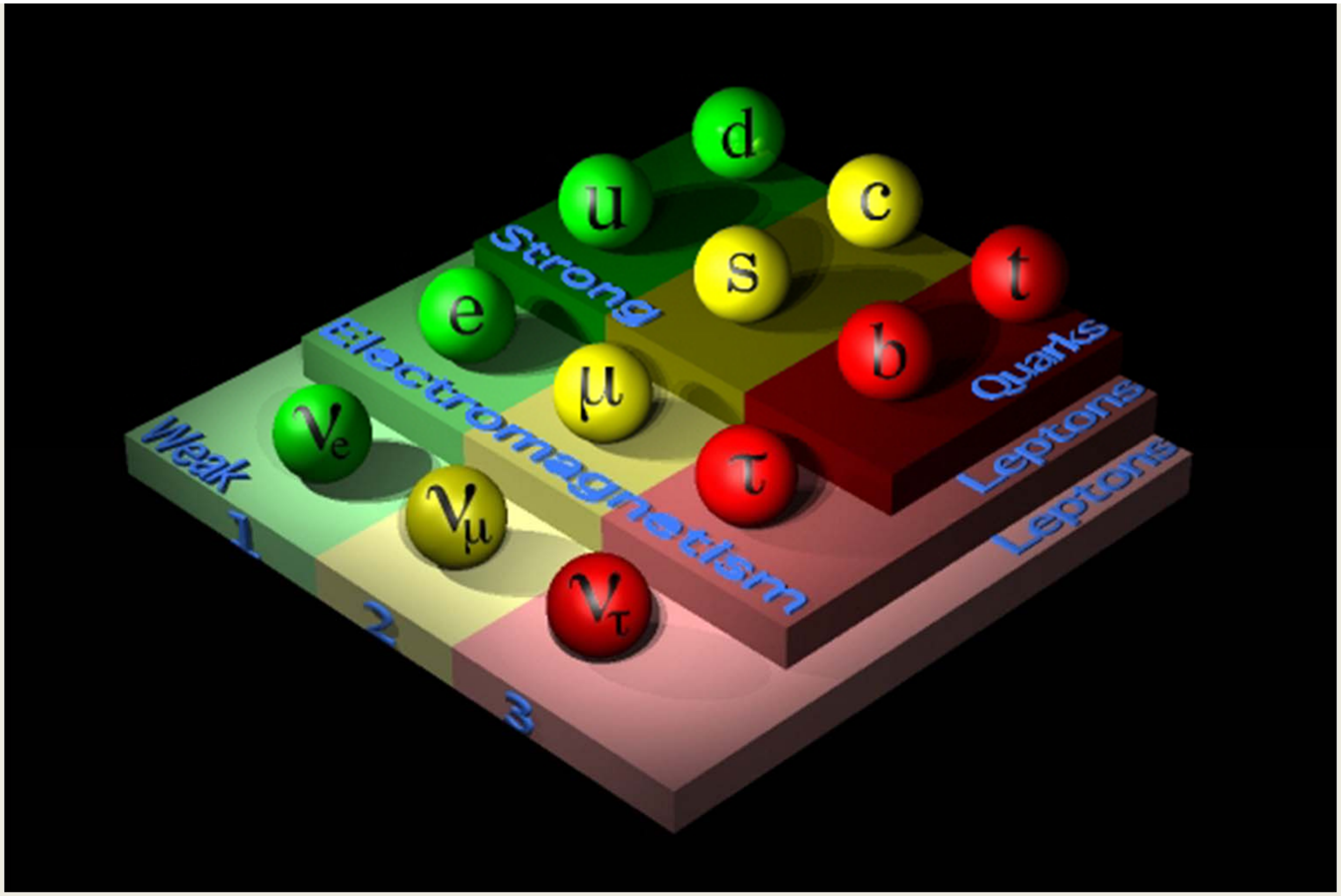


Quarknet
Syracuse Summer Institute
Strong and EM forces

Lecture 3

Topics for today

Electromagnetic & Strong Interactions

Last time

- **Basic idea introduced that, for each force there is:**
  - A force carrier
  - A "charge" that the force carrier couples to
  - A coupling constant, that gives the strength of the coupling.
- **For Electromagnetism**
  - Photon, electric charge, α_{em}~1/137
- **For the strong force**
  - Gluon, color charge, $\alpha_s \gtrsim 0.1$, but can be LARGE > 1!

QCD vs QED

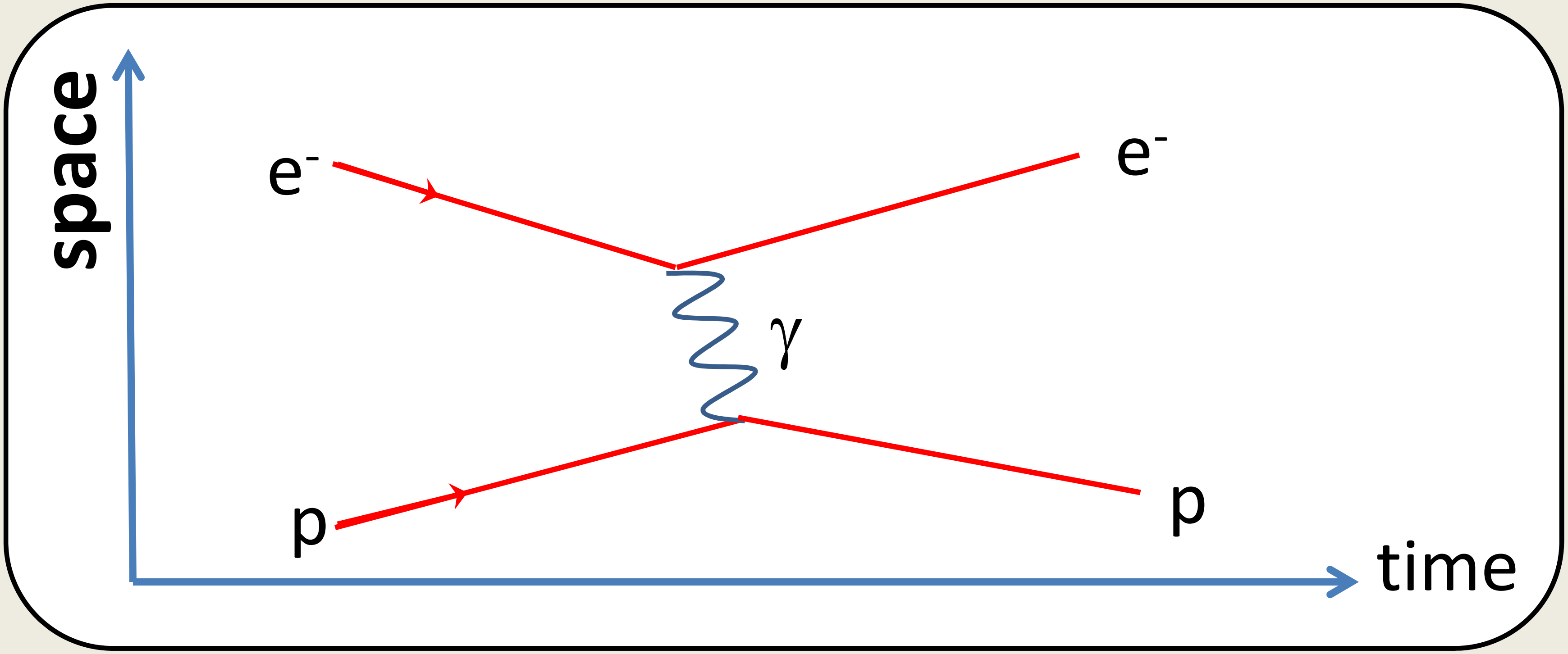
- If QCD and QED are so similar, why do they have vastly different behavior?
  - Both have massless force carriers, yet it is found that:
    - EM force is **much** weaker and infinite range
    - Strong force VERY STRONG and short range
- The vastly different behavior is predictable from QCD due to the following difference:
  - In QED **photons DO NOT CARRY electric charge**.
  - In QCD, **gluons DO CARRY color charge** (color-anticolor)

Gluons can interact DIRECTLY with other gluons !!!!!!!

Interactions and Feynman Diagrams

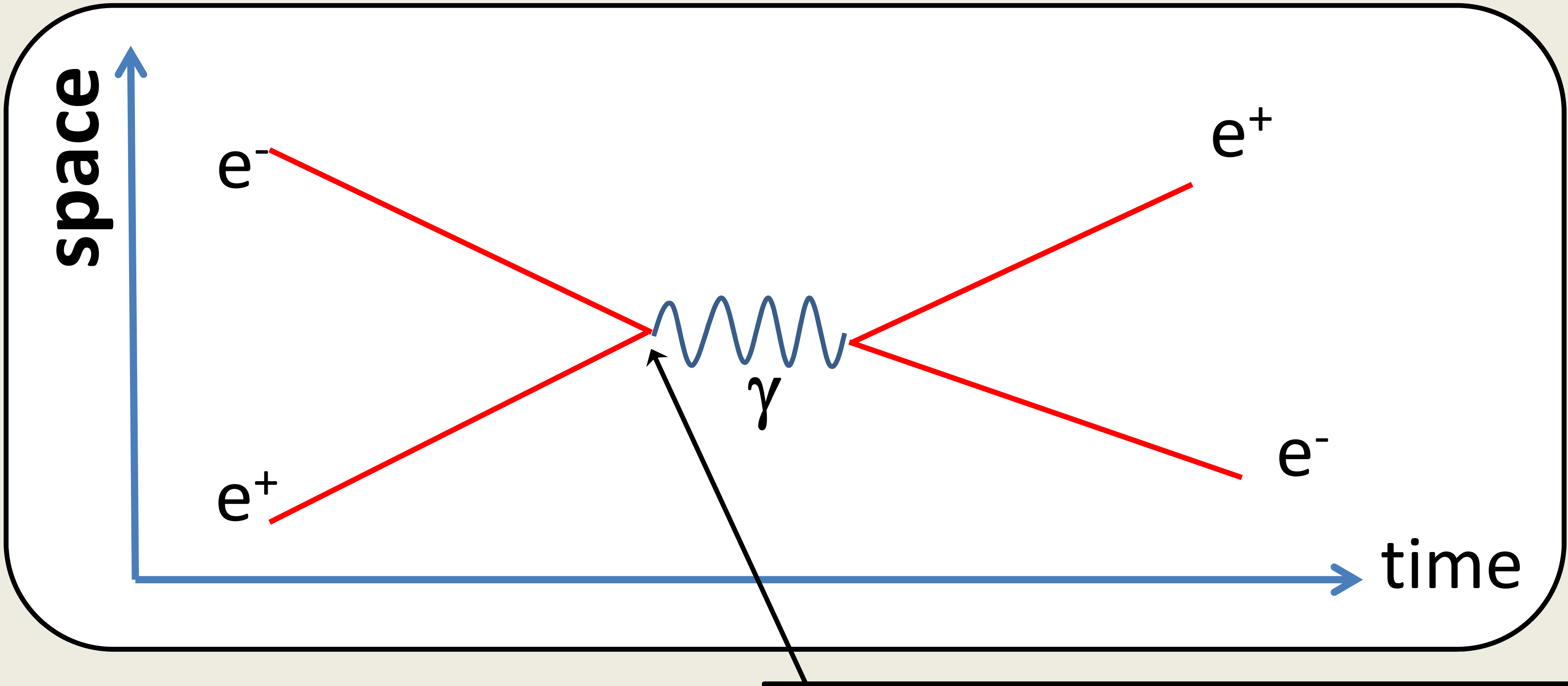
Electromagnetic Interactions

Simple Feynman Diagram



- ☐ Here, an electron and a proton interact by exchanging a photon (one emits it, the other absorbs it …)
- ☐ This is an example of an **ELECTROMAGNETIC INTERACTION**
- ☐ Processes like this are calculable within **QED**.
  It is <u>the most precise theory known</u> in all of physics.

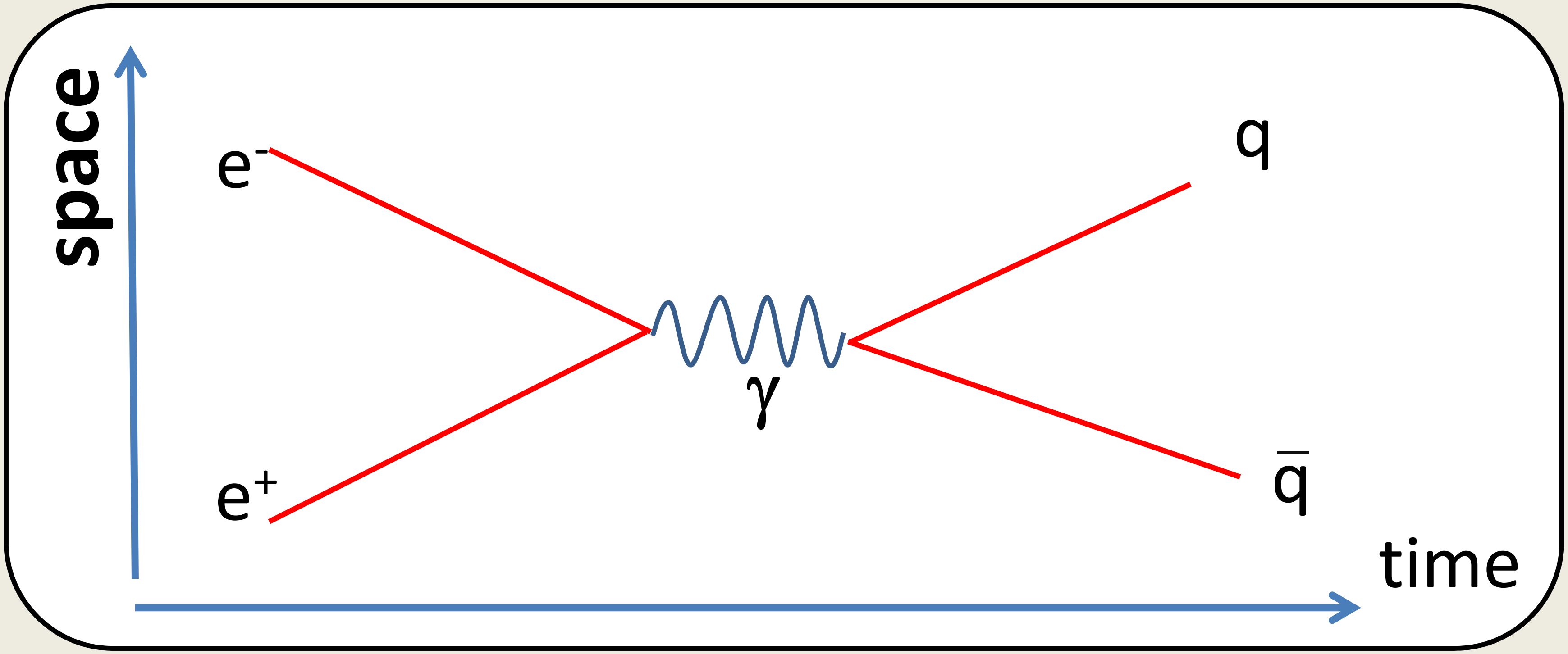
Another Interaction



Notice that the e^+ & e^- are at the same point in space at the same time
→ annihilation!

- **Here, the electron and positron annihilate into pure energy (photon), which at some later time re-materializes in the form of a (new) electron-positron pair!**

But, here's where it gets interesting



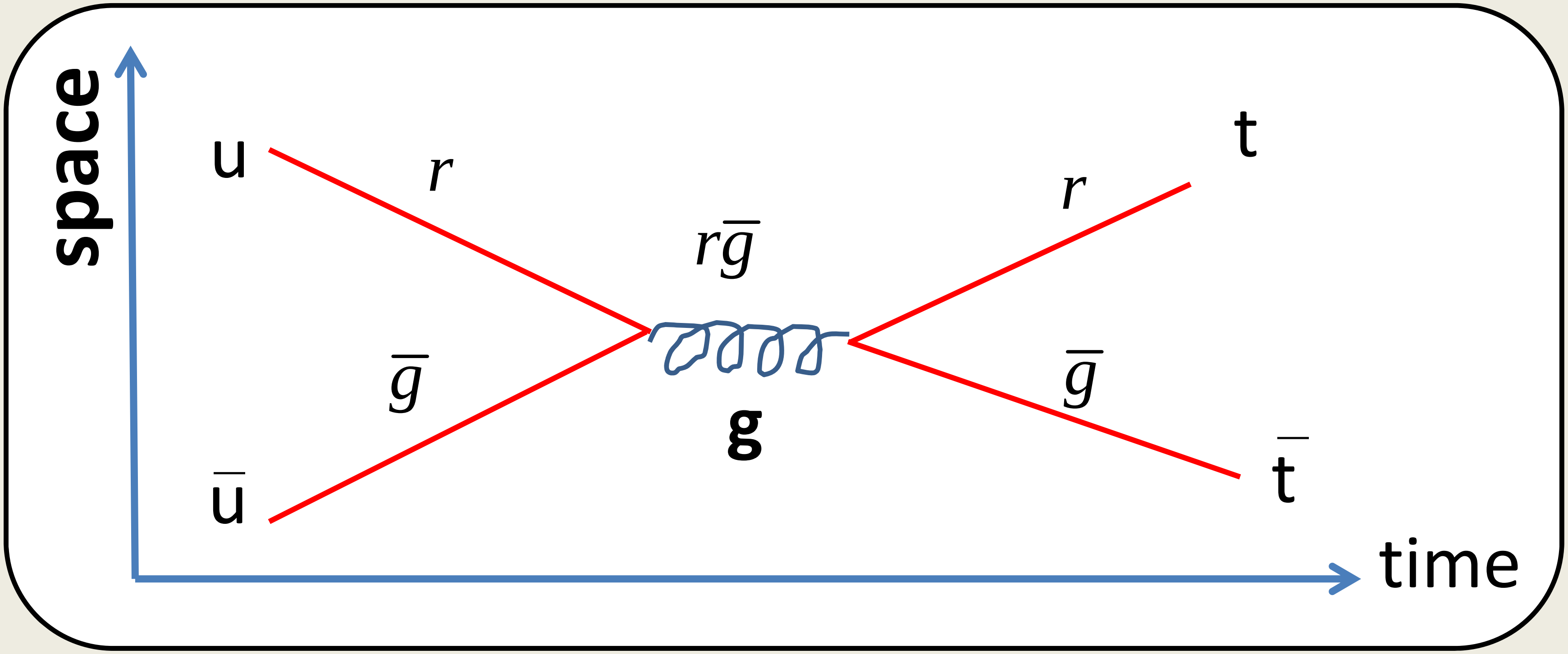
- ☐ The photon couples to electric charge, so this can occur.
- ☐ Here, the photon re-materializes in the form of a $q\bar{q}$ pair.
- ☐ The only limitation is energy conservation.

$$E_{e^-} + E_{e^+} \geq 2M_q c^2$$

If the LHS exceeds $2M_q c^2$, the rest of the energy appears as KE

Strong Interactions (QCD)

Quark-antiquark annihilation

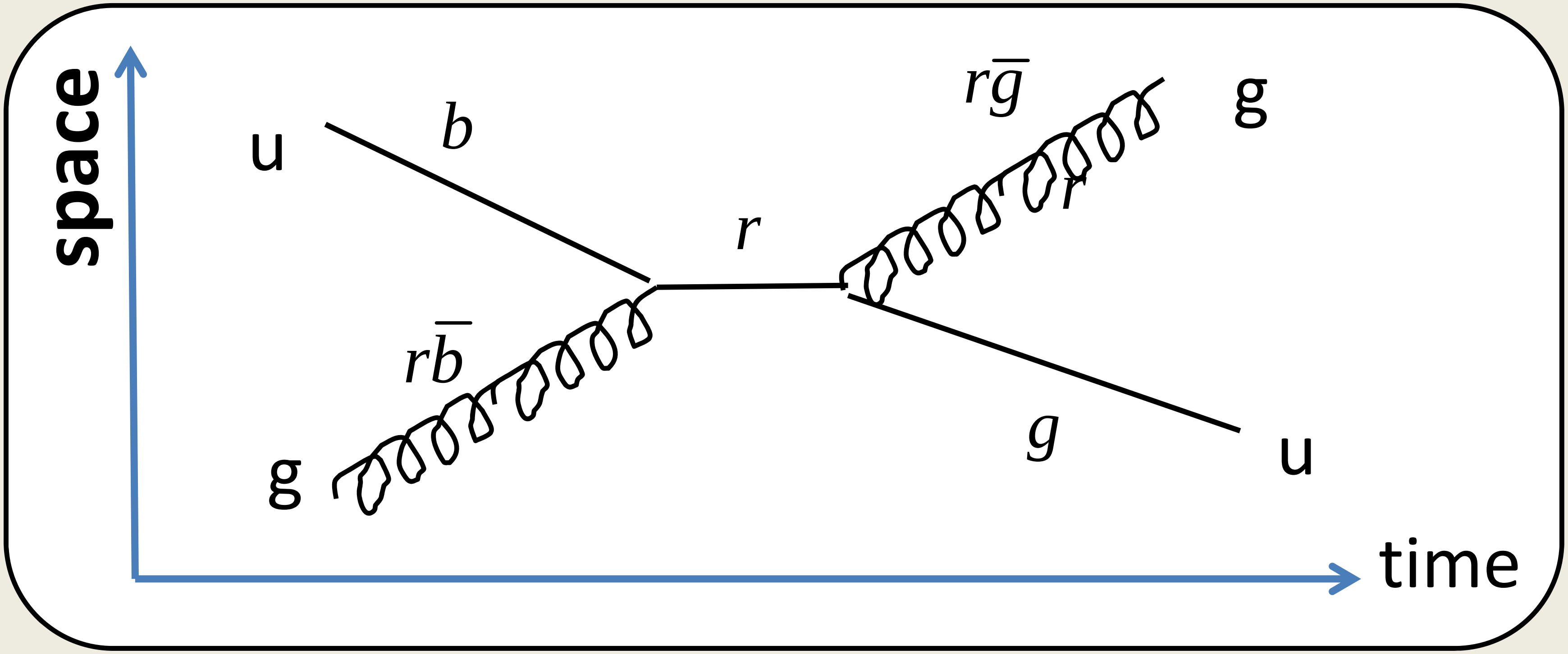


- Here, the u$\bar{u}$ annihilates into a gluon, which then re-materializes in the form of a t$\bar{t}$ pair.
- The only limitation is energy conservation.

$$E_u + E_{\bar{u}} \geq 2M_t c^2$$

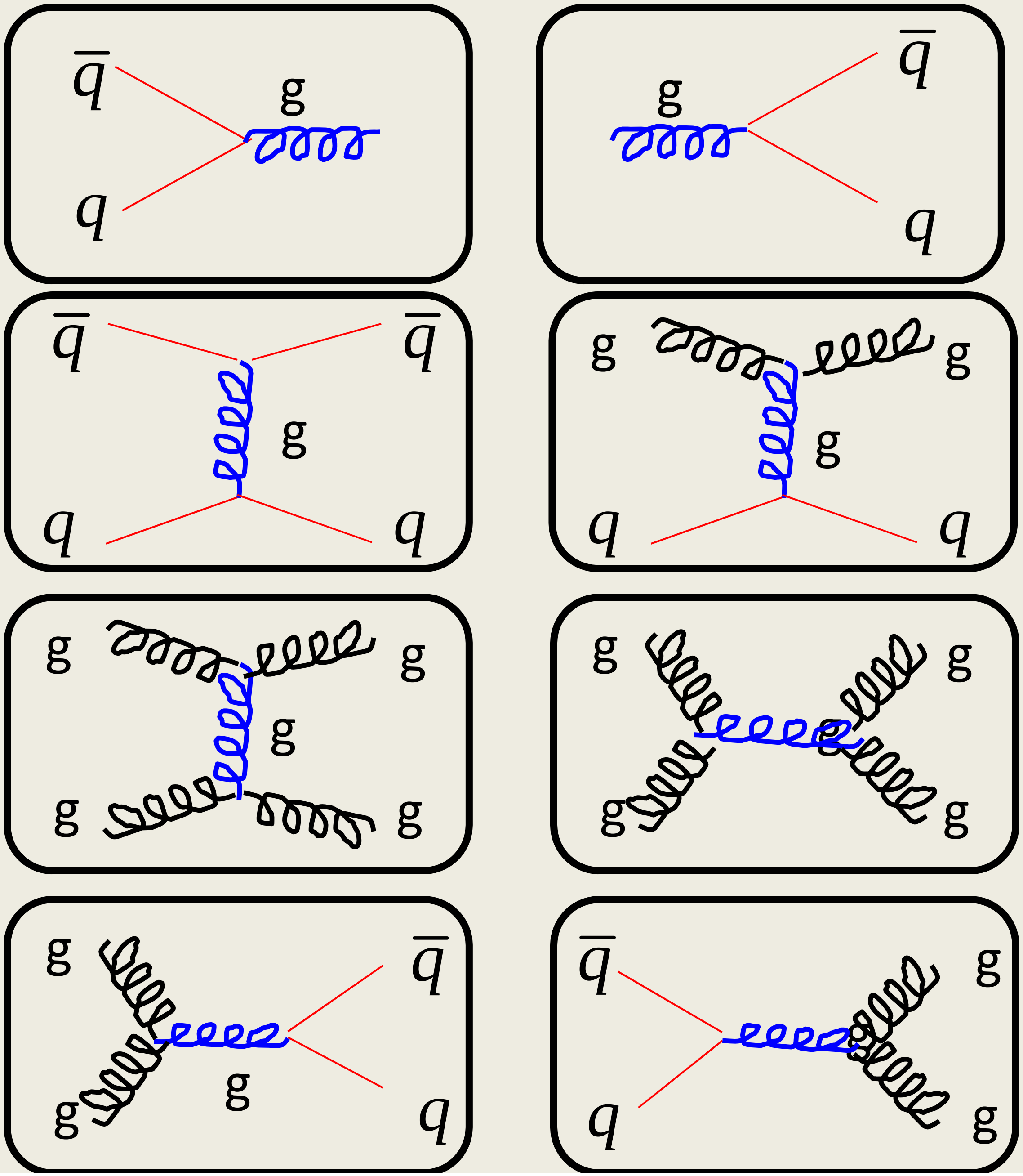
- Color is conserved at each vertex!

Quarks can even interact with gluons!



- Here, the up quark absorbs a gluon, and later it re-radiates a gluon.
- Also known as quark-gluon scattering.
- The gluons can come from the interior of a proton (more later on this)
- Again, notice how color is conserved at each "vertex"

Many possible quark and gluon interactions

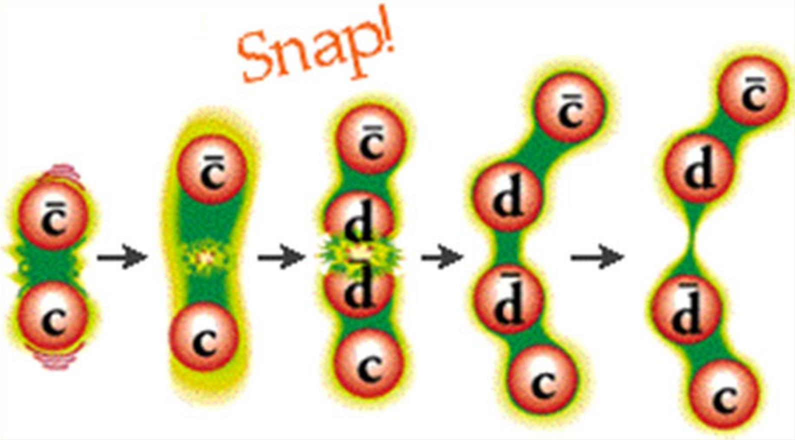


Main point is that you can get interactions of

a) Quarks with quarks
b) Quarks & gluons
c) Gluons & gluons

Strong force – short & long distances

- The coupling constants are not really constants at all.
- They will depend on the distance scale.
- At very small distances, α_s small ~ 0.1.
  - "Perturbation theory" works well here, namely a series expansion in α_s converges.
- But, as distance increases, α_s increases, and increases and



- Eventually, it becomes energetically more favorable to convert the energy stored in the field into mass (quark antiquark pair!)

Decays via the Strong and EM Interactions

Note: We’ll spend a fair amount of time
discussing weak decays after strong & EM interactions

Important point

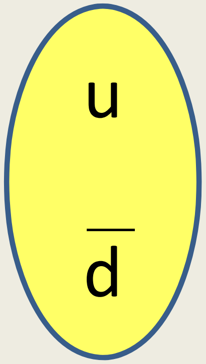
- The strong and EM interactions cannot change quark type from one to another !
  - For example:
    - They cannot mediate the decay: $c \rightarrow u + \gamma$
    - They cannot mediate the decay: $\pi^+ \rightarrow \mu^+ + \gamma$
  - Notice, these decays do not violate charge or energy conservation!
- BUT, the Strong & EM interaction can create or take away a $q\bar{q}$ pair of the same type.
- Recall a π^0 is

$$\pi^0 = (1/\sqrt{2})(u\bar{u}+d\bar{d})$$

Because the π^0 has a $q\bar{q}$ pair, and it is the lightest hadron, annihilation into two photons, is the principle decay (~100%) [EM interaction]

Another example

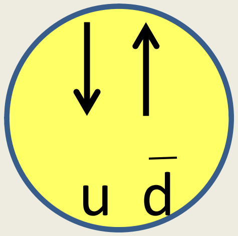
- The ρ^+ meson is an excited state of a ($u\bar{d}$).



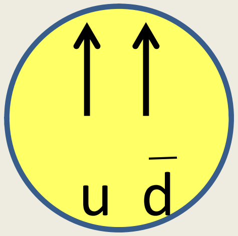
Aside …

You might be wondering: how does this meson differ from the π^+, which is also a bound state of a ($u\,\bar{d}$) ?

- In the ρ^+, the spins of the quarks are aligned in the same direction, giving total spin = 1.
- In a π^+, the spins are pointing opposite, giving total spin = 0.



π^+ (140 MeV)

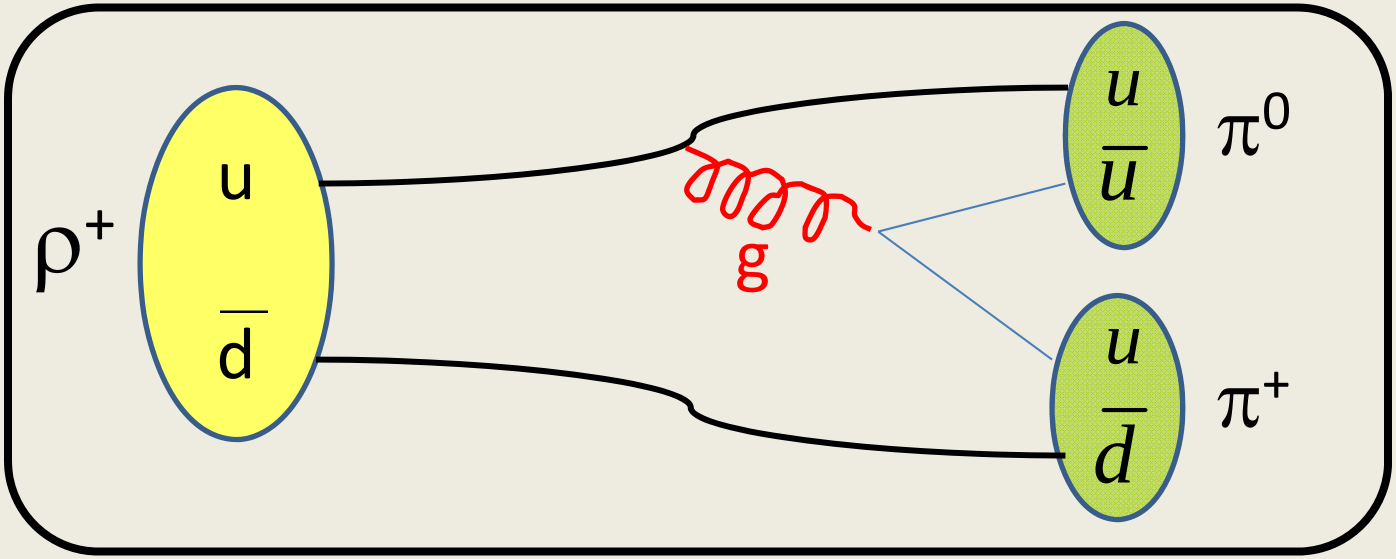


ρ^+ (770 MeV)

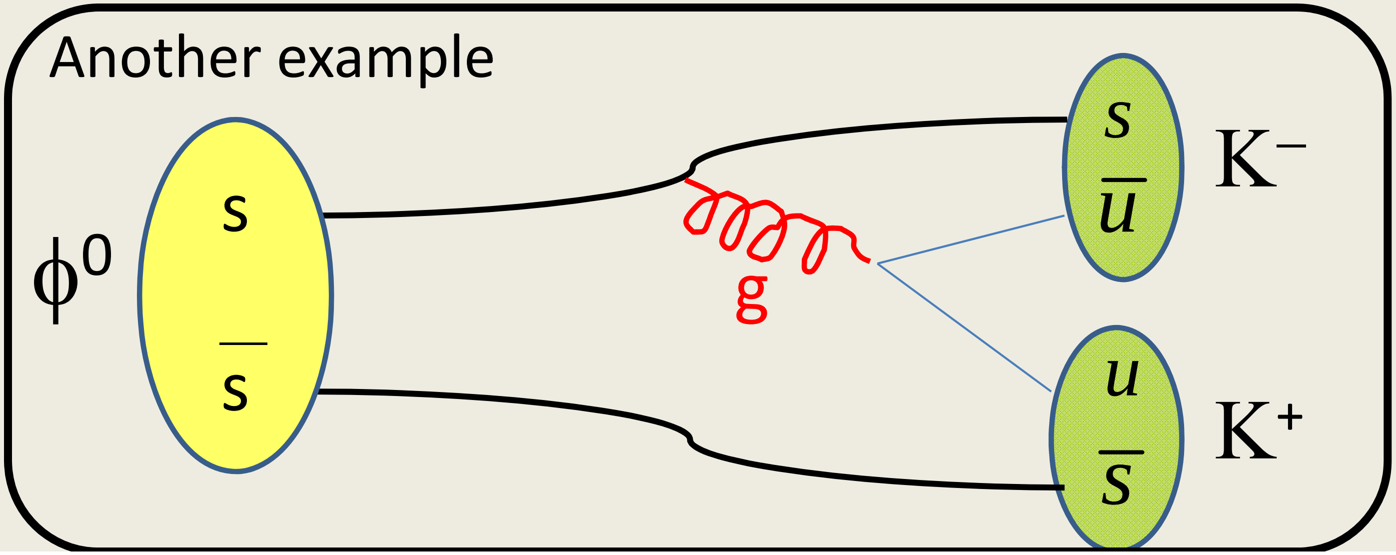
- The aligned spins give a large contribution to the total self-energy → **self-energy == mass** !!!!

OK, back to our strong decay

- The ρ^+ meson is an excite state of a $(u\bar{d})$.
- How does it decay?



Another example



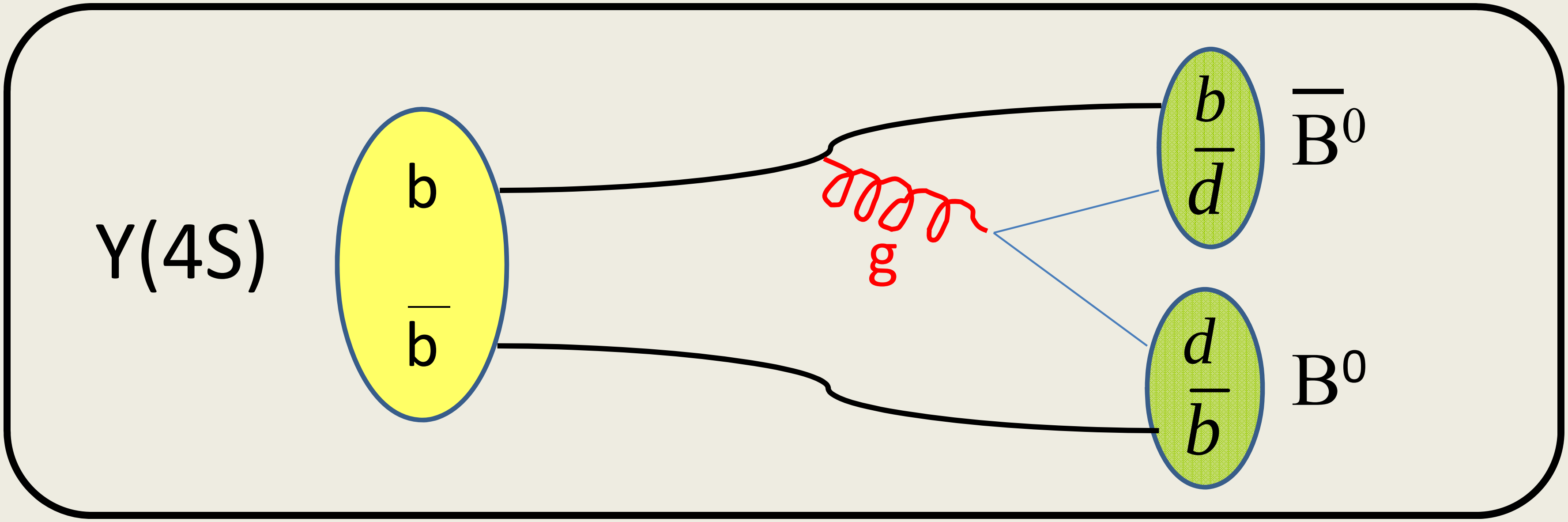
These are examples of strong decays.

Note the gluon produces a $q\bar{q}$ pair.

The original quarks are still there!

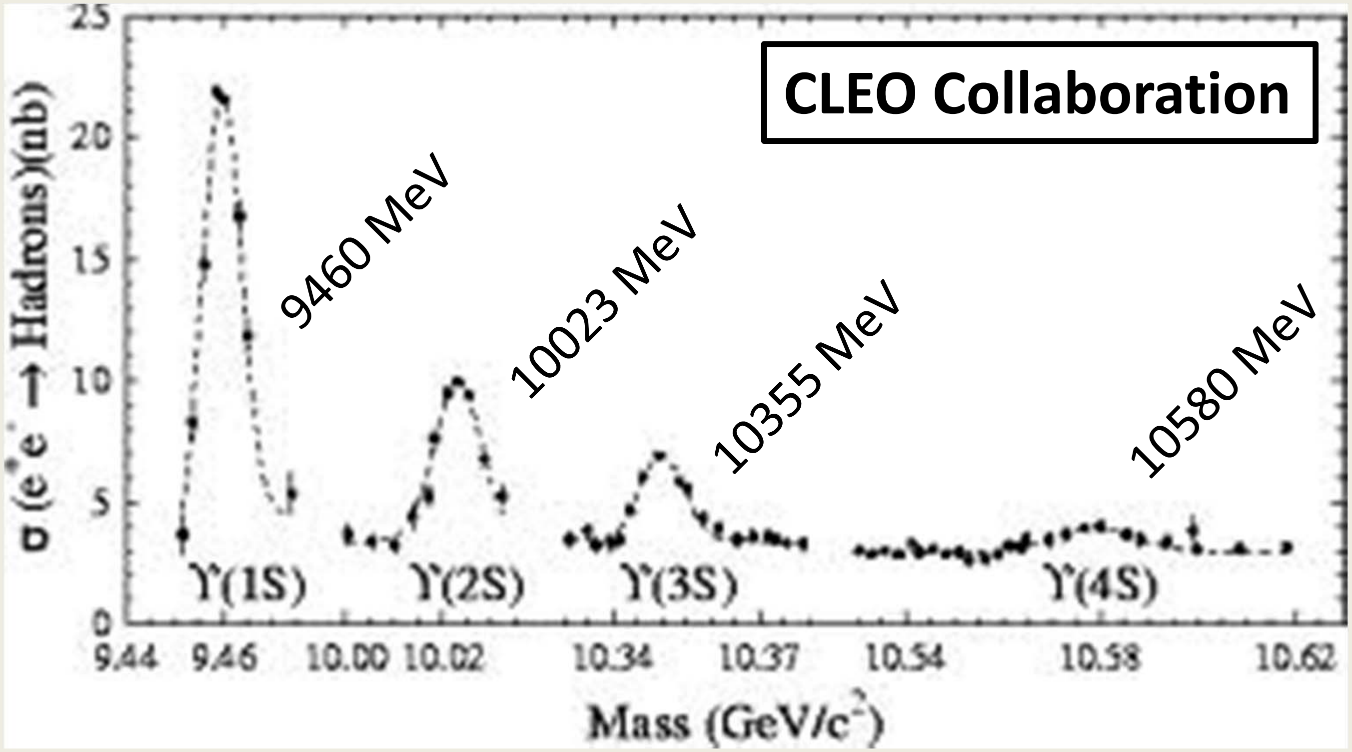
Another strong decay

- The Υ(4S) is the bound state of a ($b\,\bar{b}$)
- The "4S" is the same spectroscopic notation as in "4s" in H-atom!
  - That is, principal quantum number n = 4 & ℓ = 0 for the $b\bar{b}$ system



The Υ(4S) has been the "work-horse" for studying B meson decays over the last 20 years!

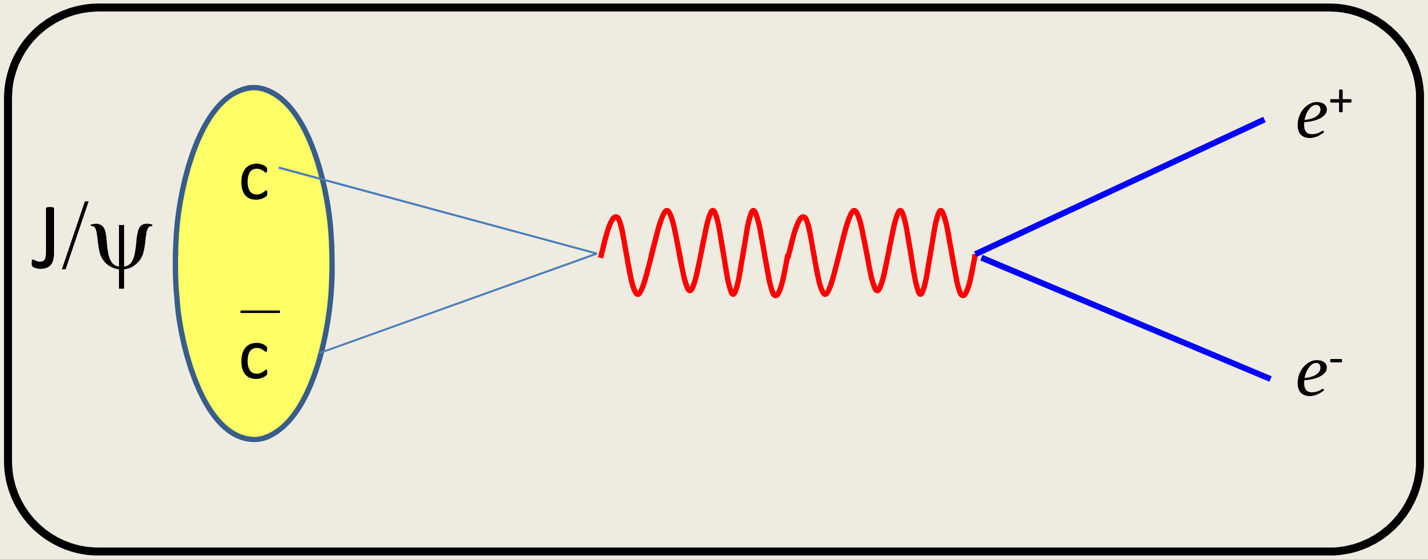
Other $b\bar{b}$ Bound States



- ☐ Only the Υ(4S) has mass > $2xM_B$, allowing it to decay into $B\bar{B}$. [M_B = 5279 MeV]
- ☐ The Υ(1S) – Υ(3S) cannot decay to $B\bar{B}$; they decay in other ways to hadrons, or even leptons
- ☐ How do the splitting here compare to the H-atom? Why?

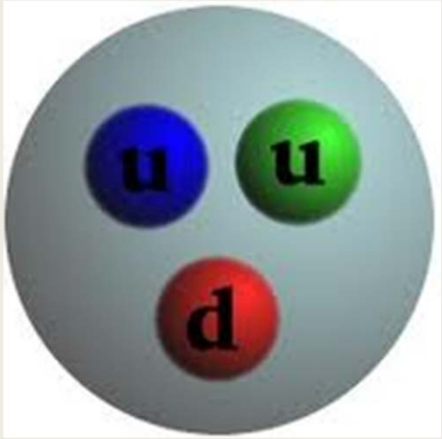
Electromagnetic decay

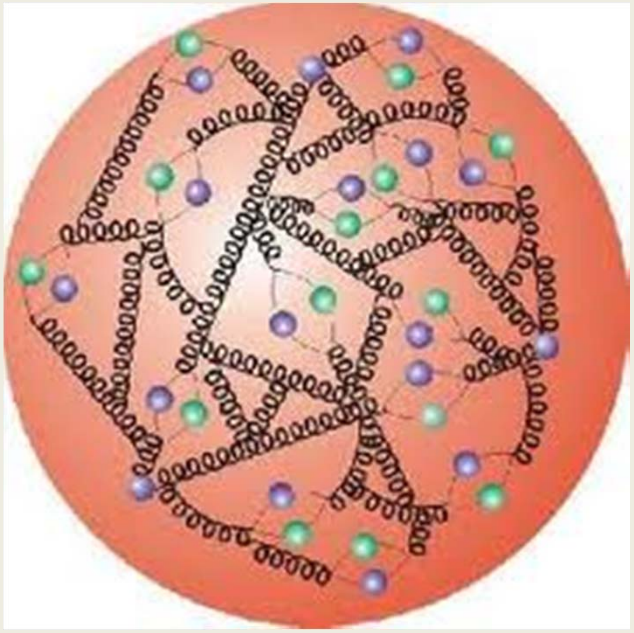
- The J/ψ meson is a (c $\bar{c}$)



- This is an example of an electromagnetic decay.
- The original c $\bar{c}$ quarks have annihilated into pure energy (a photon), which then transformed back into mass (pair of leptons).
- This J/ψ decay occurs about 6% of the time.

Back to the “simple” proton





- For a high school student, knowing it’s made of 3 quarks (uud) is probably sufficient.
- But, so you’re aware … it’s much more complicated!
- The quarks are continually interacting by exchanging gluons.
- The gluons can split into quark-antiquark pairs.
  - These $q\bar{q}$ pairs are “virtual”… they pop in & out of existence.

So, at the Large Hadron Collider we're doing this

In the collisions, we are not looking at a whole proton scattering off another whole proton.

Rather we are really looking at quarks and gluons interacting with each other.