The Standard Model

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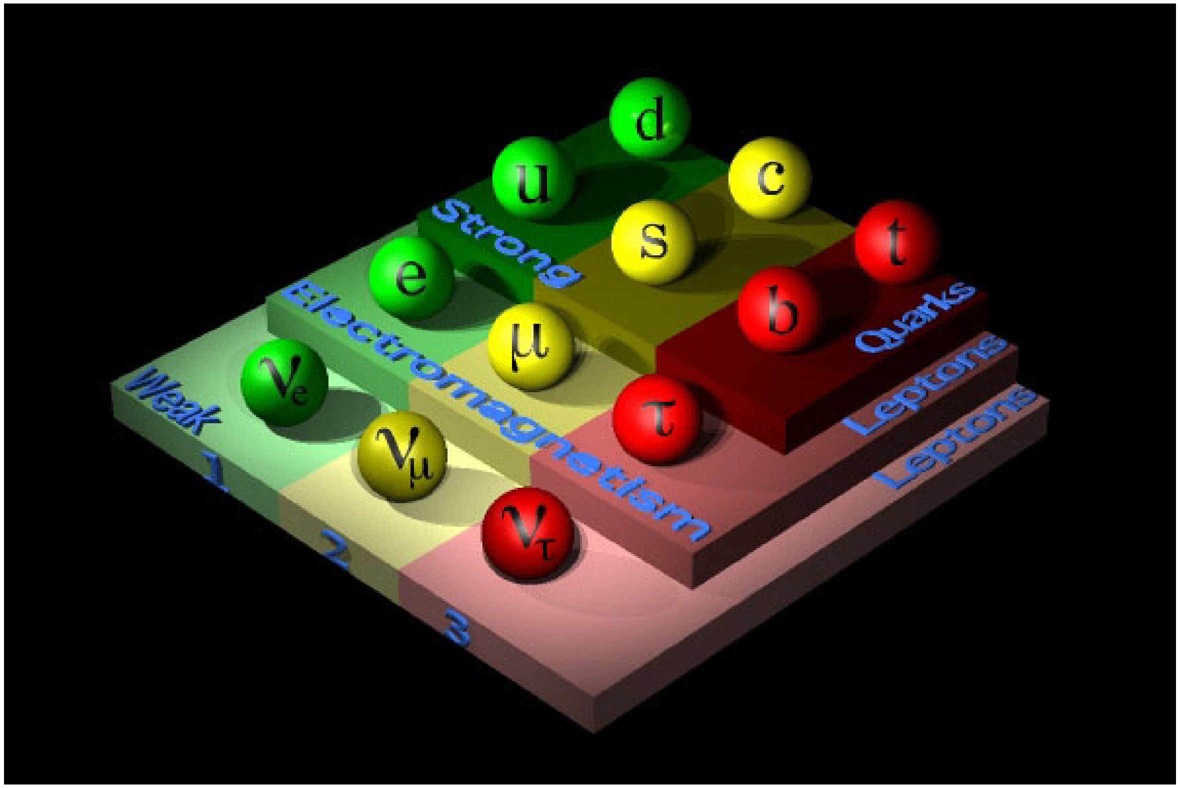


Science is an evolution

- ☐ Do the laws of nature lead to **a single fundamental theory of matter and forces** ?
- ☐ Up to now, laws of physics are almost certainly **effective theories**
  - ☐ Only guaranteed to be correct within the regime it is tested.

☐ Example 1:

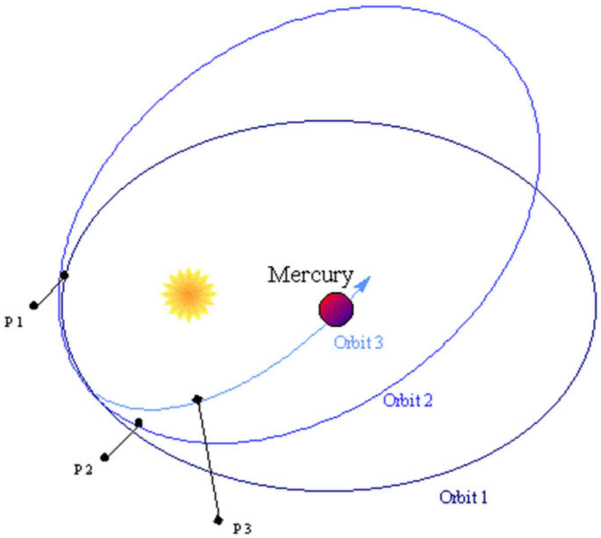
- ☐ **Precession of Mercury confronts Newton → General Relativity.**

☐ Example 2:

- ☐ **The atom confronts classical theories → Quantum mechanics**

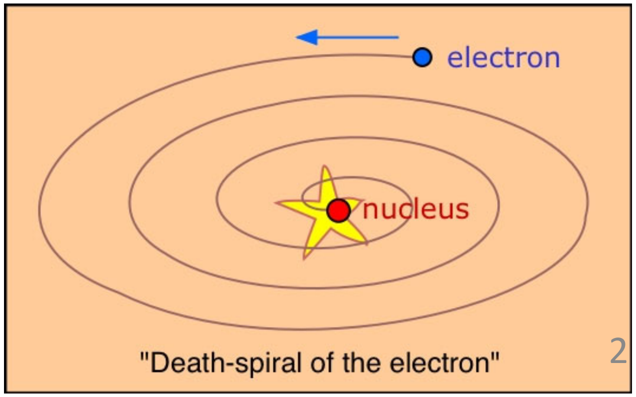
☐ But, we have a problem:

- ☐ 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?**



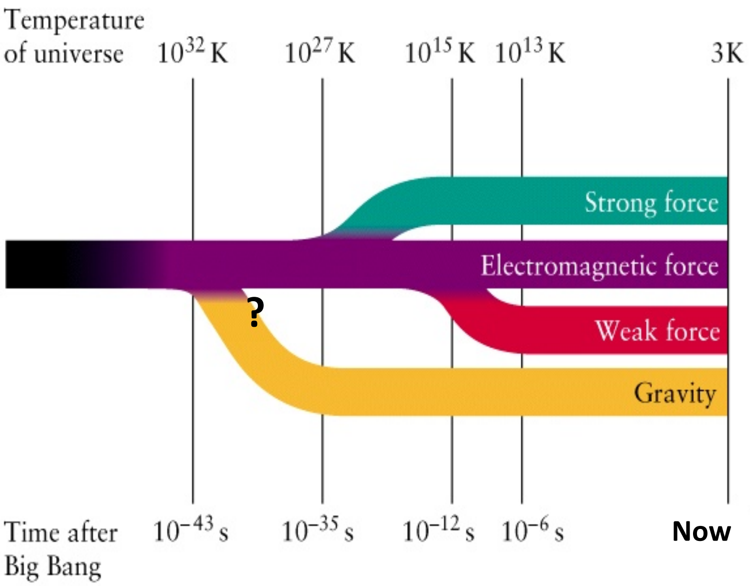
Physical Laws must be Unified

(presumably into a new theory)



"Death-spiral of the electron"

Towards unification of the forces

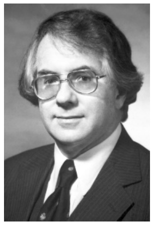


- ☐ **In 1860's, Maxwell** unified electricity, magnetism and light into **Electromagnetism** (classical) [**superseded by QED**]

1831-1879

$$\nabla\cdot\mathbf{E}=\frac{\rho}{\varepsilon_0}$$
$$\nabla\cdot\mathbf{B}=0$$
$$\nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$$
$$\nabla\times\mathbf{B}=\mu_0\mathbf{j}+\frac{1}{c^2}\frac{\partial\mathbf{E}}{\partial t}$$

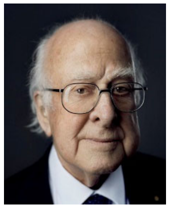
- ☐ **In 1967**, **Weinberg & Salam** unified the EM & **Weak forces** (**Electroweak [EW] force**).
  - ☐ Predicted $W^{\pm}$, Z^0 bosons discovered at CERN. **1979 Nobel prize to W&S.**



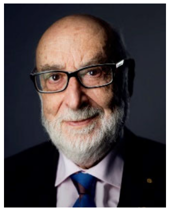
1933 -

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 -

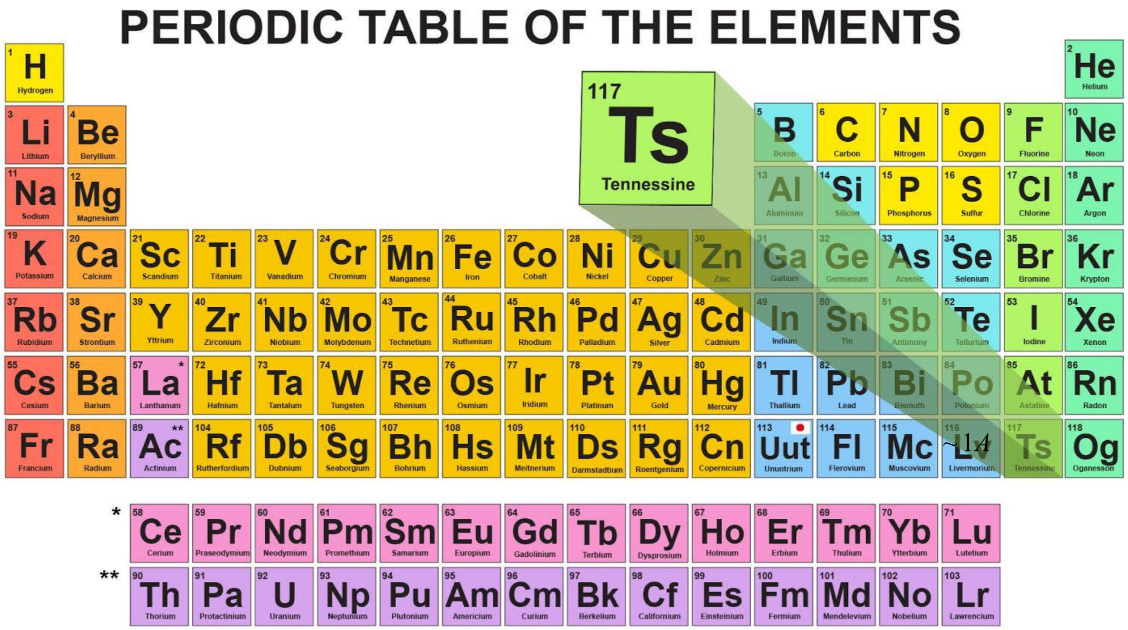


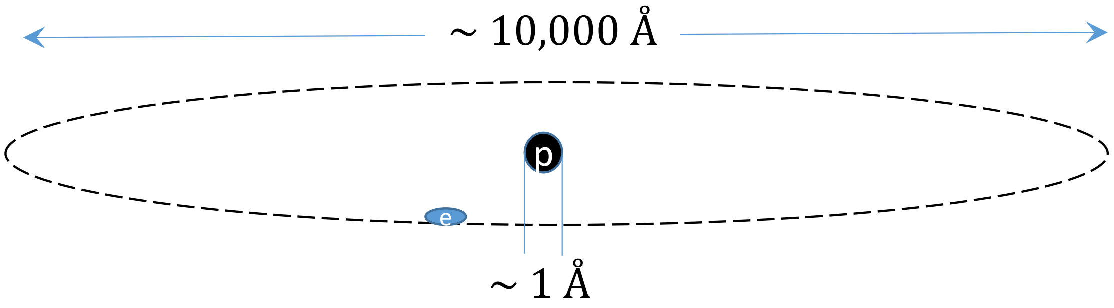
1932 -

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 …

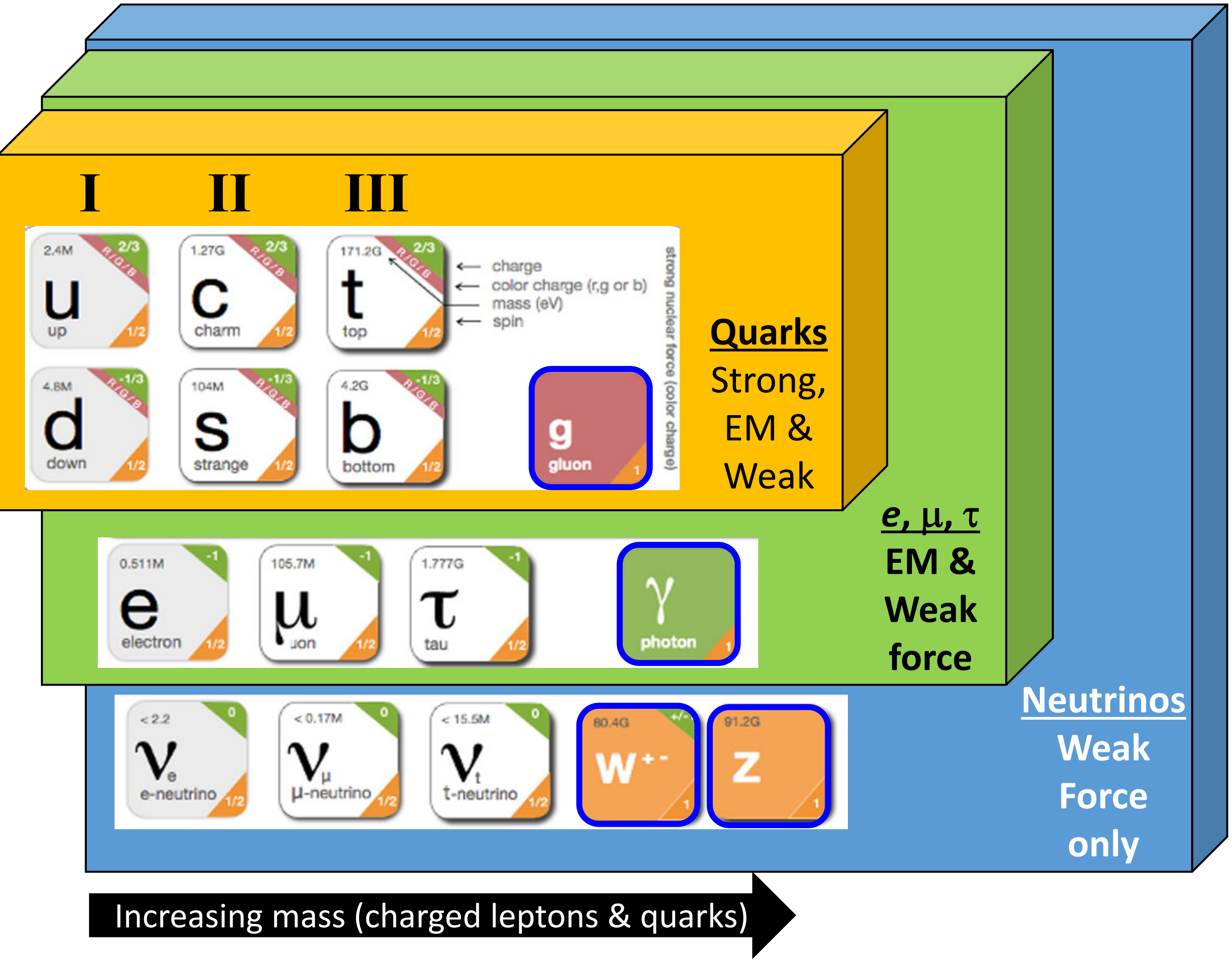




- As humans, we naturally seek some sort of “order”..

- 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



Quarks
Strong, EM & Weak

e, μ, τ
EM & Weak force

Neutrinos
Weak Force only

Increasing mass (charged leptons & quarks)

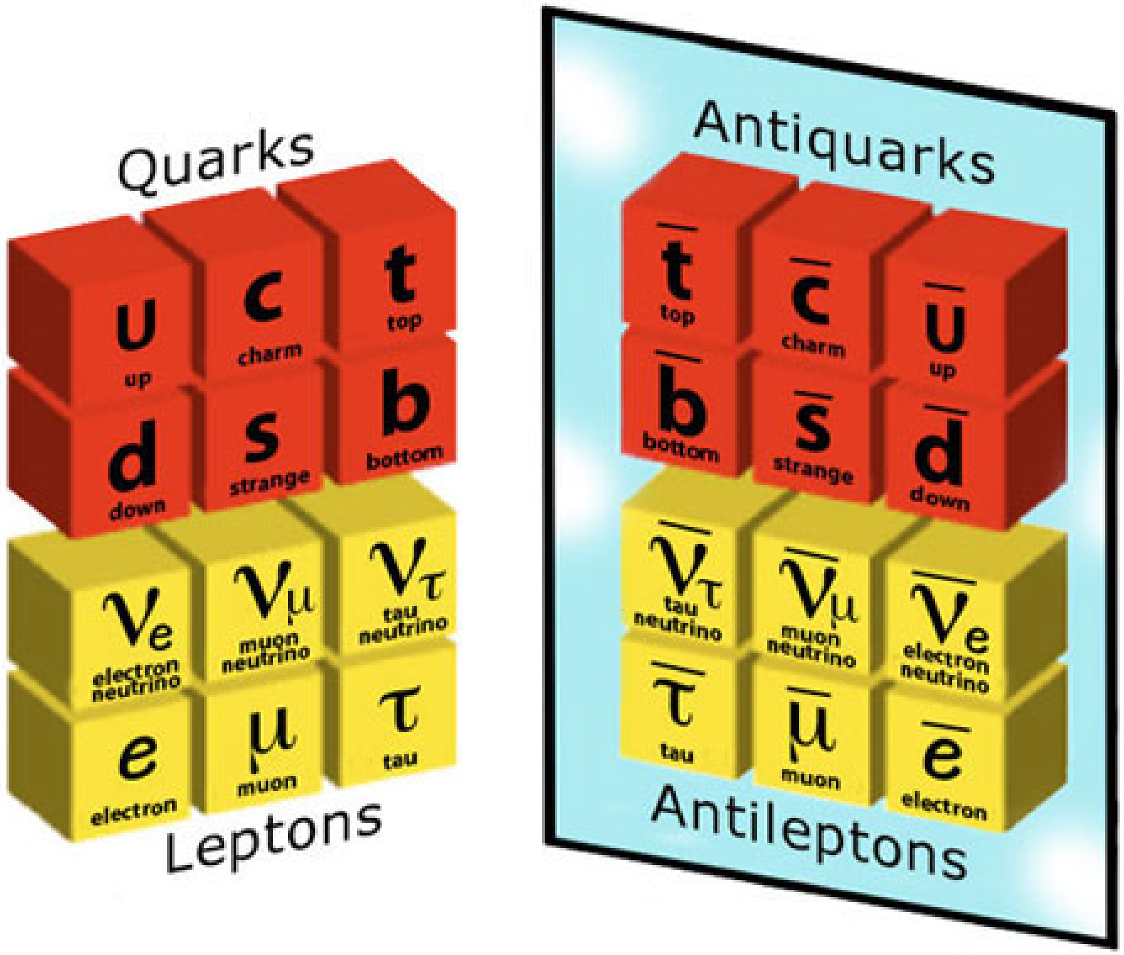
- ☐ **Matter particles consist of:**
  - ☐ 3 "families" of quarks.
    3 families of leptons
- ☐ Particle in families II, III are unstable and **decay** into family I (excluding neutrinos).

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

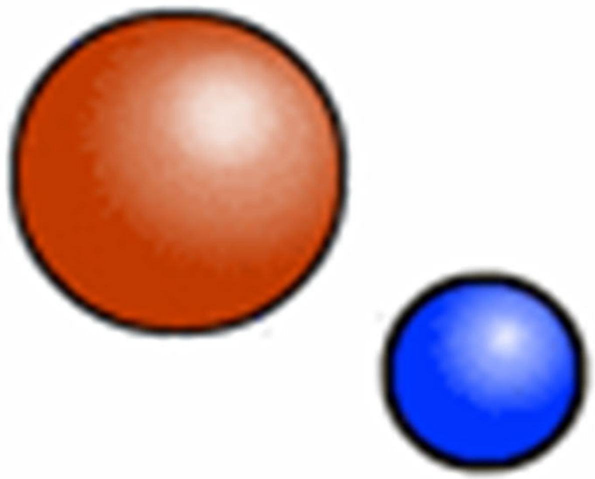
- ☐ **Force carriers** only interact with particles carrying the **correct charge**.
  - ☐ Quarks: Color, electric & weak
  - ☐ e^-, μ^-, τ^-: Electric, weak
  - ☐ Neutrinos: Weak

Antiparticles

- All of the matter particles have corresponding *antiparticles*.
- 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?**

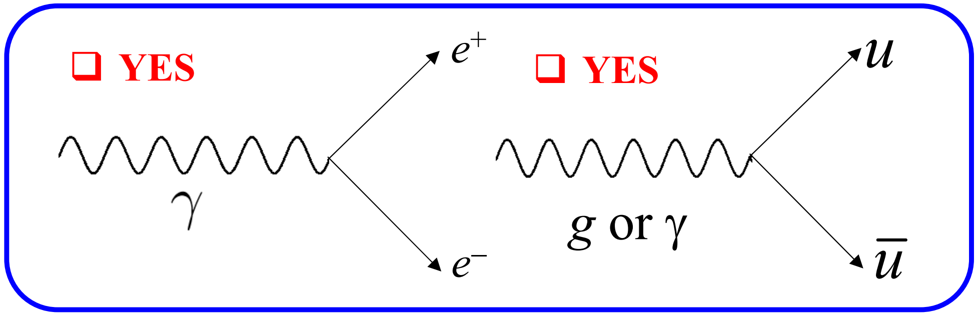


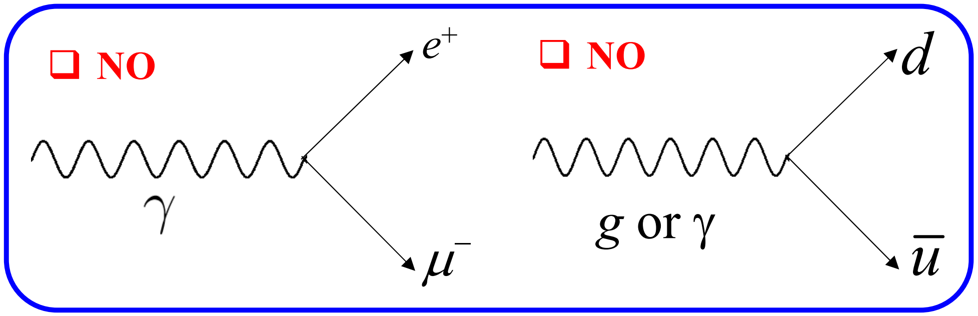
Modern view of fundamental forces



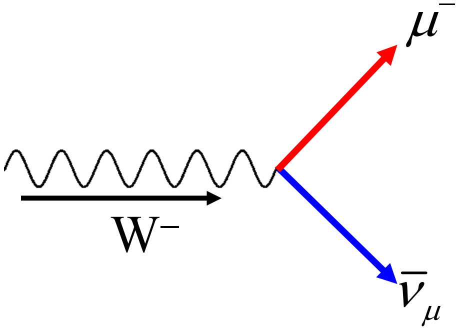
- ☐ **Force** == exchange of force carriers between particles carrying "*correct*" charge
- ☐ For an atom, photons are continuously exchanged between electrons and protons.

How do Strong, EM and Weak decays differ?

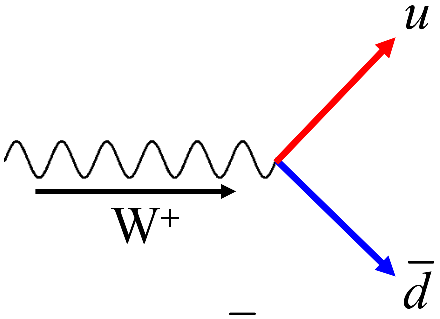




- ☐ Strong and EM forces can **only** produce $q\bar{q}$ or $\ell^+\ell^-$ **of same type**.
- ☐ However, the W$^+$ and W$^-$ (**weak interaction**) are charged!

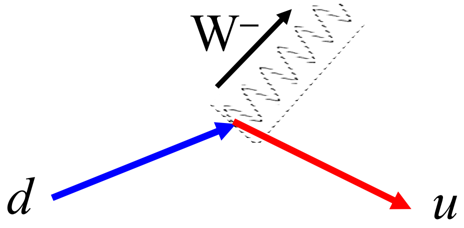


$W^- \to \mu^- \bar{\nu}_\mu$



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

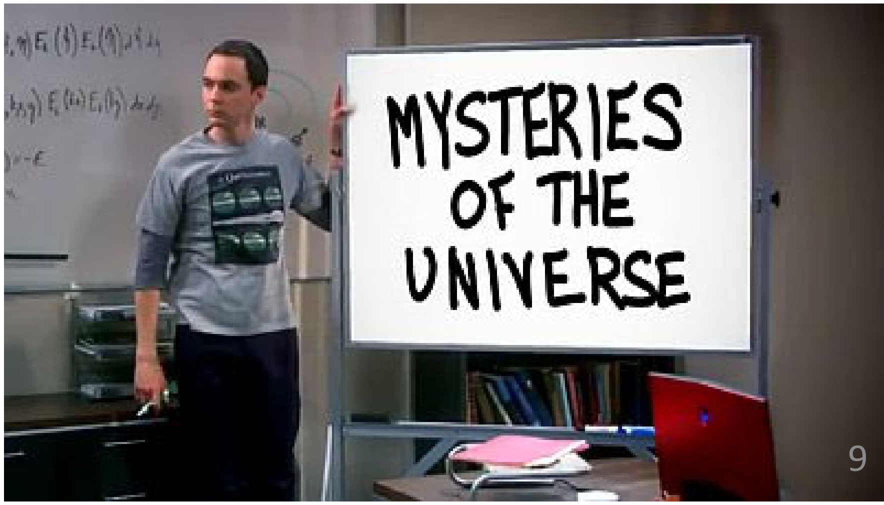
- ☐ The W$^-$ can also "mediate" the transition of a d into a u quark (or a lepton into a neutrino).
- ☐ Strong & EM forces cannot!



$d \to uW^-$

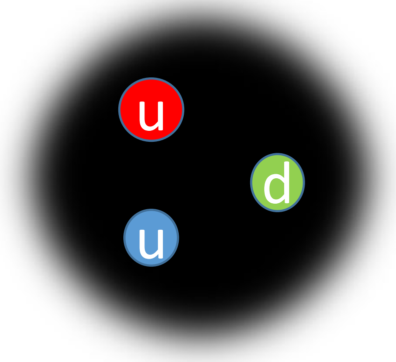
With this model, we can begin to ask, and answer, some basic questions that arise.

- ☐ And maybe even answer some of the



Q: How are protons and neutrons formed?

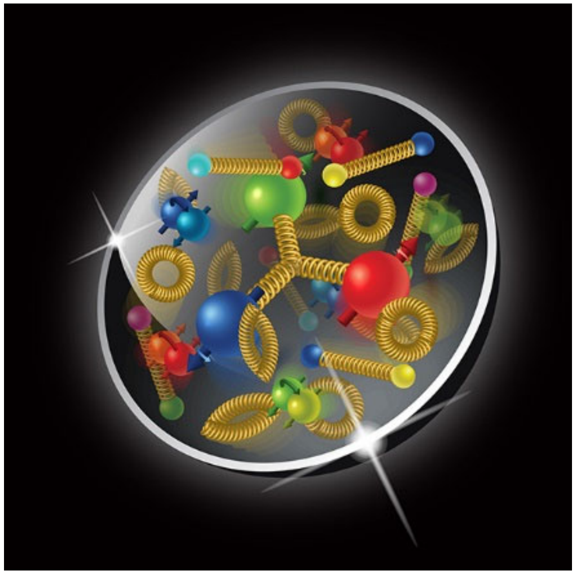
- Protons and neutrons belong to a general class of particles called "**baryons**".
- **Baryons are formed when any 3 quarks (except top) bind together due to the strong force.**



Proton

Neutron

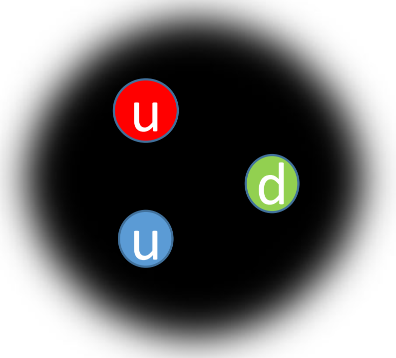
- Not to scale
- Quarks are at least 10,000x smaller than the proton.



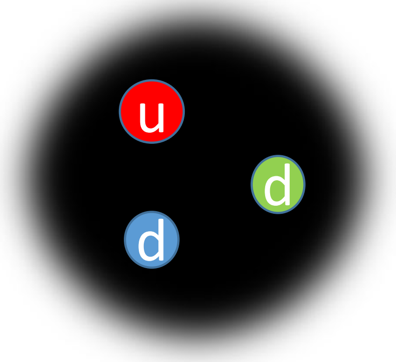
- **Interestingly, the proton and neutron only differ by an up quark being replaced by a down quark!**

Quarks carry a "charge" of the strong force!

- ☐ We know that particles carry *intrinsic properties* (mass, electric charge, spin, …)
  - ☐ 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**).
  - ☐ Gluons "see" the quark's **strong charge,** not their electric charge**.**
  - ☐ Within QCD, there is **strong attraction** when you have **one of each color**. Alternately, composite particles are "*color-neutral*" (r+g+b = neutral).



Proton



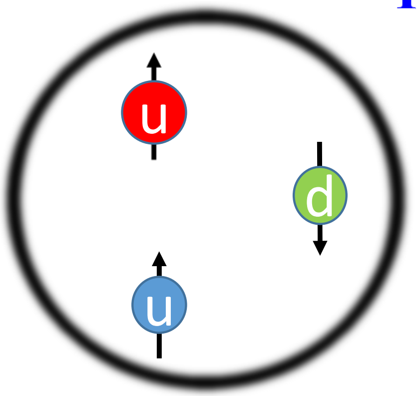
Neutron

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**.
- ☐ Baryons have ½ integer spin → **Fermions**

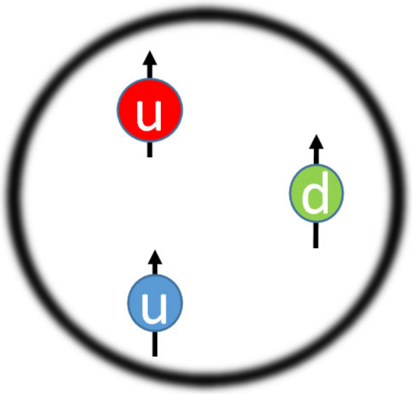
- ☐ Beauty baryon containing a *b* quark.
- ☐ Its mass is ~6x larger than that of a proton.

Proton



Mass = 938 MeV/c²

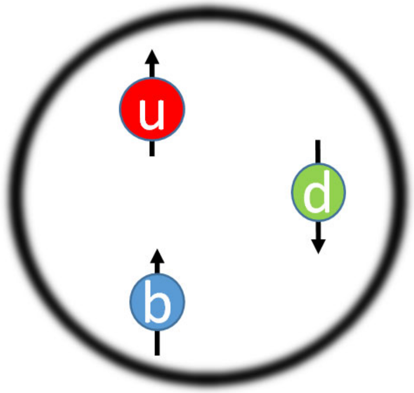
Δ^+



Spin: (½ + ½ + ½) = **3/2 ℏ**.

Mass = **1232 MeV/c²**

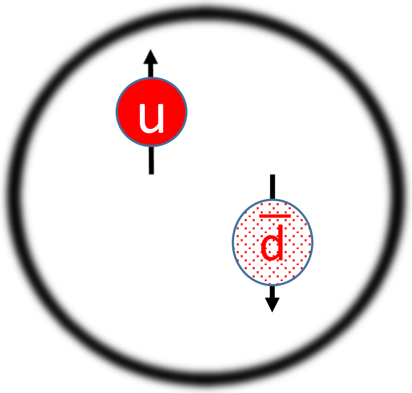
Λ_b^0



Mass = **5620 MeV/c²**

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

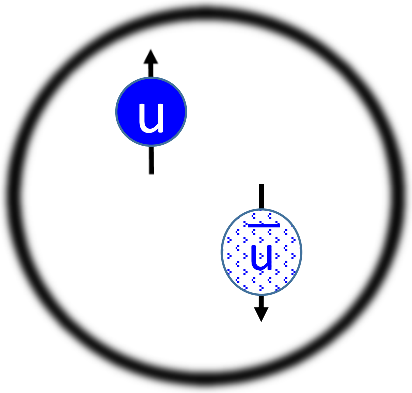
- **Absolutely!**
- A **quark & antiquark** can combine to form “**mesons**”.
  - Lightest mesons formed from **up** & **down** quarks.
  - Even # quarks → integer spin [**bosons**].
  - **All mesons are unstable**, and decay to lighter particles.
  - Quarks carry color, antiquarks carry anticolor.



π^+

Spin: (½ - ½) = **0**

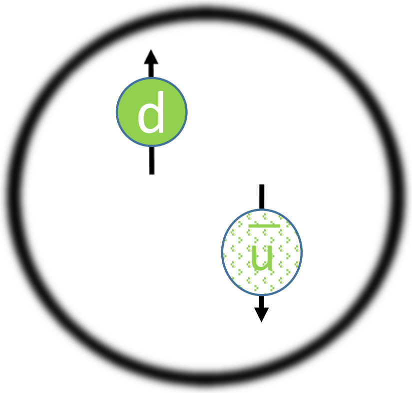
Mass = 139.6 MeV/c^2



π^0

Spin: (½ - ½) = **0**

Mass = 135 MeV/c^2



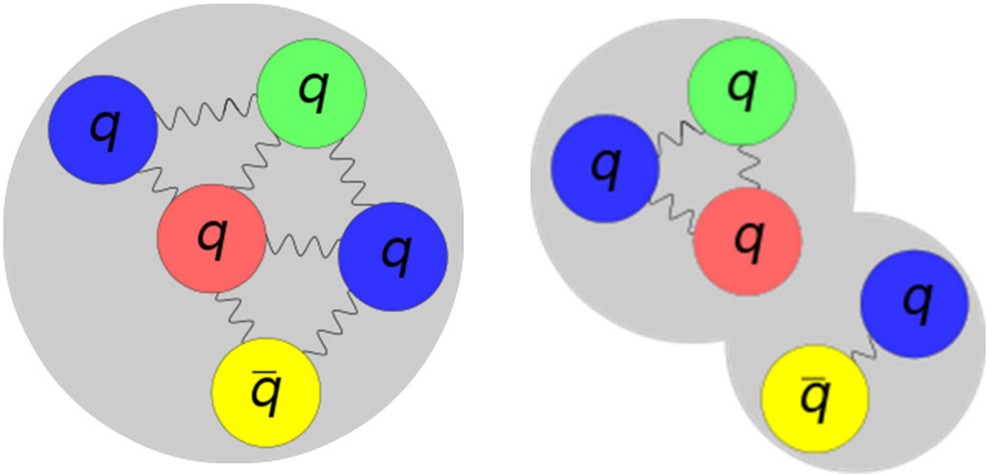
π^-

Spin: (½ - ½) = **0**

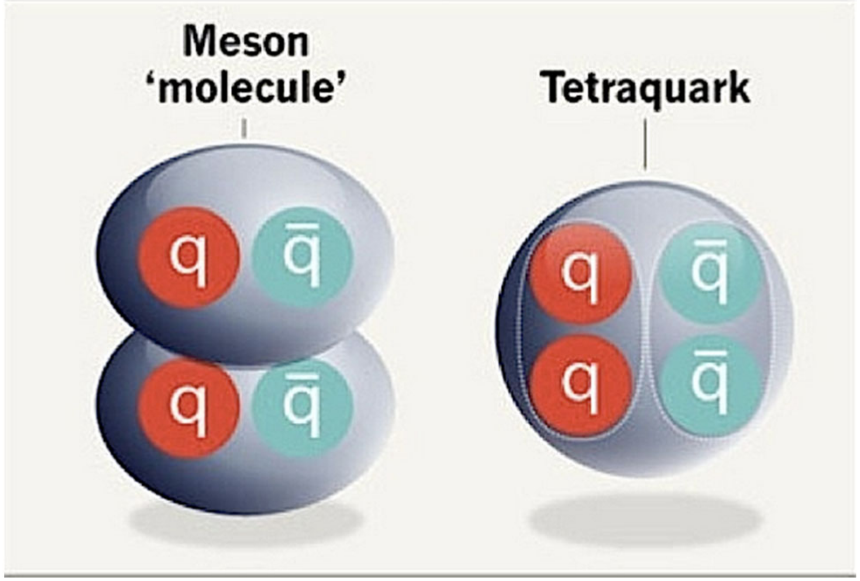
Mass = 139.6 MeV/c^2

Other funky states?

- The quark model permits other “color-neutral” combinations



- Pentaquarks: 4 quarks + 1 antiquark



- States with 2 quarks + 2 antiquarks

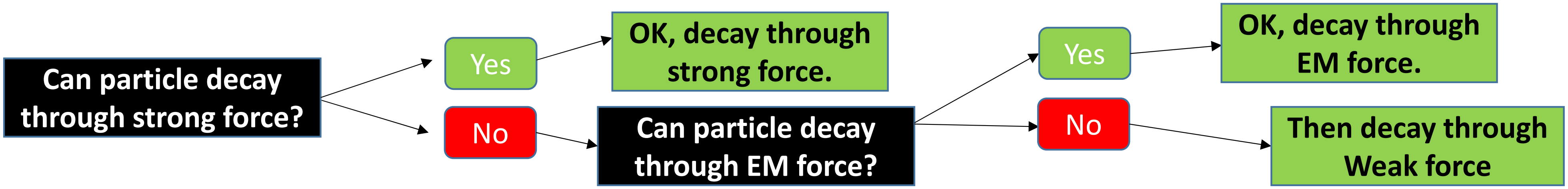
- Are other combinations possible?

- 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.

Why science teachers should not be given playground duty.

Q: How does the Δ^+ decay?

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


Can particle decay through strong force?

Yes

OK, decay through strong force.

No

Can particle decay through EM force?

Yes

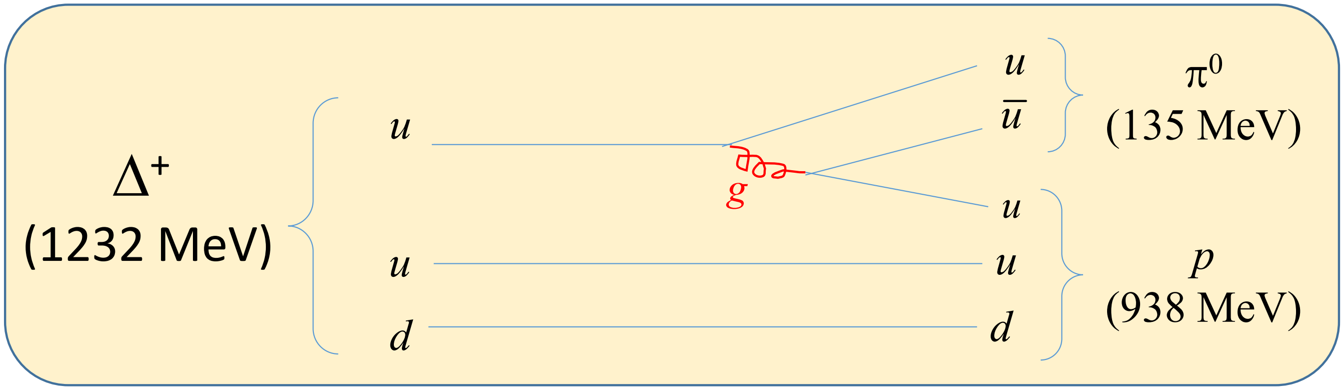
OK, decay through EM force.

No

Then decay through Weak force

- There are exceptions, but this usually holds true.

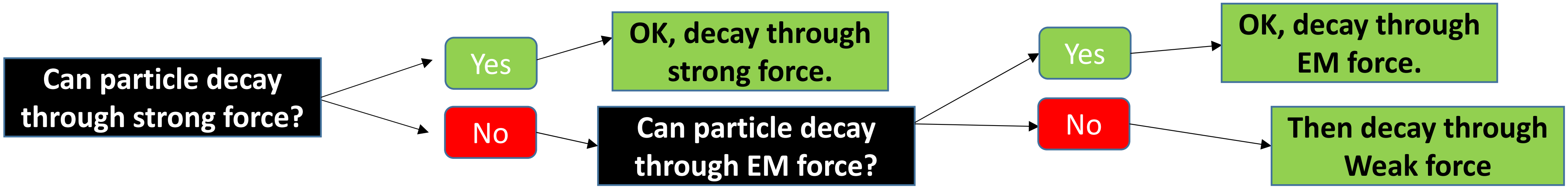
- Often use so-called **Feynman diagrams** to represent **interactions or decays**. The Δ^+ decay could be drawn as:



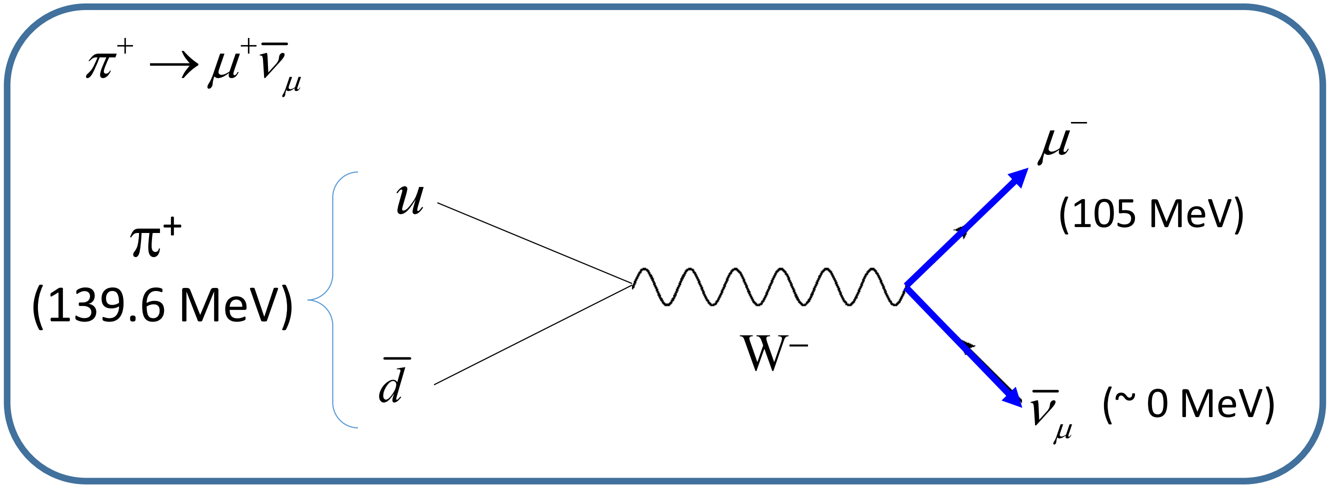
- Note: **energy is conserved, not mass !**

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

Q: What about the π$^+$?



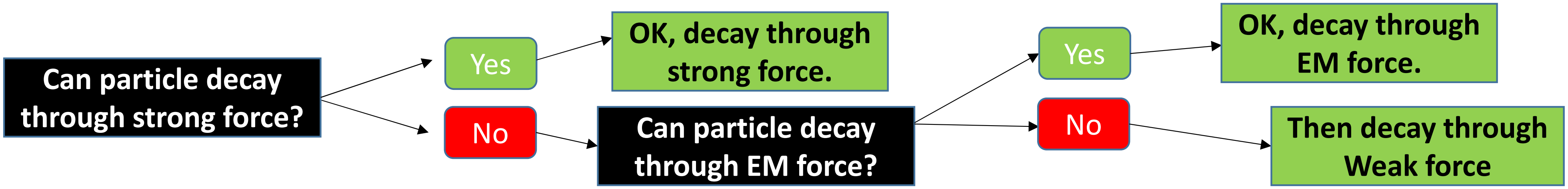
- Since the π$^+$ is the lightest meson, it cannot decay to other mesons. **No strong decay allowed**!
- Final state must have a charged lepton → Decay must "*annihilate*" the $u\bar{d}$ quarks.
- Only the weak interaction can do this!



$\pi^+ \to \mu^+ \bar{\nu}_\mu$

- It decays this way 99.98% of the time.

What about the π^0?



Can particle decay through strong force?

Yes

OK, decay through strong force.

No

Can particle decay through EM force?

Yes

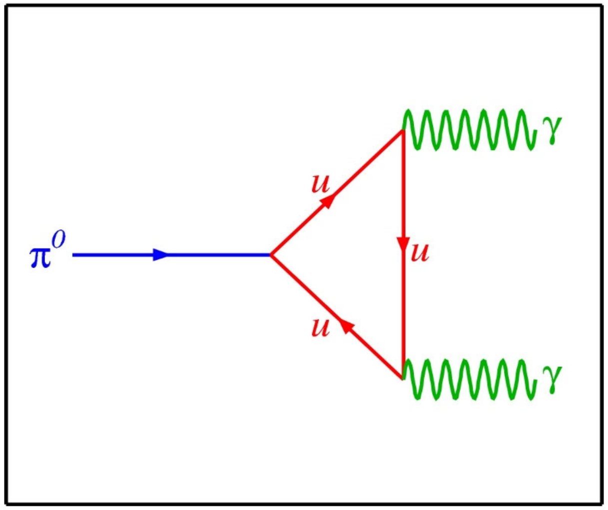
OK, decay through EM force.

No

Then decay through Weak force

- 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!**

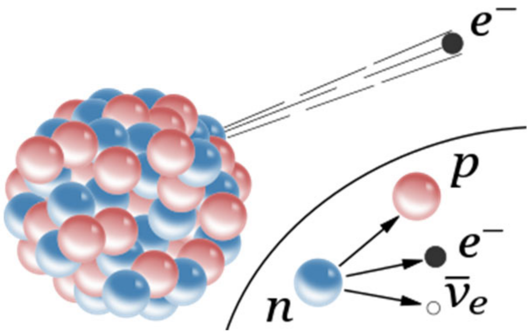
π^0 Decay



- 98.8% probability it decay this way.

β Decay (Example of a weak decay)

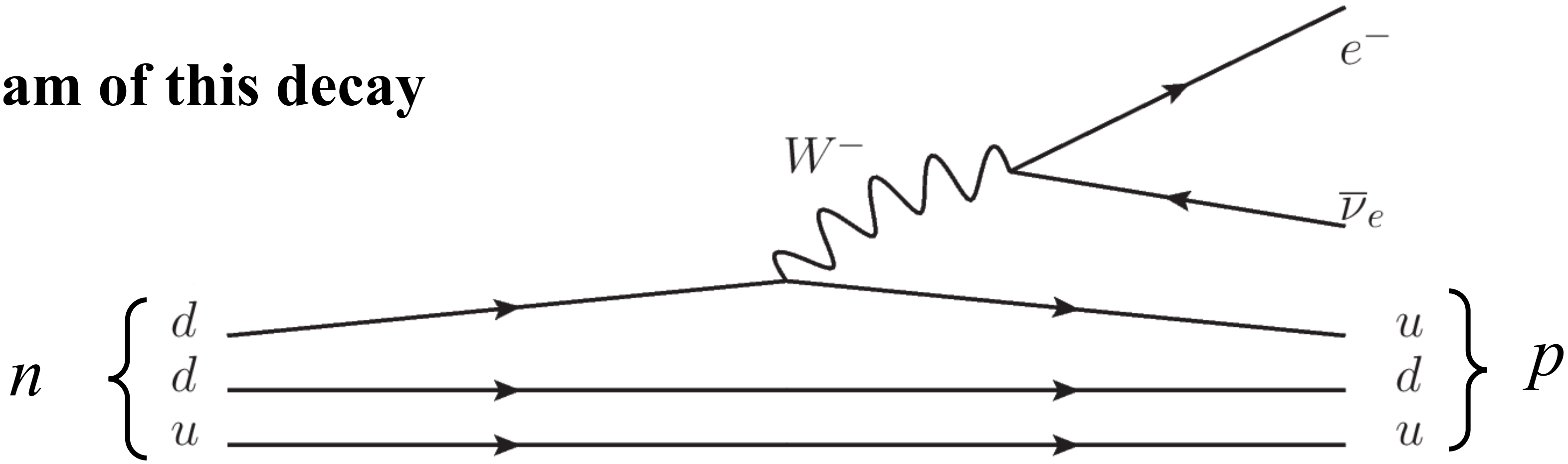
- **Radioactive nuclei can undergo beta decay, for example:** ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \overline{\nu}_{e}$



- 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**



Summary

- The Standard Model provides a very economical explanation of all particles we have observed to date (6 quarks, 6 leptons).
- The force carriers (γ, g, $W^{\pm}$, Z^0) describe how the quarks and leptons interact.
- The Higgs boson is responsible for particles acquiring mass
- But, It. Cannot. Be. The. End.
    - Dark Matter?
    - Why is the Universe is made almost entirely of matter?
    - How to “unify” strong and electroweak forces?
    - Then, how to include gravity?

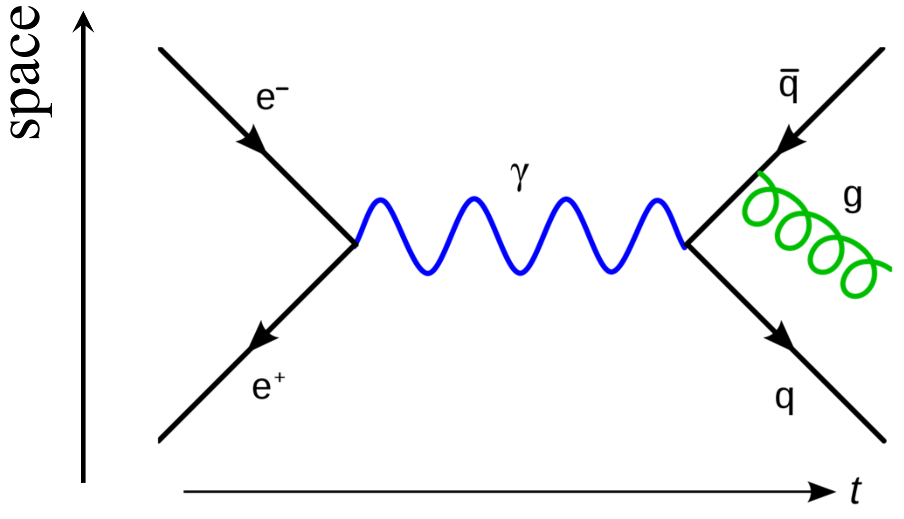
Your questions

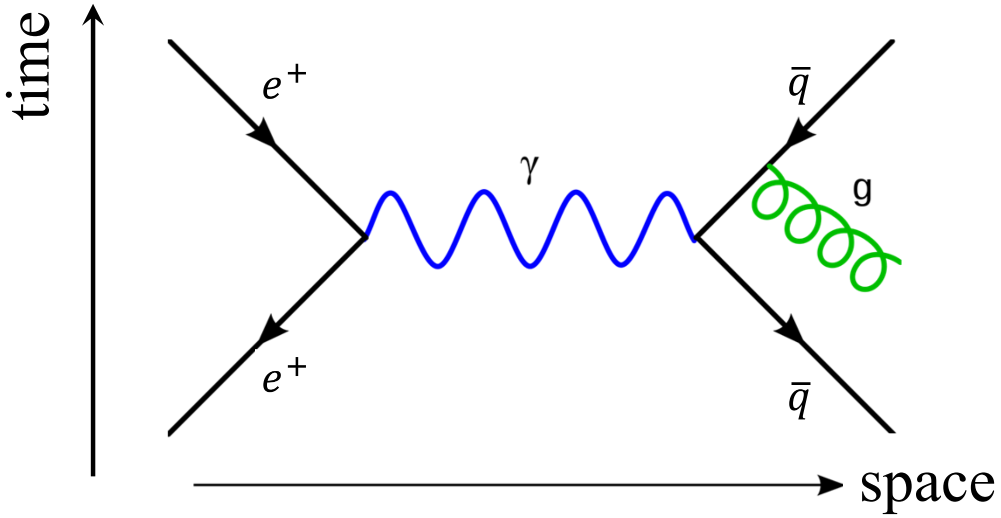
What exactly does the weak nuclear force do? Why is it important? How would life be affected if it didn't exist?

- **Nuclear β decay** (in many nuclear isotopes)
  → Engine for stars convert mass into energy → critical to life as we know it!
- **Decays of heavy quarks**: Without the weak force, heavy quarks *e.g.* (t, b, c, s), etc, would have no way decay! Also,the heavy charged leptons, $\mu^{\pm}, \tau^{\pm}$, also would have no way to decay.
  → Protons, neutrons and electrons would not longer be the only stable particles!
  → Could have an atom composed of a $\Lambda_b(bud) + \mu^-$!
  → Would have a greatly extended periodic table of elements, and forms of matter, molecules, etc that could form!
  → Life would likely have evolved very differently!

How does time factor into Feynman diagrams?

☐ Feynman diagrams give a pictorial representation of an interaction. The axes are time & space, as shown. But, beware, as there are 2 conventions, and many people have these axes flipped.





☐ This represents electron positron annihilation into a photon, which then produces a quark and an antiquark. The antiquark then radiates a gluon.

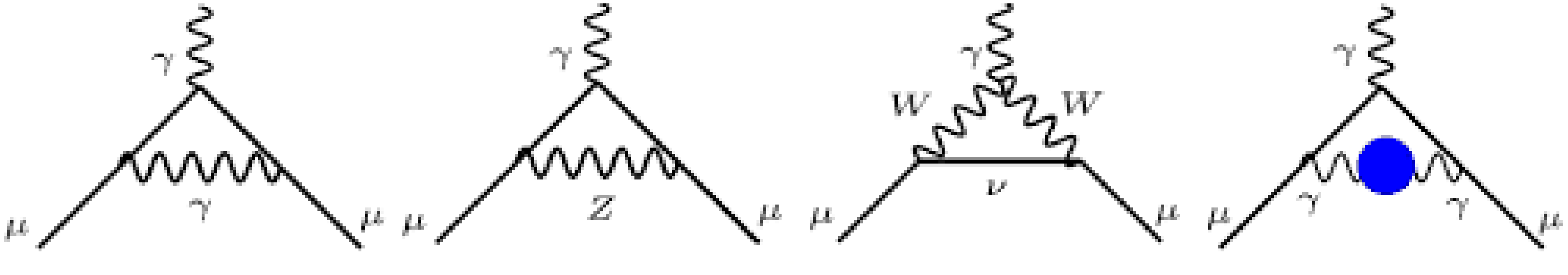
☐ This represents a positron interacting with antiquark via exchange of a photon. Both the positron and antiquark come in and emerge from the interaction. The outgoing antiquark then radiates a gluon.

☐ For more details, I refer you to these references

- http://scipp.ucsc.edu/outreach/22StandardModelofParticlePhysics.pdf
- http://scipp.ucsc.edu/outreach/23FeynmanDiagrams.pdf
- https://www.youtube.com/watch?v=oBNZOOuqO6c&t=340s

Could you give any more details about the magnetic moment experiments at Fermilab?

- Great interest in measuring “*g*-2” of the muon, because:
    - $\vec{\mu} = g(\frac{e}{2m})\vec{S}$: Relates the magnetic moment to the spin.
    - “*g*” can be **predicted very precisely** in the Standard Model.
    - New particles could alter the value.
- For a spin ½ point-like particle, with no “virtual particles” popping in & out of existence, the quantity “*g*” in the SM would equal 2 (exactly).
- But, in the real world**, there is** a “virtual cloud” of particles that surround the muon. It includes many of the



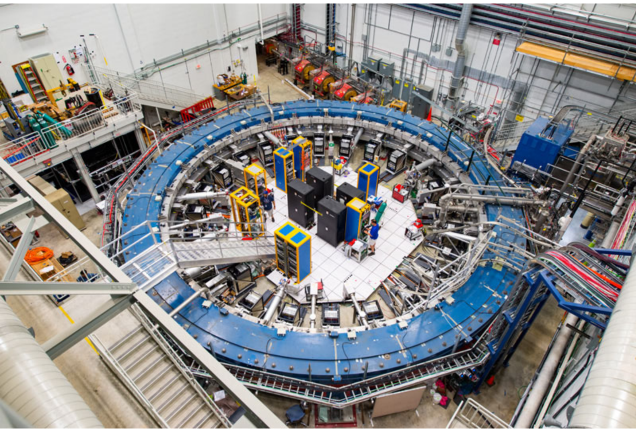
QED **Weak** **Hadronic**

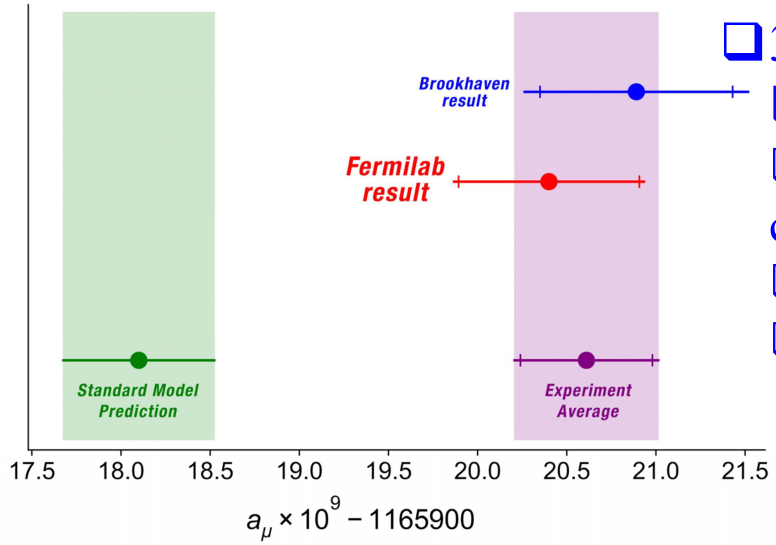
- But, if there are “new particles” (beyond SM) that exist, they may significantly alter the measured value outside what is expected from the SM.

Nice articles:

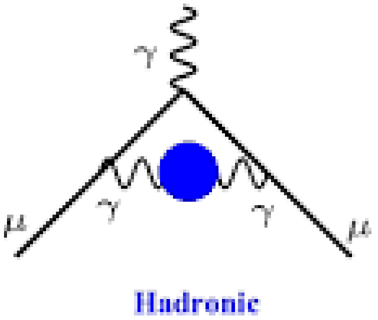
- https://www.wired.com/story/a-last-hope-experiment-finds-evidence-for-unknown-particles/
- https://www.forbes.com/sites/startswithabang/2021/04/08/why-you-should-doubt-new-physics-from-the-latest-muon-g-2-results/?sh=21f83a246c4b

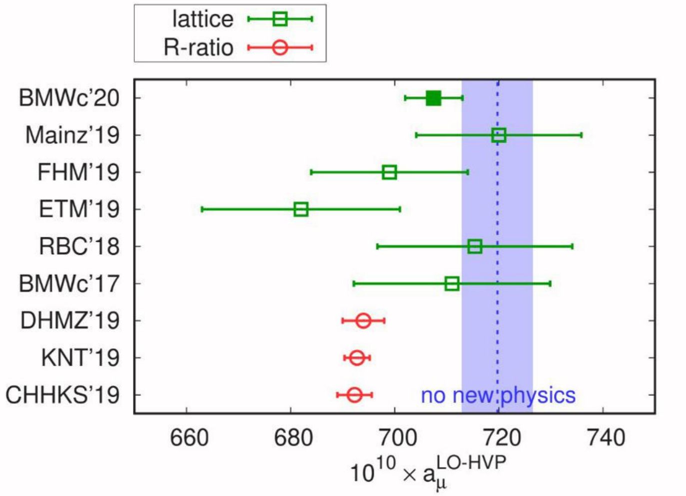
Could you give any more details about the magnetic moment experiments at Fermilab?





- 3.3σ discrepancy!
  - New Physics?
  - Not all SM contributions correctly accounted for?
  - Underestimate of uncertainties ?
  - Time will tell …





- Largest correction to g-2 is the "hadronic" (or HVP) contribution.
- Some hint from recent lattice QCD predictions (BMWc20) that the discrepancy is small/non-existent. (Other groups eagerly working on this calculation too!)

Other questions that you all asked

What employers in the Mohawk Valley Region utilize and or explore applications of particle physics.

- Perhaps a reading of this web page would be instructive?
  https://science.osti.gov/hep/Benefits-of-HEP/Benefits-of-HEP

Particle physics in regards to NGSS implementation and teaching strategies?

- Maybe this is a discussion topic at the workshop.

- **What are some good hands-on demonstrations I can use to engage my students when we study particle physics?**
  - Maybe a topic for discussion. Consider some of the activities in this workshop.

Has quantum entanglement been observed with particles other than photons?

- Not an authoritative source, but in this Wikipedia, https://en.wikipedia.org/wiki/Quantum_entanglement, there are references to experimental evidence for entanglement with neutrinos, electrons, molecules, and possibly even small diamonds. (Of course by "observe" if this to mean 5 sigma from the null hypothesis, one would have to look at each of the experiments & measurements).

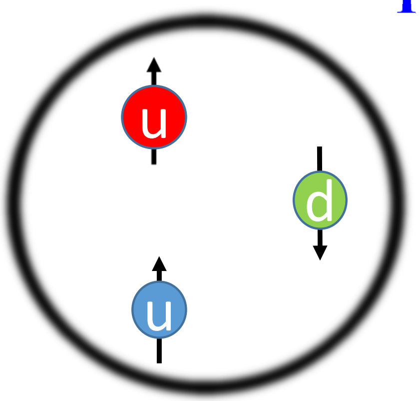
Backup

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 !!**

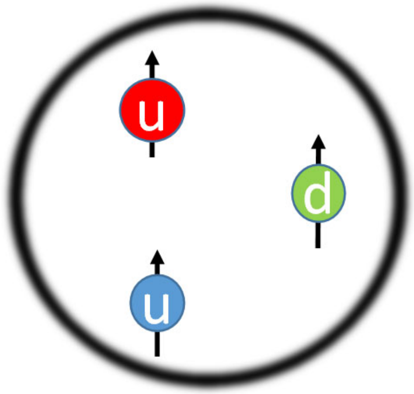
Proton



Spin: (½ + ½ - ½) = ½ $\hbar$.

Mass = 938 MeV/c^2

Δ^+



Spin: (½ + ½ + ½) = **3/2** $\hbar$.

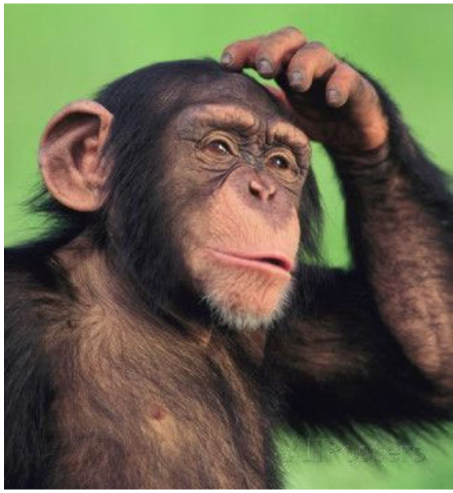
Mass = **1232 MeV/c^2**

- 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!**
  - $\Delta^{++}(uuu)$, $\Delta^- (ddd)$, $\Delta^- (udd)$

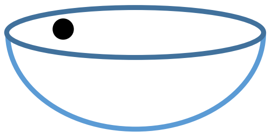
- **Each of the 125 baryons can have many "excited states", each one is its own particle!**

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

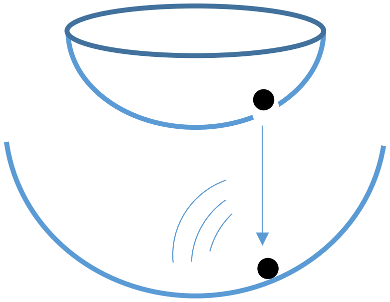
Particle decays



- 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 $\mathbf{E_{tot}}$ **always stays the same**.
- The system is **infinitely stable**. It would never cease to exist.

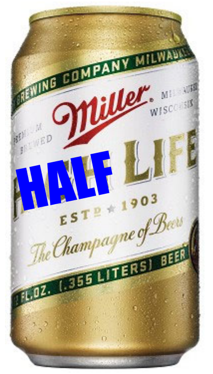


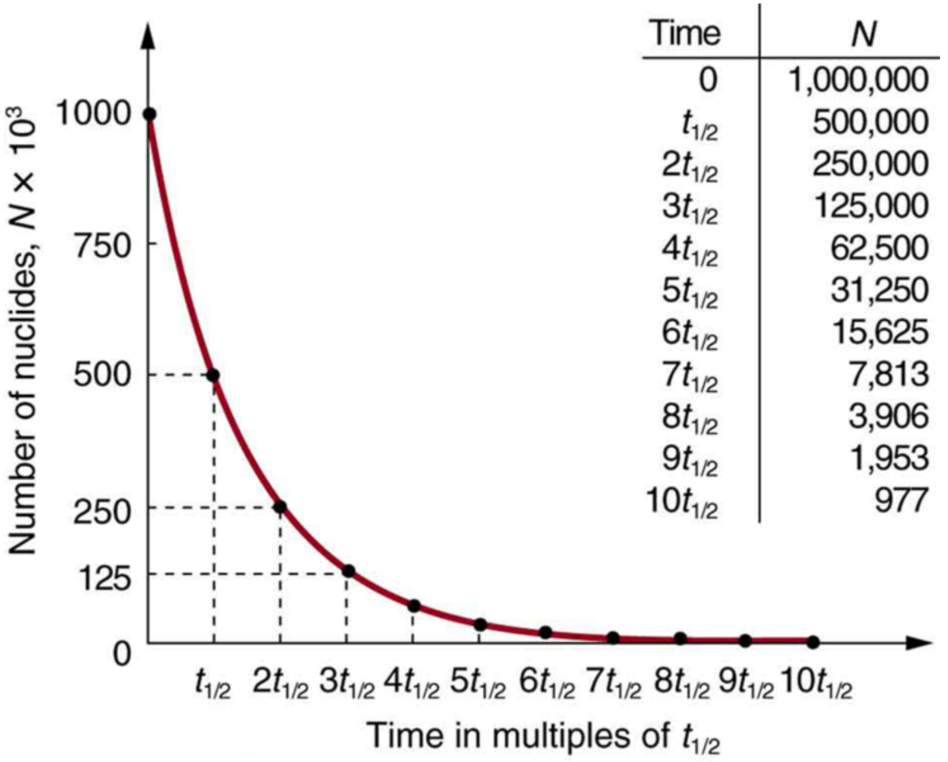
- Now, imagine I drill a small hole, just big enough for the ball to get out.
- After some amount of time, the ball **will drop to the lower energy state**.
- **The ball has “no choice”!** It will eventually happen, and **the initial state will cease to exist**.
- In it’s place is a new lower energy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

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

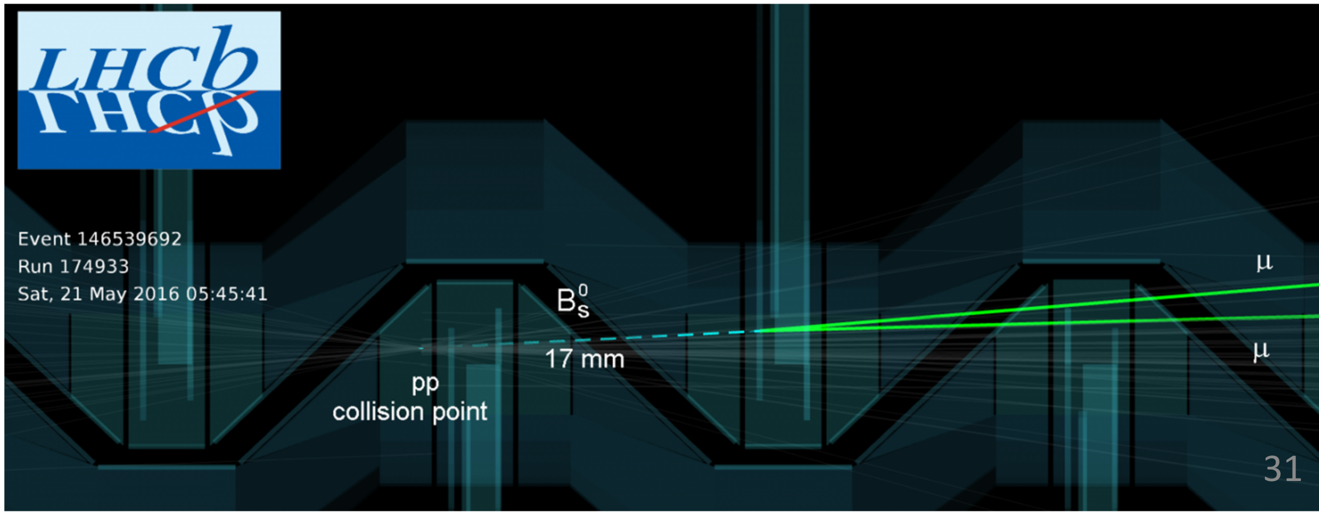
☐ In either case, it’s just **a measure of how quickly the particle in question decays to something else**.

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 ?