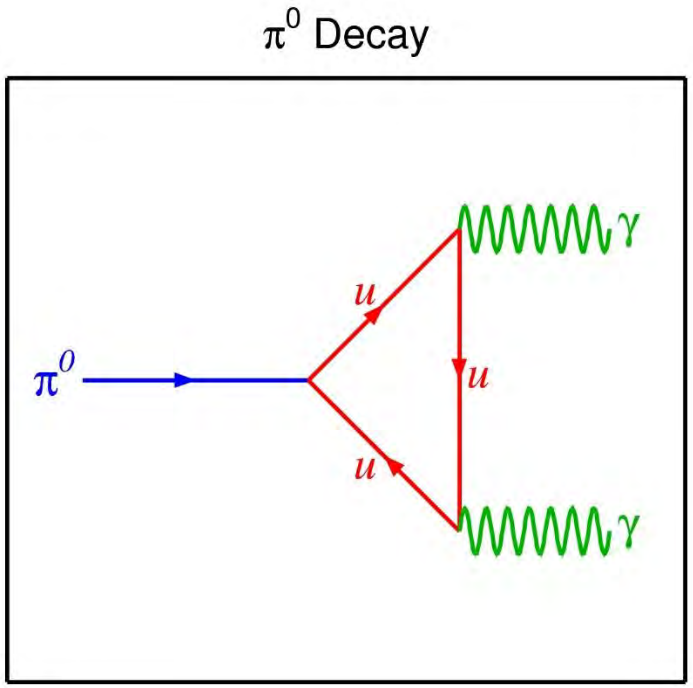


- ❑ It decays this way 99.98% of the time.

What about the π^0?



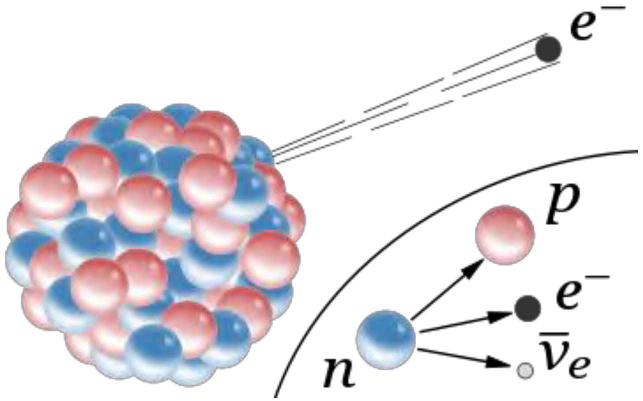
- ❑ Because the π^0 actually can decay via the EM force, it does!
- ❑ The dominant decay is **$\pi^0 \rightarrow \gamma\gamma$.**
- ❑ **No weak or strong decay!**



- ❑ 98.8% probability it decay this way.

β decay

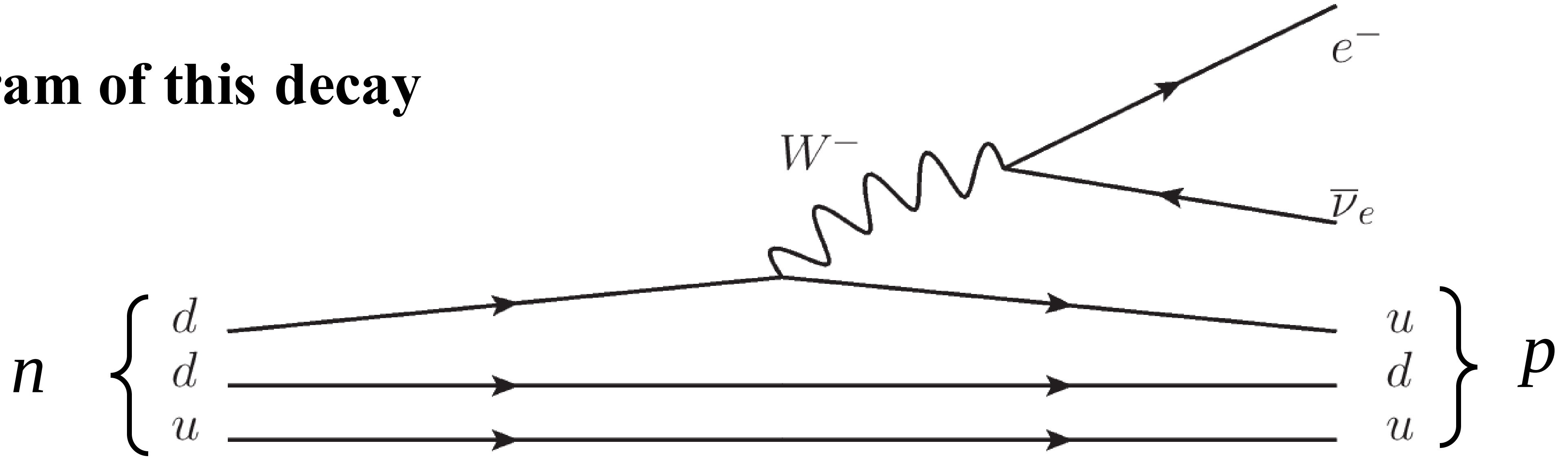
- ❑ **Radioactive nuclei can undergo beta decay, for example:** $^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-} + \overline{\nu}_{e}$



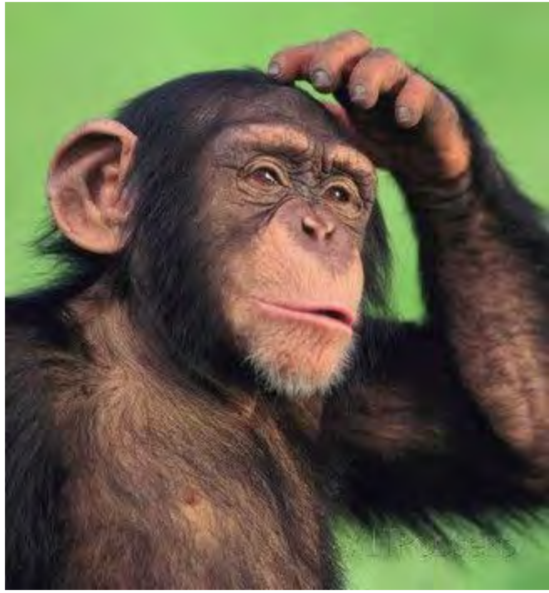
- ❑ The electron has large KE, and comes shooting out of the nucleus (as does the neutrino).
- ❑ The proton "*stays put*", and leads to an increases Z by 1 unit (with no change in atomic mass)

- ❑ **Half-life = 5700 years**

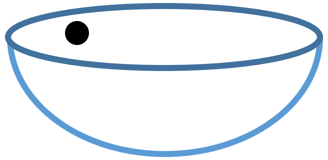
- ❑ **Feynman diagram of this decay**



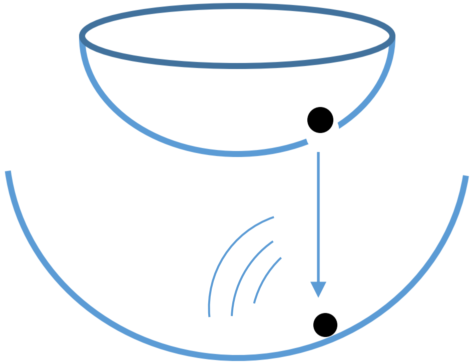
Particle decays



- ❑ It is interesting to note that **particle decay** is "**normal**", and "**stability is odd**".
- ❑ Y'all know, if a system can reach a lower energy / more stable state, **it will do it**.



- ❑ Consider a small ball I bowl with some total energy & no energy loss.
- ❑ KE ←→ PE, but **E_{tot} always stays the same**.
- ❑ The system is **infinitely stable**. It would never cease to exist.

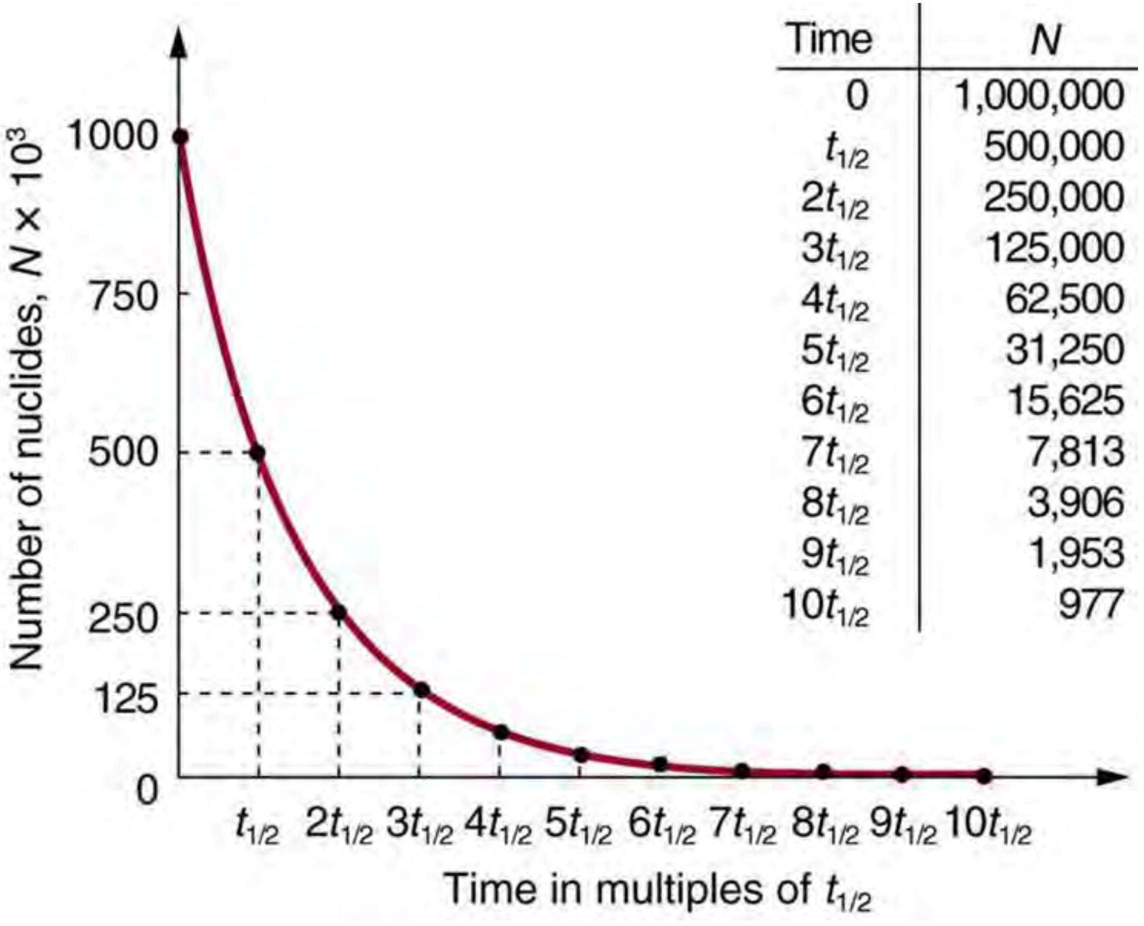


- ❑ Now, imagine I drill a small hole, just big enough for the ball to get out.
- ❑ After some amount of time, the ball **will drop to the lower energy state**.
- ❑ **The ball has "no choice"!** It will eventually happen, and **the initial state will cease to exist**.
- ❑ In it's place is a new lower energy state.

- ❑ **Analogously, if a particle can decay to a lower energy state, it will, with some characteristic time, called the lifetime.**
- ❑ **The only way a particle will not decay, is if the laws of physics forbid it!**

Lifetime

- Unstable particles/nuclei follow an exponential decay law



Time	N
0	1,000,000
$t_{1/2}$	500,000
$2t_{1/2}$	250,000
$3t_{1/2}$	125,000
$4t_{1/2}$	62,500
$5t_{1/2}$	31,250
$6t_{1/2}$	15,625
$7t_{1/2}$	7,813
$8t_{1/2}$	3,906
$9t_{1/2}$	1,953
$10t_{1/2}$	977

- Many sciences use the “half-life” to measure radioactivity.
- This curve is an exponential function.
- Particle physicist use a quantity called the **lifetime,** τ.

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

- You can easily show that:

$$T_{1/2} = 0.693\tau$$

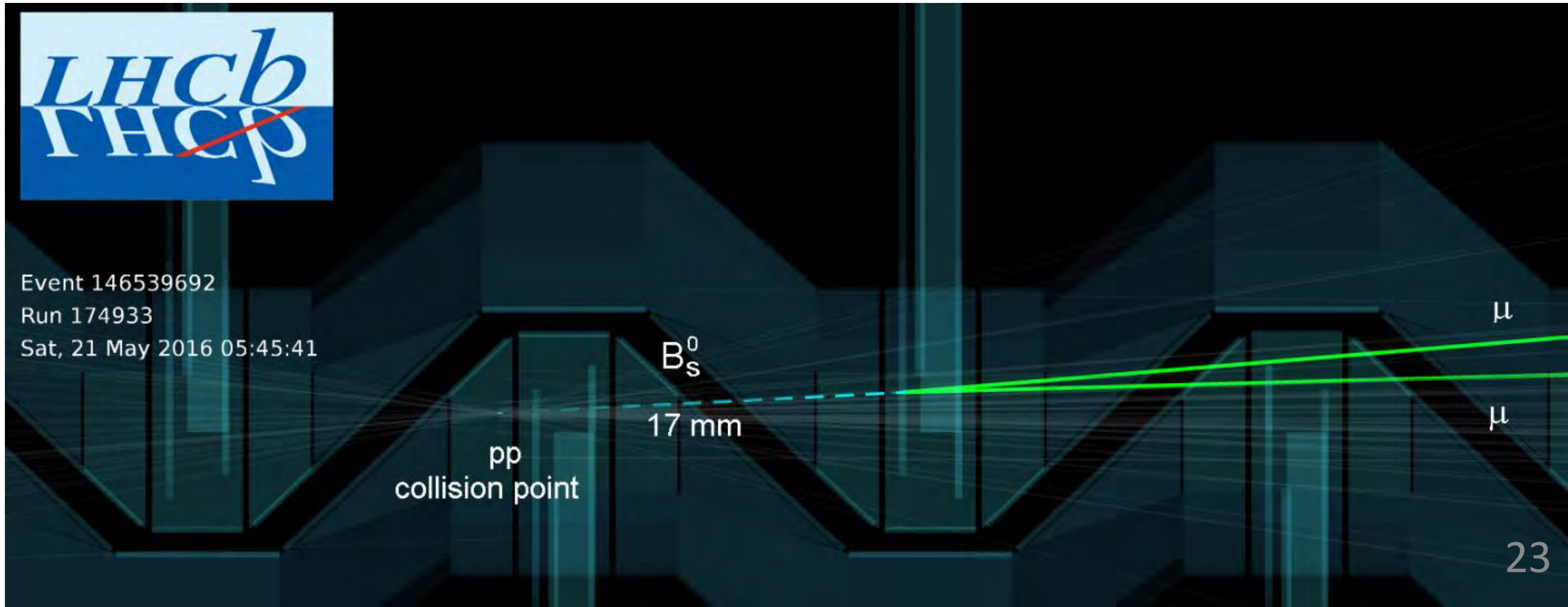
- In either case, it’s just **a measure of how quickly the particle in question decays to something else**.

Typical particle lifetimes

In the rest frame of the decaying particle:

- **Strong force decays:** ~10^{-23} sec. This is immeasurably small.
- **EM force decays:** ~$10^{-19} – 10^{-20}$ sec Again too small to ever measure.
- **Weak force decays:** ~$10^{-6} – 10^{-13}$ sec.

- **Example: A B_s^0 meson ($\bar{b}s$) has a lifetime of ~ 1.5 x 10^{-12} sec.**
  - In the lab frame, $< d > \approx \gamma ct \sim$ **10 mm.**
  - **We can actually observe the B_s^0 meson decay!**
  - **This is what we do all the time in LHCb, and measure interesting effects that can occur in B mesons.**
  - **This decay is extremely rate, and only occurs ~1 out of a billion times.**



So, why don’t protons and electrons decay?

- ❑ Because nature forbids it !
- ❑ Any decay you can think of would violate some “sacred” conservation law.

- ❑ So, in the Standard Model, the proton & electron do not decay!

- ❑ **People intensely look for proton decay, because if you it, you will have disproven the Standard Model!**

Summary

- I hope this brief overview has given you a deeper understanding of particle physics, and some of its fundamental aspects.
- There is so much more. You can find more details from our Quarknet 2012 http://hepoutreach.syr.edu/QuarkNet/QuarkNet%202012%20f/Lectures%202012.html

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{2}\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\,W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& +(D_\mu\phi)^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \frac{1}{2}\lambda\left(\phi^\dagger\phi\right)^2 \\
& +\sum_{f=1}^{3}\left(\bar{\ell}^f_L i\not{D}\ell^f_L + \bar{\ell}^f_R i\not{D}\ell^f_R + \bar{q}^f_L i\not{D}q^f_L + \bar{d}^f_R i\not{D}d^f_R + \bar{u}^f_R i\not{D}u^f_R\right) \\
& -\sum_{f=1}^{3} y^f_\ell\left(\bar{\ell}^f_L\phi\ell^f_R + \bar{\ell}^f_R\phi^\dagger\ell^f_L\right) \\
& -\sum_{f,g=1}^{3}\left(y^{fg}_d\bar{q}^f_L\phi d^g_R + (y^{fg}_d)^*\bar{d}^g_R\phi^\dagger q^f_L + y^{fg}_u\bar{q}^f_L\tilde{\phi}u^g_R + (y^{fg}_u)^*\bar{u}^g_R\tilde{\phi}^\dagger q^f_L\right),
\end{aligned}
$$

Questions ?