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LECTURE 2: PARTICLE DYNAMICS

ANNOUNCEMENTS

- We are in MP1115!
- Problem set 1 is posted
  - due Tuesday 6 October.
  - There is a drop box (#7) in the basement of MP
- Office hours today (Thursday) 1500-1600

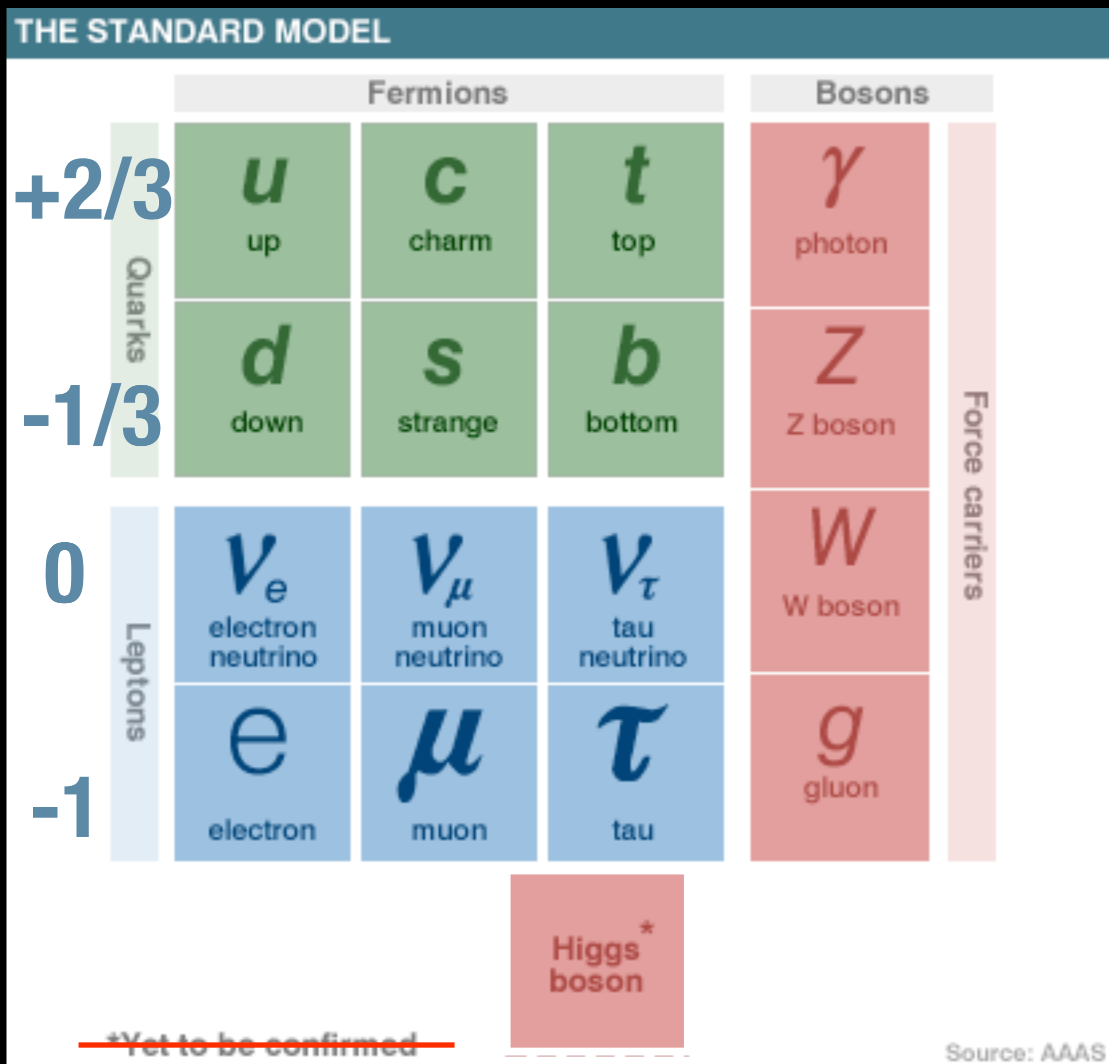
OUTLINE AND GOALS

- Review qualitatively some elementary properties of the fundamental interactions and particles
- Introduce Feynman diagrams as a way to describe interactions
  - In the future, they will correspond to mathematical expressions that allow us to calculate things
  - For now, it will be a way of determining how certain reactions can (not) proceed, and deduce some basic properties
  - Won't really get to what they fundamentally mean; that is QFT
- Determine which reactions are allowed, which are not
  - which interactions are involved or are dominant
  - get an idea for the "strength" of an interaction.

NOTE

- Details on particle masses, properties, etc. can be found on the Particle Data Group site:
  - pdg.lbl.gov
- Most (all?) of the relevant information is also in tables in the textbook.

THE STANDARD MODEL

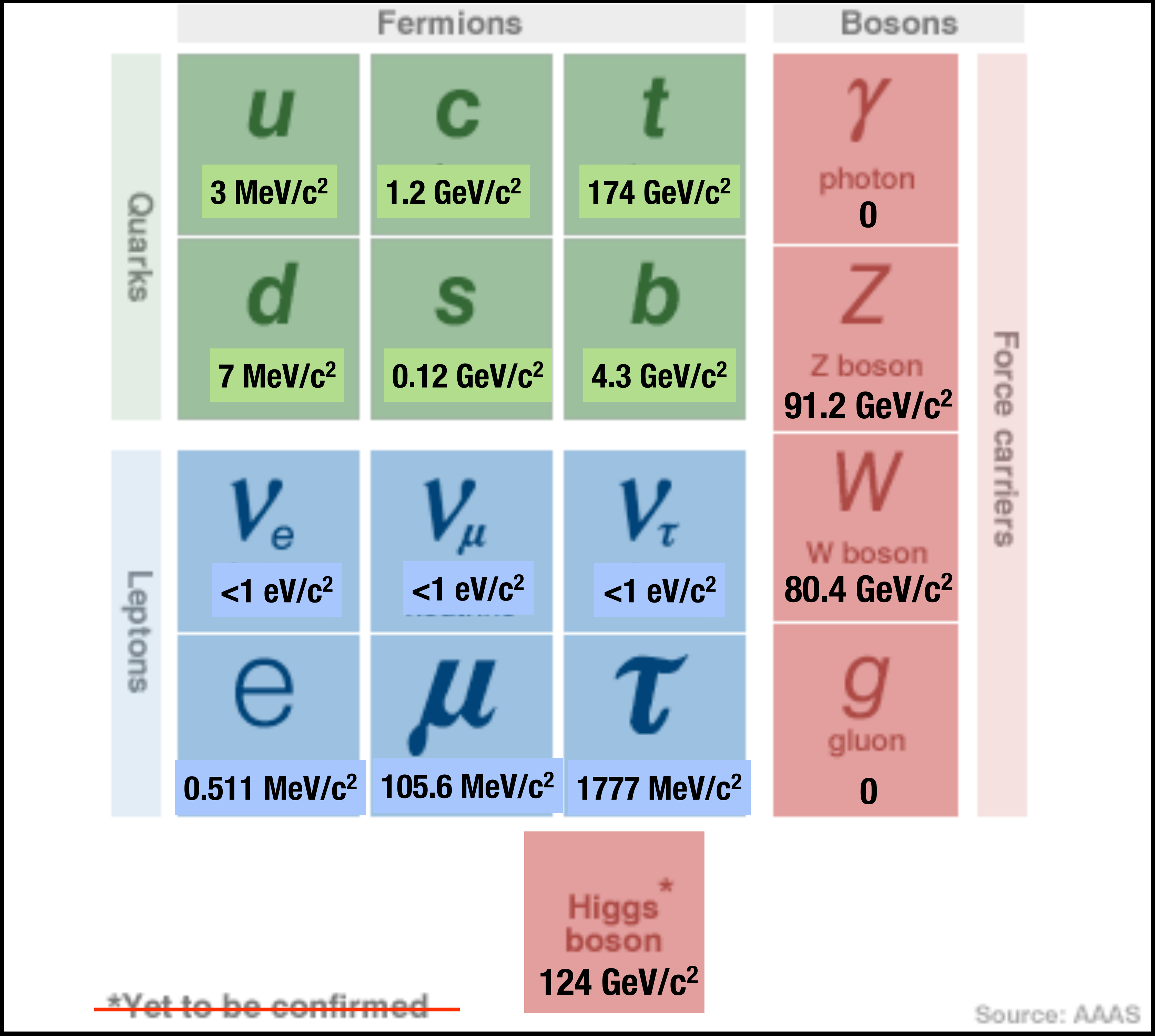


- The fermions make what we usually call "matter"
  - neutrons, protons, electrons
- the "bosons" correspond to what we sometimes call interactions or forces
  - electromagnetic
  - weak
  - strong

- They also differ in a a fundamental way:
  - particles are endowed intrinsically with angular momentum
    - "spin"
  - fermions have half integer spin: 1/2, (3/2, 5/2, . . .)
  - bosons have integer spin: 0, 1, (2, 3, ...)

MASSES

- The particles span an enormous range of masses:



REACTIONS

- Thus far, we have specified reactions by specifying the initial and final state, e.g.

$$n \to p + e^- + \bar{\nu}_e \qquad e^+ + e^- \to \mu^+ + \mu^-$$
$$\pi^+ \to \mu^+ + \nu_\mu \qquad p + \bar{p} \to W^- + X^+$$

  - reactions that start with one particle and result in many are called "decays"
  - reactions that involve the interaction of more than one initial state particle are called "scattering"
- We will talk now about what happens during "→"
  - i.e. we will talk more about the reaction "itself"

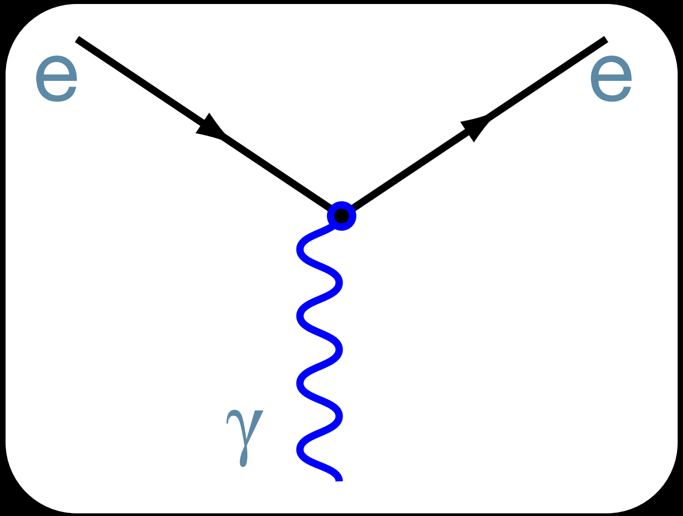
At a McDonald's in the US midwest:

Person: Why do you have Feynman diagrams all over your van?

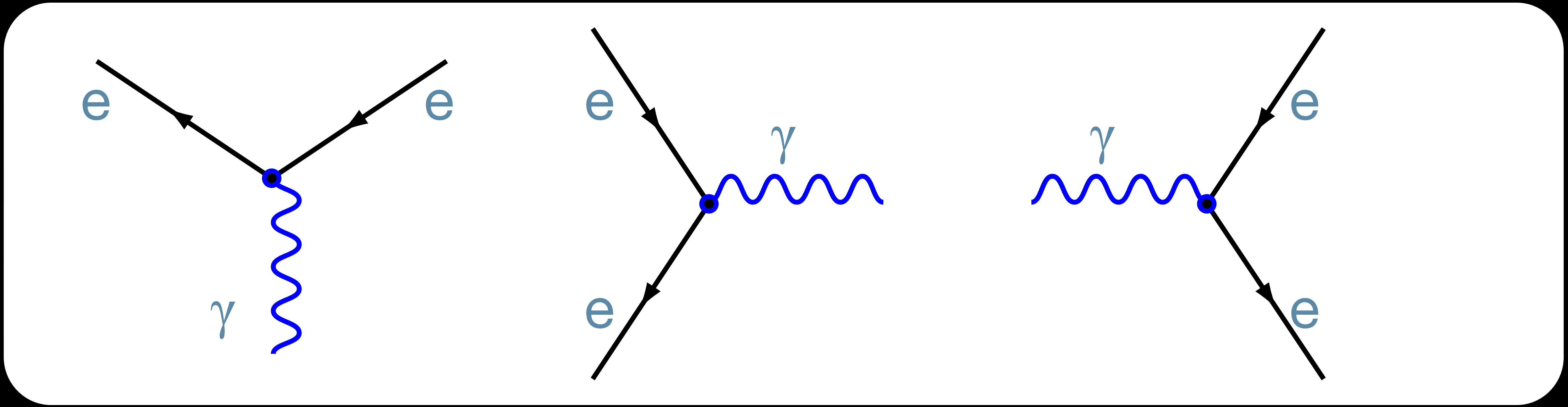
Feynman: Because I AM Feynman!

Person: "Ahhh . . . . . "

FEYNMAN DIAGRAMS

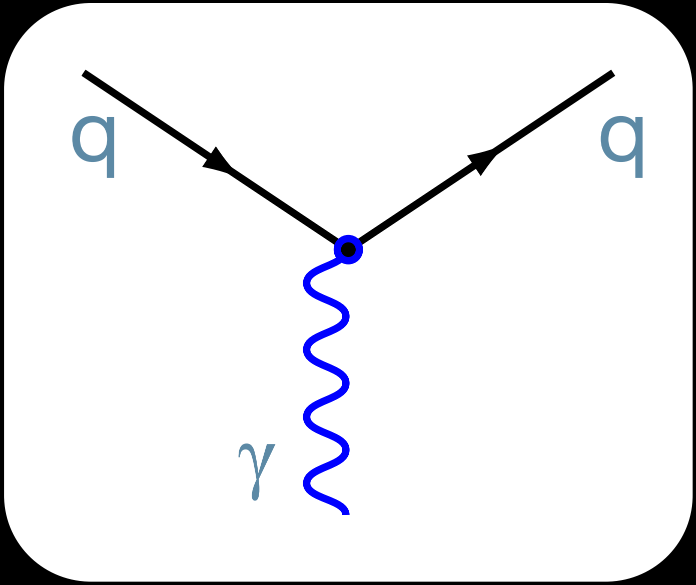


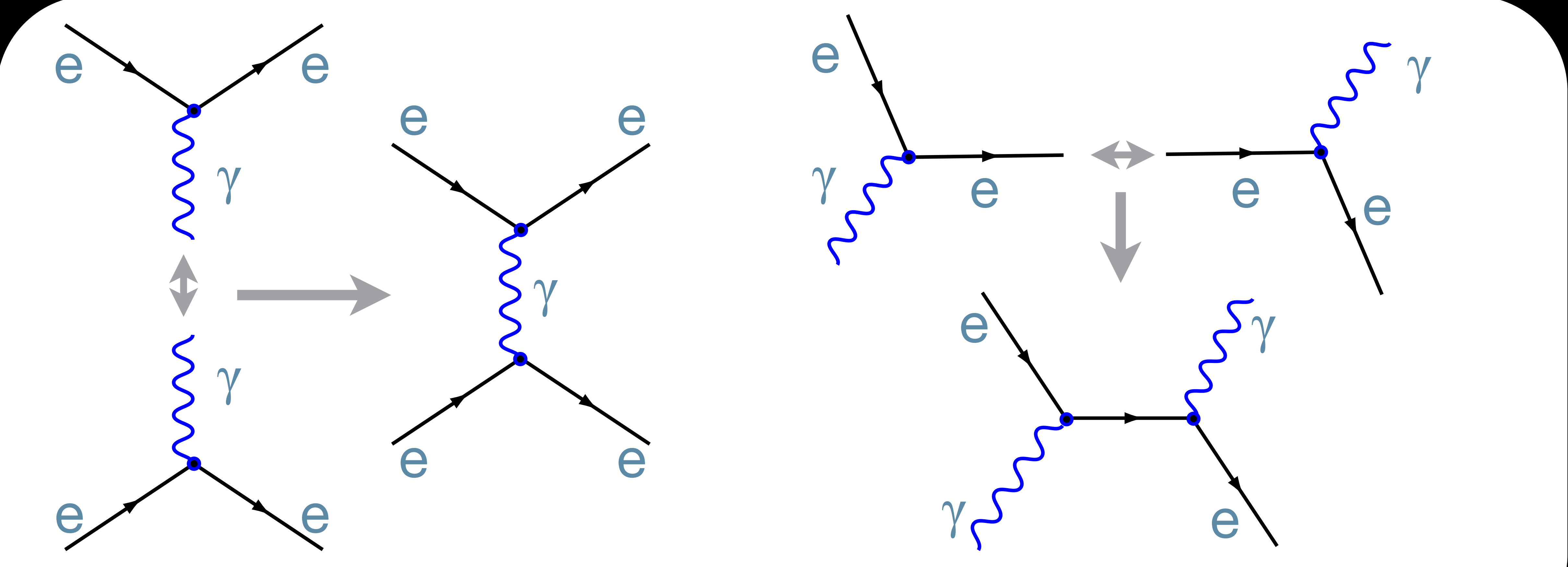
- The basic building blocks are "vertices"
  - defines a basic interaction
  - usually read from left-to-right in time
  - "e came in, γ emitted, e came out."
  - Direction of arrows matter! reverse implies antiparticle
  - The vertex itself has a number implied called the "coupling constant."
    - This characterizes the "strength" of the interaction: ~1/137 for EM
    - E, **p** conserved at each vertex (i.e E, **p** flow in = E, **p** flow out)
- The vertices can be arranged in any way:



ELECTROMAGNETISM (QED):

- This is it!
  - EM interaction consist of vertices like this where "q" can be any charged particle (quark for example).
  - Put together matching legs to make reactions



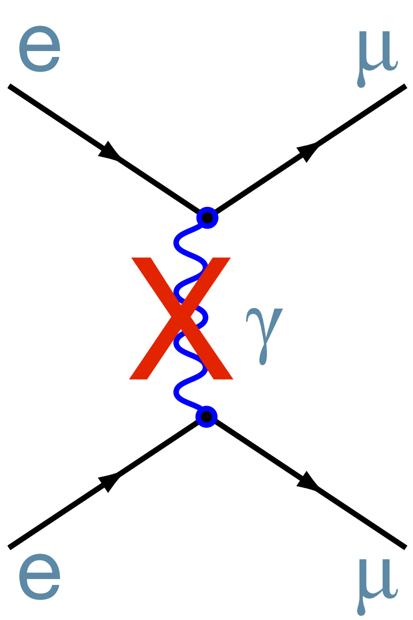


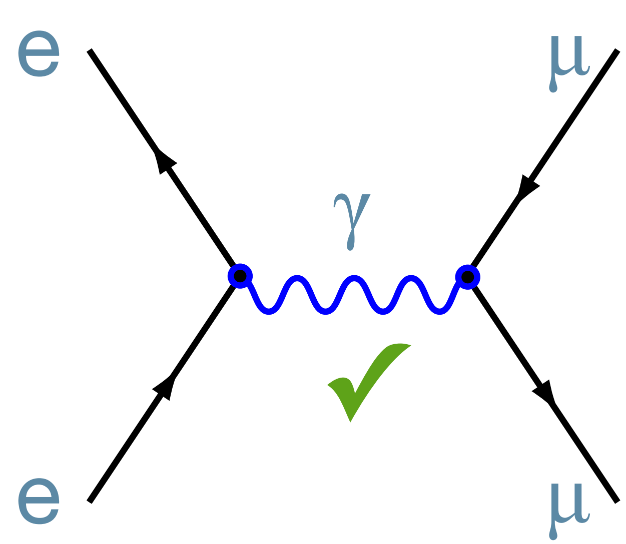
$$e^- + e^- \to e^- + e^-$$

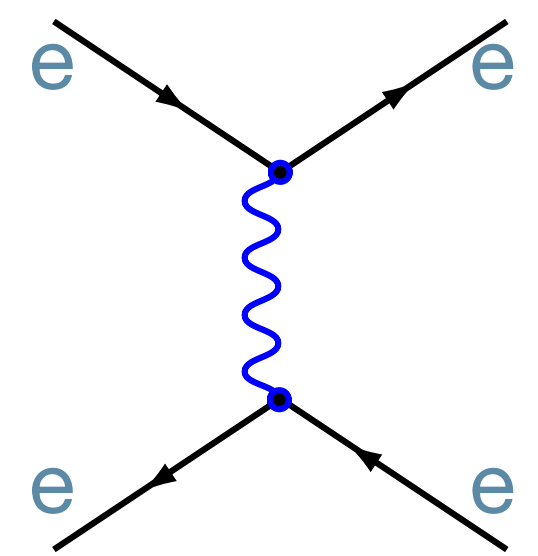
$$e^- + \gamma \to e^- + \gamma$$

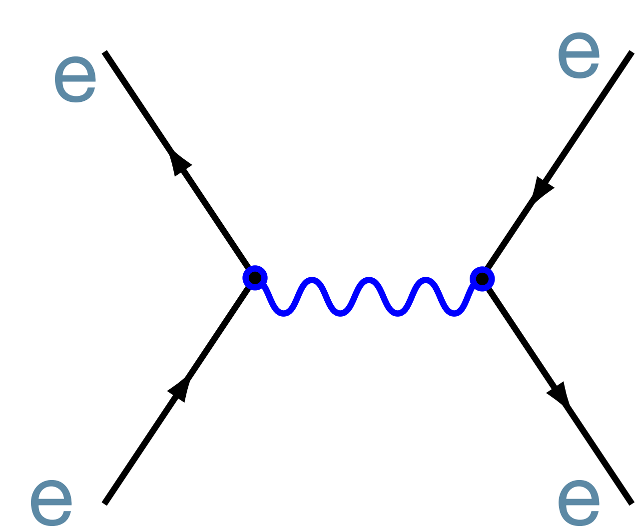
TWISTS AND TURNS

- You can use different particles, but
  - (in QED) particles that lie along a line must be the same type
  - The arrow flow must be consistent (particle/vs. antiparticle)





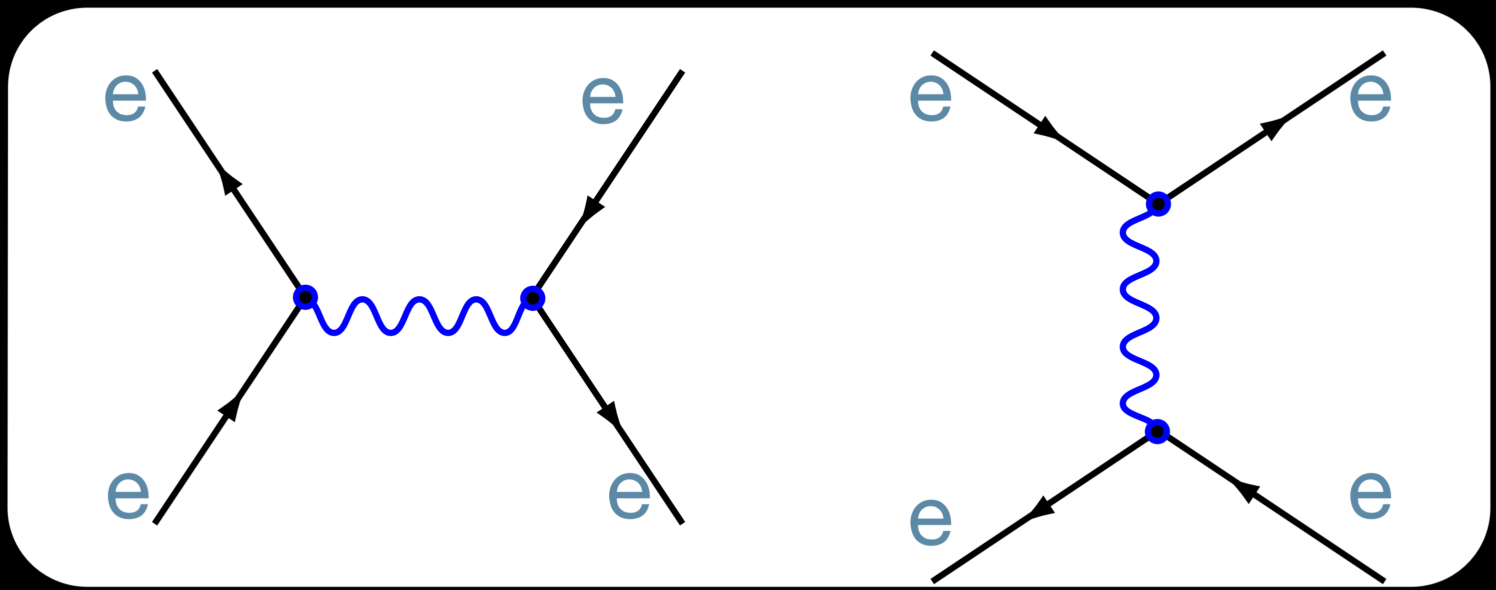




EM IS "FLAVOUR-CONSERVING"

MULTIPLE DIAGRAMS

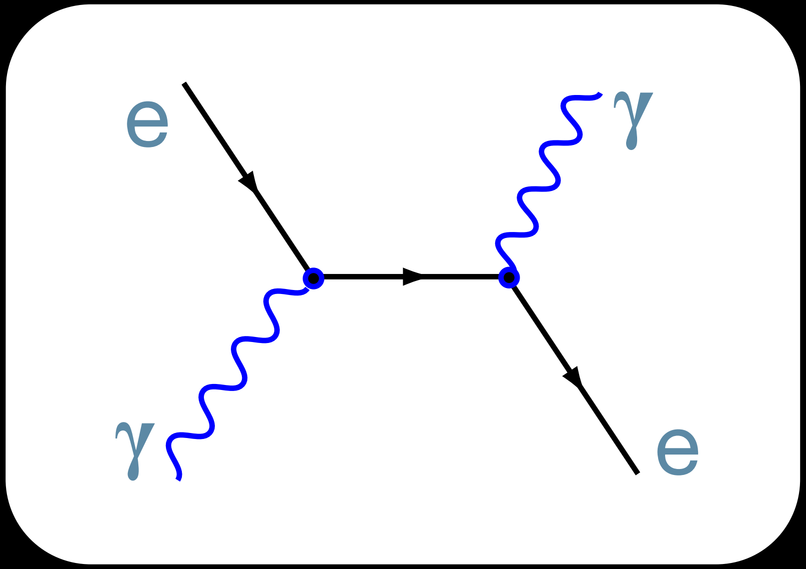
- Note that we had two diagrams for $e^+ + e^- \rightarrow e^+ + e^-$



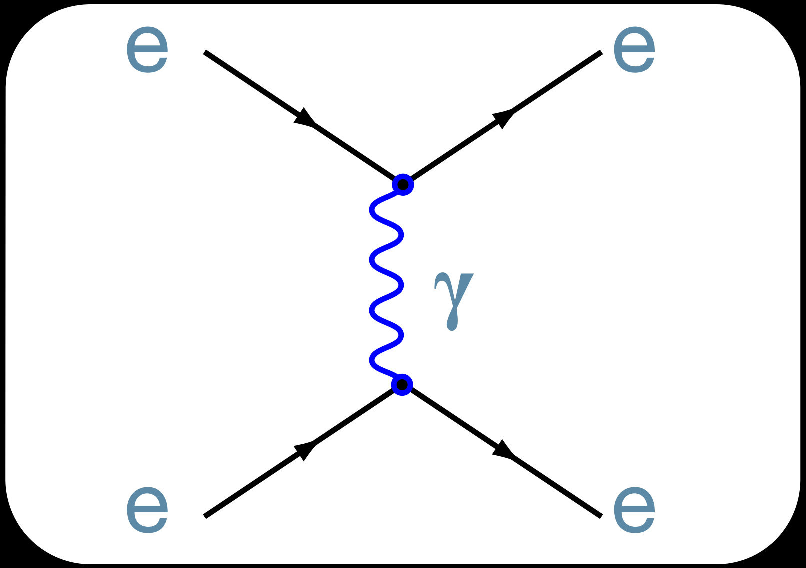
- actually, any allowed process has an infinite number of diagrams.
  - they all contribute to the process (recall QM)
  - so how do we do anything at all?
- Recall the coupling constant: if this is small, then diagrams with more vertices have smaller contribution.
  - For EM, this constant is ~1/137 for each vertex
  - to do a calculation at "order N" consider ALL diagrams with up to N vertices.
    - this makes QED "work"; allows expansion based on order

EXAMPLES:

- Compton Scattering:

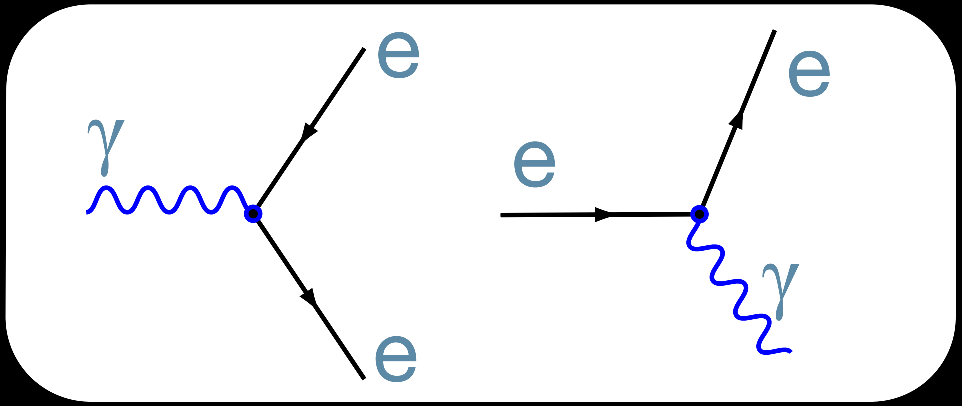


- Möller Scattering:



ON VS. OFF SHELL:

- Diagrams must also be kinematically valid
  - In addition to QED rules, there are kinematic rules
    - e.g. these are valid QED diagrams
    - but they violates E/p conservation



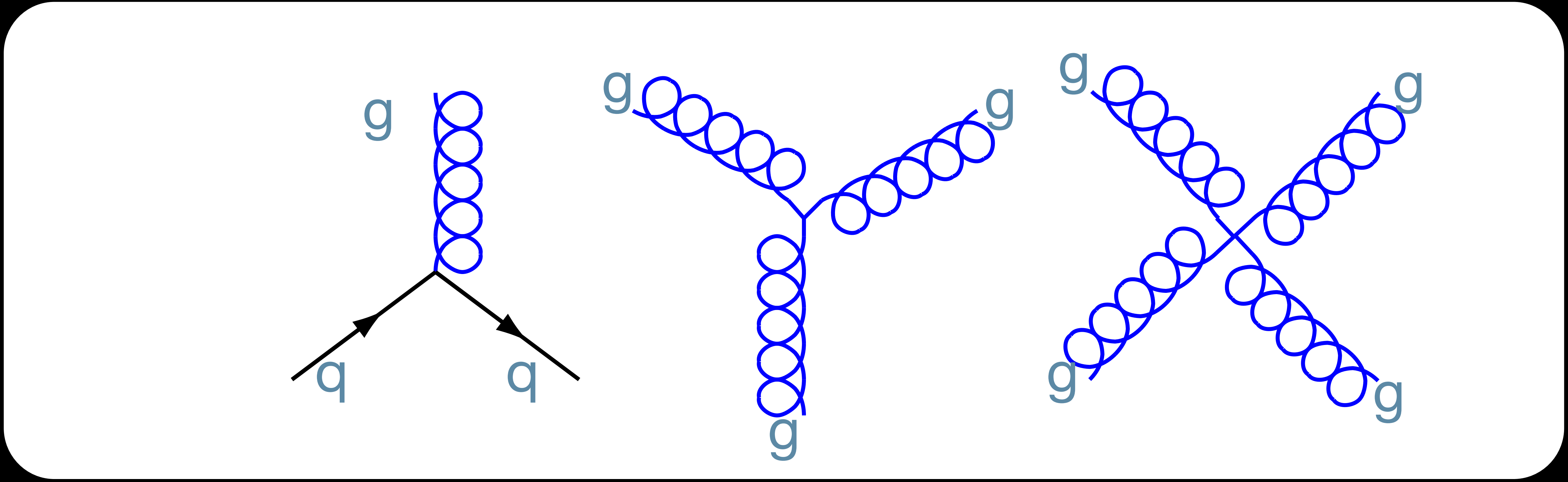
- However, lines and diagram components that are "internal" can have any momentum/energy
  - "internal": lines terminate into other lines (do not end)
  - there is no mass constraint: particle are "off-shell" or virtual
  - so long as the overall E/p coming in is equal to the overall E/p coming out (and this is possible) diagram okay
  - we call these "virtual" parts of the diagram that we don't see.

PHASE SPACE:

- How does the "strength" of an interaction manifest itself?
  - in decays, how long does a particle last?
  - in scattering, how often does it happen (as opposed to the particles passing by each other without interacting)?
  - in binding, how tightly are the particles bound?
- There are many factors that affect this:
  - the coupling constants (i.e. what interactions are involved)
  - some peculiar dynamic issues (will come back to this)
  - "phase space":
    - how much "room" is there kinematically for the process
    - in particular, decays to lighter particles are favored over decays to heavier ones.

QCD (STRONG INTERACTIONS)

- As photons "couple" to electric charge, gluons couple to "colour", of 3 there are 8 types
  - Quarks have colour, but leptons do not.
- Much the same with two exceptions
  - The gluon, which takes the role of the photon, carries charge (colour) itself, and hence can couple to itself:



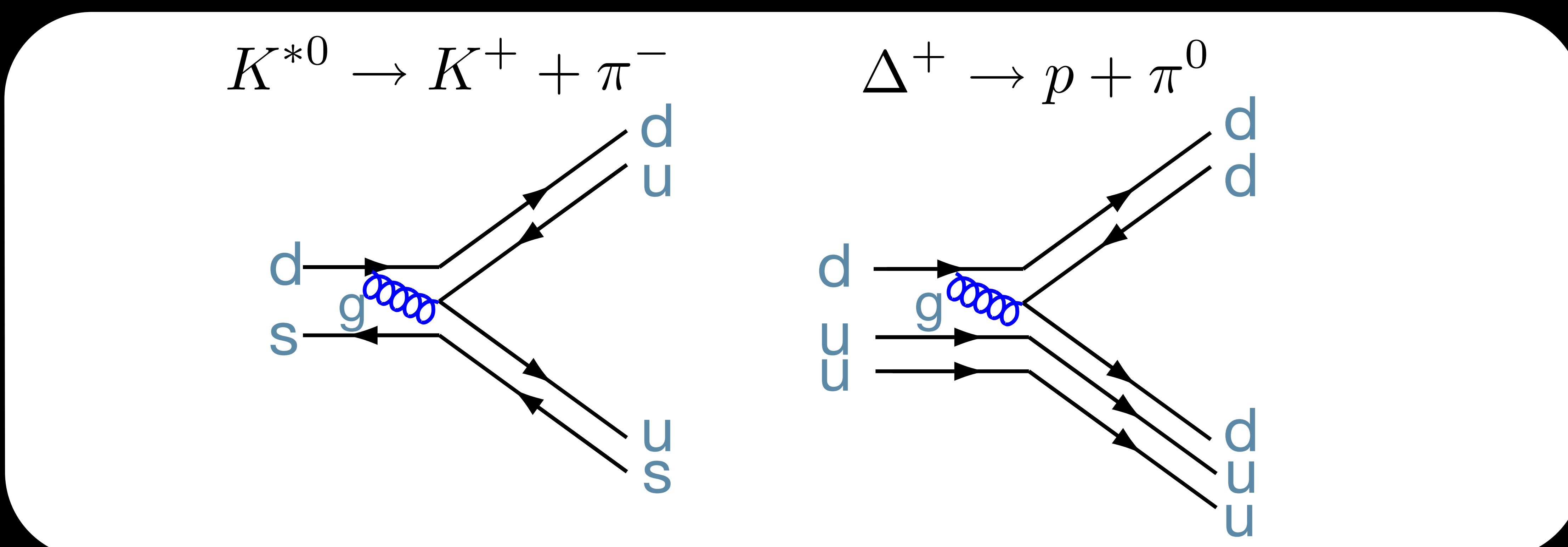
    - the same quark must come in and out (flavour conservation)
  - The coupling constant can be large: ~O(1)

ASYMPTOTIC FREEDON

- The strong interaction has a strange property:
  - The strength of the interaction increases with distance!
  - (in Fourier-space: the softer the gluon, the stronger its coupling).
- How does this happen?
  - In general, the strength of an interaction varies with distance (softness of the intermediate boson).
  - t'Hooft (followed by Gross, Politzer and Wilczek) suggest that it may actually increase!
  - (Nobel Prize 2004)

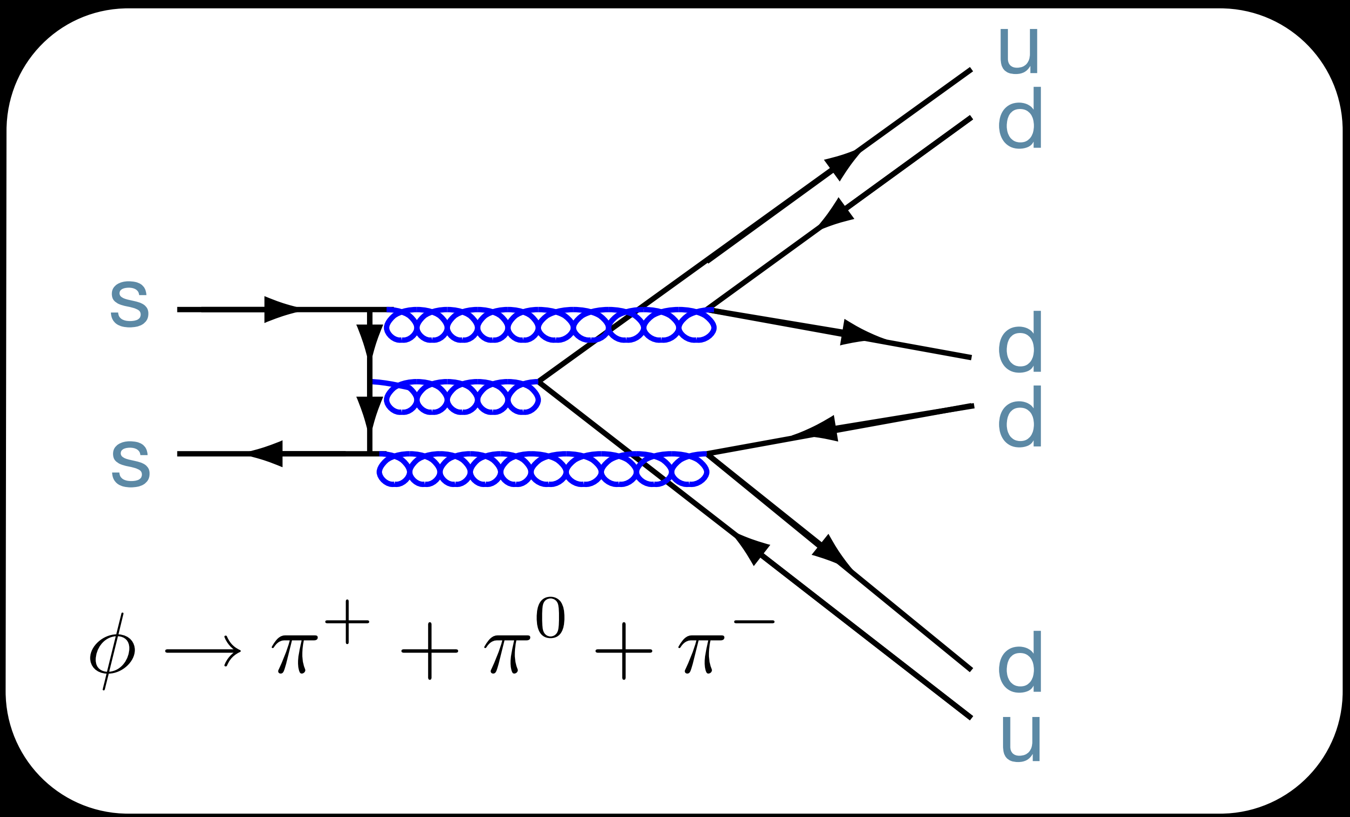
QCD OF HADRONS

- In the laboratory, we never see quarks, only
  - mesons (quark, anti-quark pairs)
  - baryons (three (anti-)quarks)
- To understand the underlying QCD interaction, we need to know the quark content of both the initial and final state



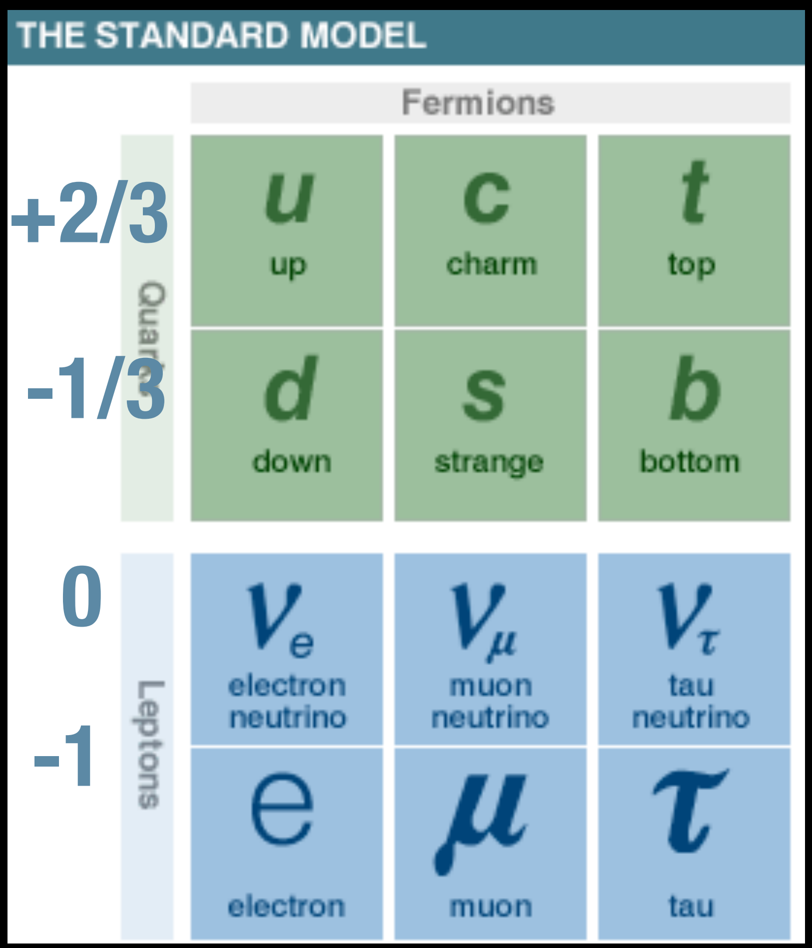
OZI RULE

- Diagrams which can be “cut” along gluon lines are suppressed

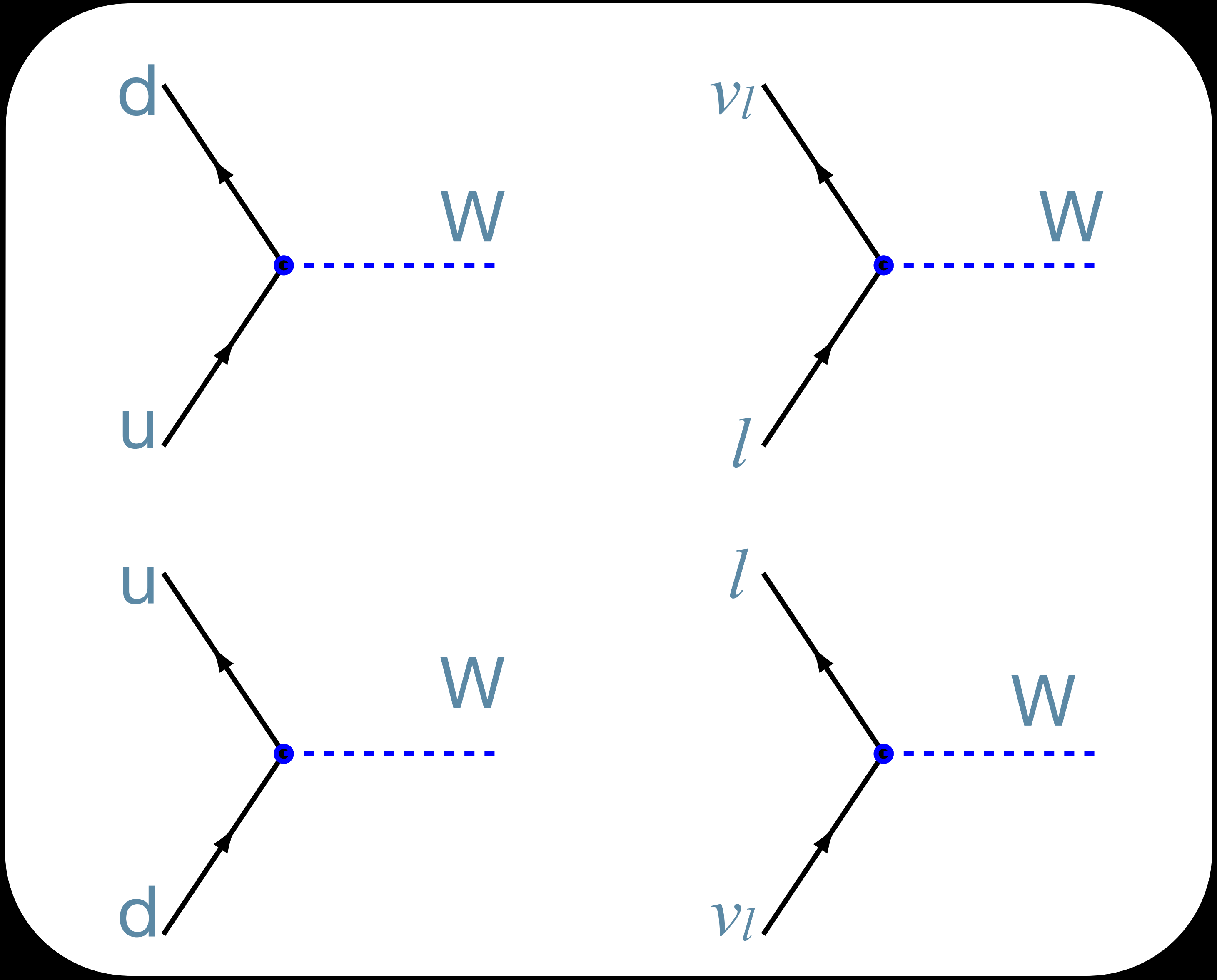


- Comes back to asymptotic freedom;
  - hard gluons interact more weakly
  - therefore, interactions that require hard gluon exchange are suppressed.

WEAK INTERACTIONS:



- Note that the fermions come in pairs
  - one unit of charge apart
  - The weak charged-current (CC) interaction can result in conversion between these pairs

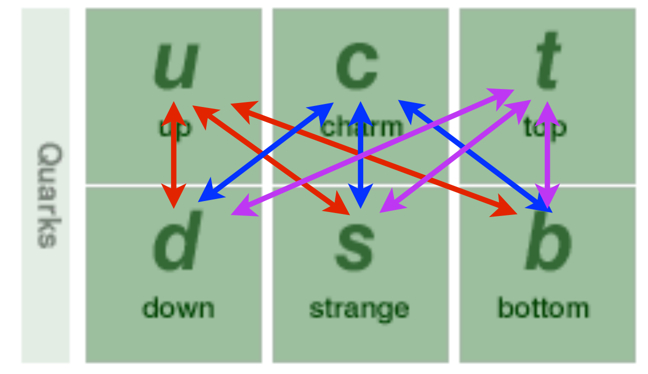


Column of fermions is called a "generation"

Note arrow directions and charge/direction of W

CC INTERACTIONS

- For the leptons (neutrinos, e, μ, τ) that's all there is to it:
  - the weak CC changes a ν_l into lepton l (and vice versa)
- For the quarks, the situation is more complicated
  - The weak interaction can "cross generations"



- so not just **u** ↔ **d**, **c** ↔ **s**, **t** ↔ **b**
- but also **u** ↔ **s**, **u** ↔ **b**, **c** ↔ **d**, **c** ↔ **b**, **t** ↔ **d**, **t** ↔ **s**
- but they are not equal!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad |U_{CKM}| \sim \begin{pmatrix} 0.9738 & 0.2272 & 0.0040 \\ 0.2271 & 0.9730 & 0.0422 \\ 0.0081 & 0.0416 & 0.9991 \end{pmatrix}$$

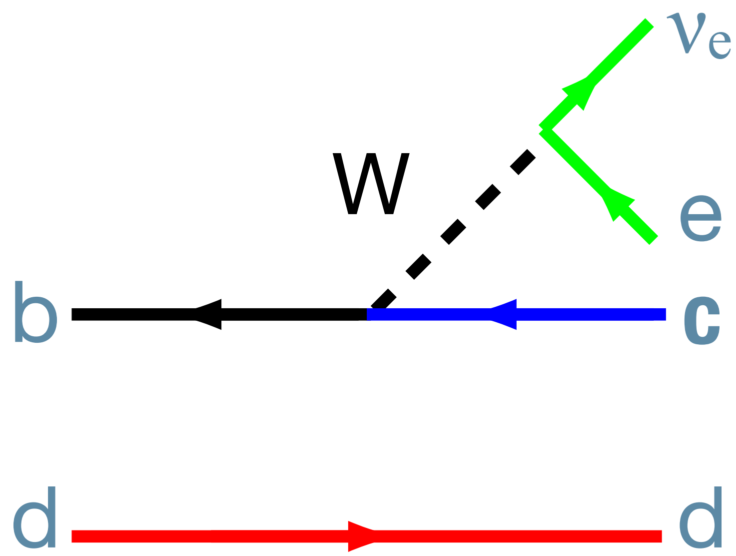
- Transitions within a generation are preferred (e.g. u↔d)
- Transitions that one cross generation are suppressed
  - those that cross two are even further suppressed.

WHAT DOES THIS MEAN?

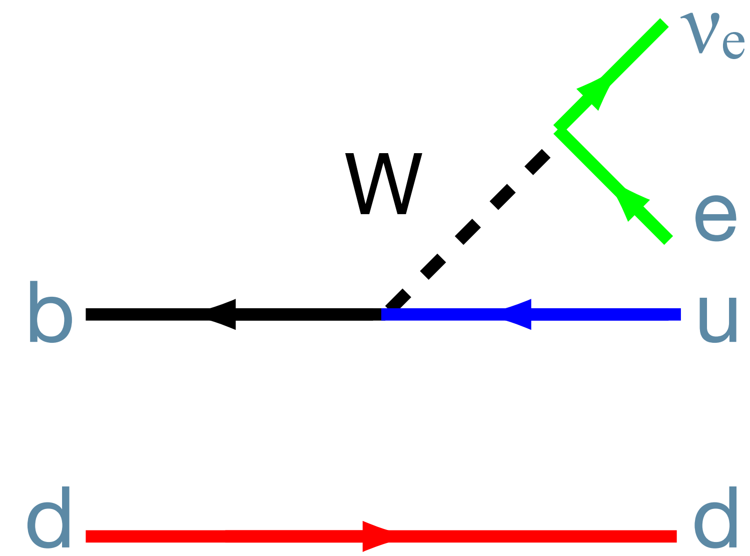
- This explains why “strange” particles last long:
  - Coupling of **u** ↔ **s** required is much smaller than for **u** ↔ **d**
- This holds more generally:
  - if a decay or a transition involves quarks within one generation, these are favored
  - if a decay or a transition hops one generation we say that it is “CKM-suppressed”
  - if a decay or a transition hopes two generations we say that it is “doubly CKM-suppressed”
- Note that the weak-charged current is the only interaction that can enact flavour change!

EXAMPLES:

$$B^0 \rightarrow D^{*-} + e^+ + \nu_e$$

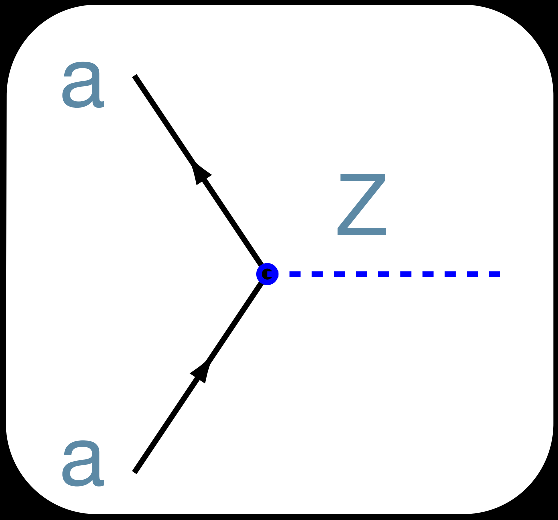


$$B^0 \rightarrow \rho^- + e^+ + \nu_e$$



- Note that the d quark doesn't participate in the weak interaction
  - "spectator quark"
- A particle may decay via many modes: "branching mode"
  - the fraction of times it decays via a particular mode is called its "branching fraction"
  - a more favored decay mode has a high "branching fraction"
  - sometimes there is reference to "branching ratio"
    - ratio of the branching fractions.
    - sometimes loosely used to also refer to "branching fraction"

NC INTERACTIONS



- Much like the EM interaction
  - instead of a photon, we have the Z
  - "a" can be any fermion, including a neutrino
  - note inbound "a" is the same as outbound "a"
- We'll see later that the EM interaction and the weak interaction are very intimately related
  - this is why, at least as Feynman diagrams, EM and NC behave nearly the same
  - at low energies ($E<M_Z$), the EM interaction is much stronger
    - this has to do with the massiveness of the Z

RULES OF THUMB:

- Check simple things:
  - does the interaction conserve charge?
  - for a decay, is the total mass of the products less than the initial?
  - if there are baryons/mesons involved, find the quark content
- Which interaction? (There may be more than one)
  - if there's a photon in the initial/final state, EM must be involved
  - if there's a neutrino, the weak interaction must be involved
  - if there are leptons ($e/\mu/\tau$), then the weak or EM interaction must be involved.
  - if the total quark content (i.e. quark - antiquarks of each type) changes in an interaction, weak CC must be involved

WHICH IS FAVORED?

- If a process can occur through QCD, it will go dominantly through this channel
- At low energies (E< M_W,M_Z), the electromagnetic interaction is stronger than the weak.
- For weak charge current interaction of quarks, look at the quark transitions
  - this determines the CKM factors.
- Look at phase space.
  - Decays to lighter particles are favored.

SUMMARY

- The fundamental particles roughly come in three forms:
  - spin 1/2: fermions: quarks, leptons
  - spin 1: gauge bosons (g, W, Z, g)
  - spin 0: Higgs Boson
- Feynman diagrams illustrate how we get from initial to final state via the fundamental interactions
  - interactions are summarized in “vertices” which connect different particles
  - need to know “rules” and also account for kinematic constraints
- Strong interactions:
  - weaker in short range/“hard” interactions
- Weak interactions:
  - charged current (W): interactions transition **u** ↔ **d** quarks and $\nu \leftrightarrow l$
    - in quarks, inter-generational transitions are suppressed
  - neutral current (Z): flavor-conserving interaction with all fermions (including ν)