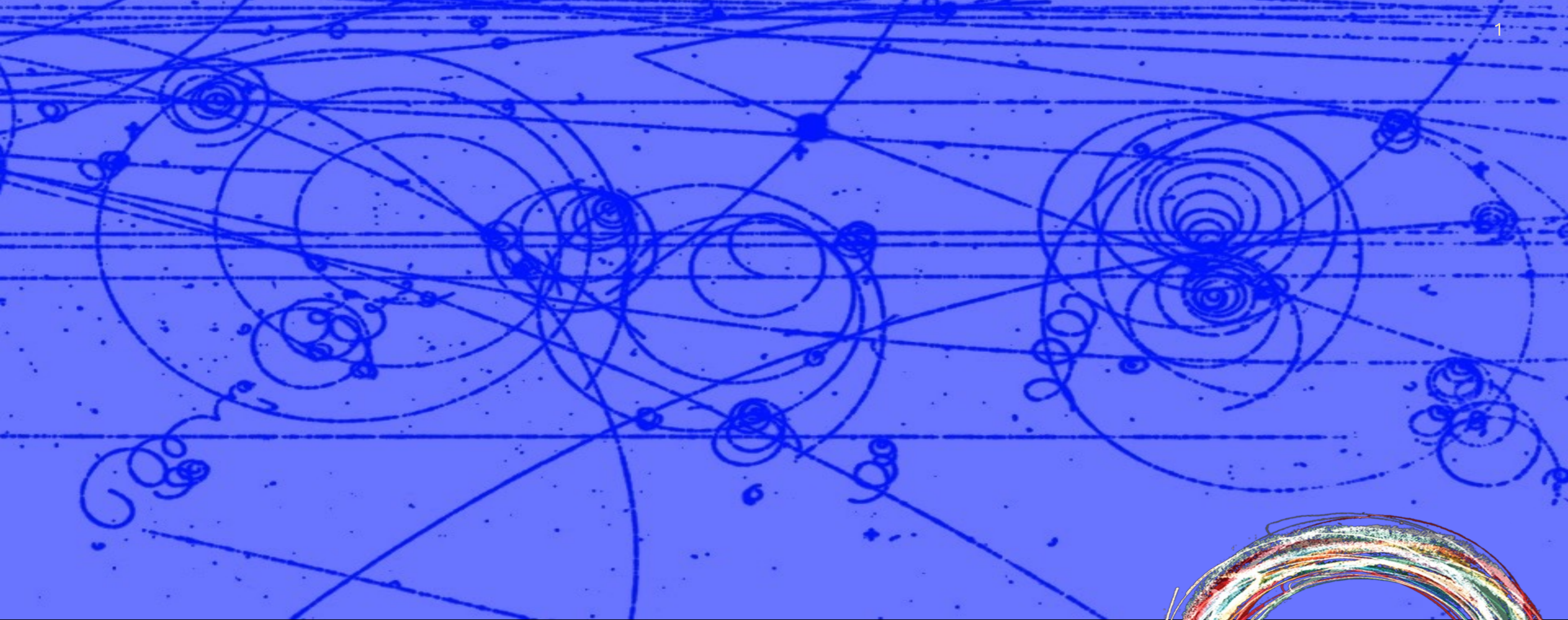
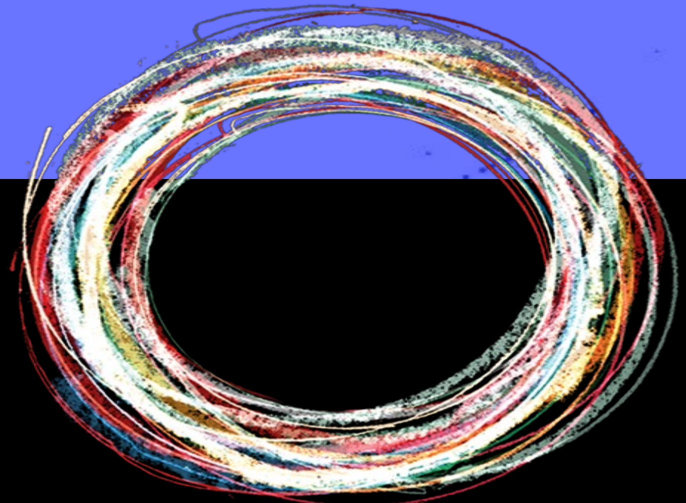


LECTURE 3
ELEMENTARY PARTICLE DYNAMICS

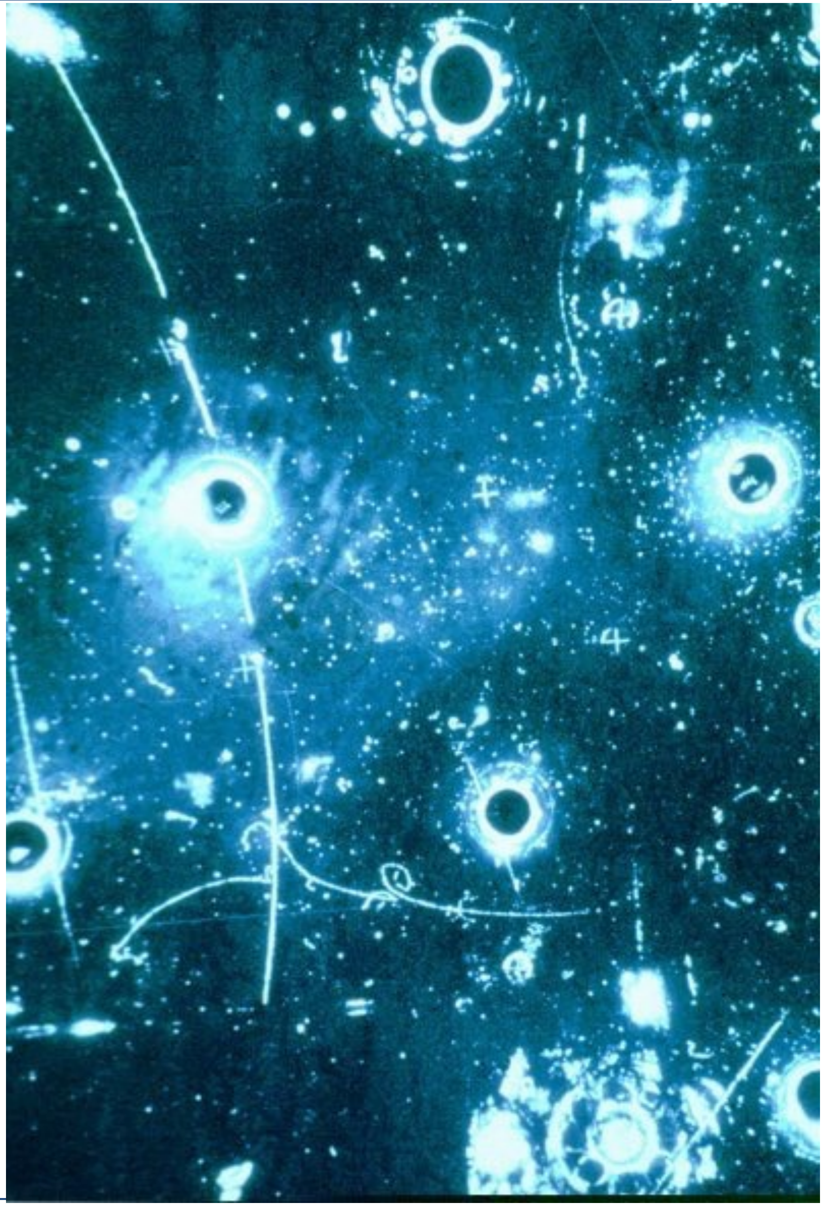


PHY 493 / 803

Announcements

Homework: due Monday at the start of class (3pm)
-will submit homework on gradescope (open by next class)
- Upload either pictures of handwritten work or typeset work
- There will be two versions of the assignment on gradescope, you will submit to the one for your section (803 or 493) – (this is also the only one that should be visible to you)
-If you have not used gradescope before you can make an account with your MSU email address

Reading: Chapter 2 of Griffiths



Recap / Up Next

<u>Last time:</u>

The particle zoo

- Quarks, leptons, bosons

Basic concepts

- Units, decays, anti-particles

Some history, two important cases

1. Discovery of the electron
2. Discovery of the nucleus

<u>This time:</u>

Particle dynamics & interactions

Exchange forces

Conservation laws

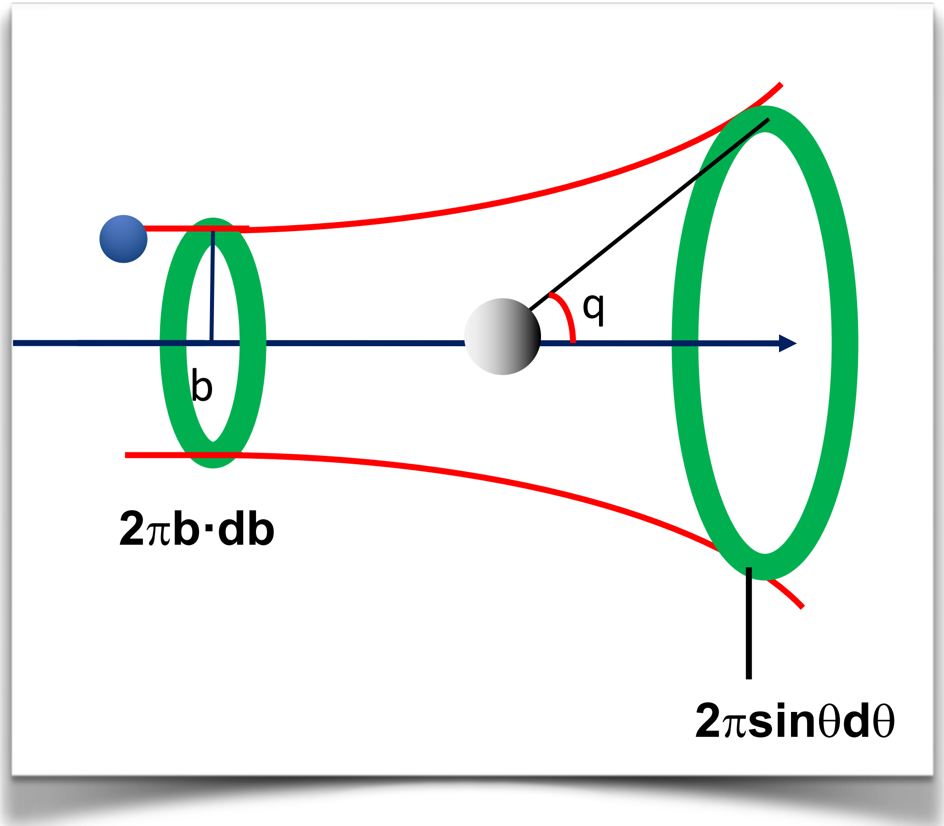
Interactions

Last time: particle interactions in Rutherford scattering experiment.

Today:

1. How these interactions occur and what we can learn from them.

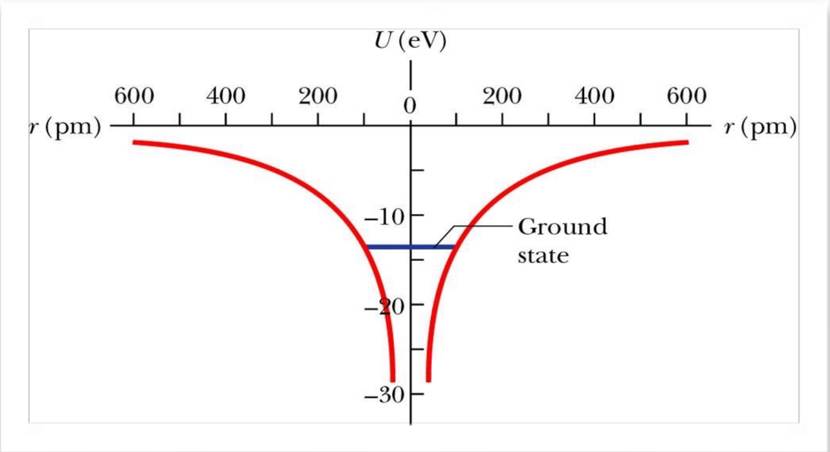
2. Feynman diagrams as a tool for representing and (eventually) calculating particle interactions

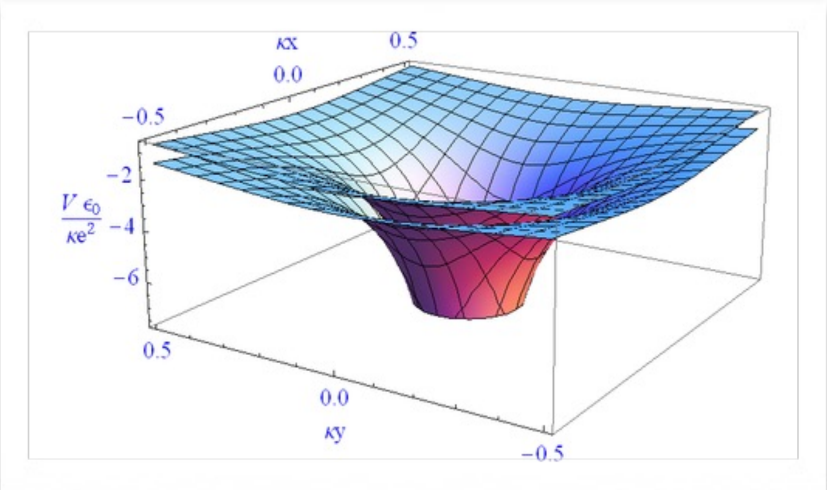


Interactions

A particle (ie, a field) can be shown to interact with a Hamiltonian (operator corresponding to total E of system).

For example: the Coulomb potential in which charged particles interact.





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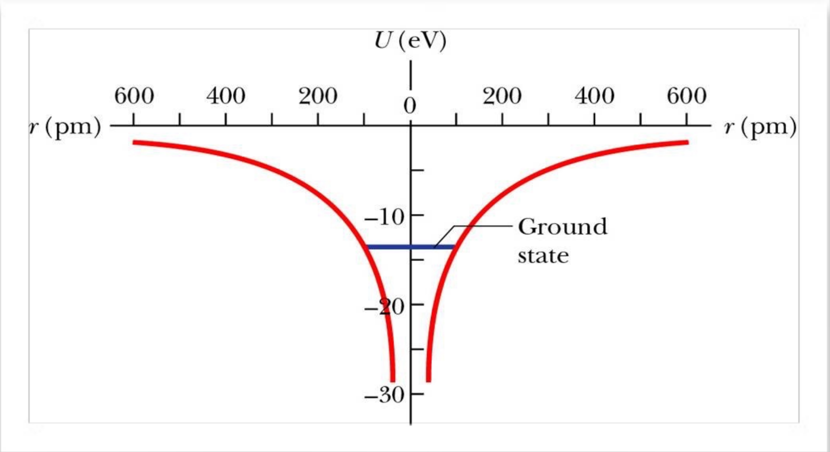
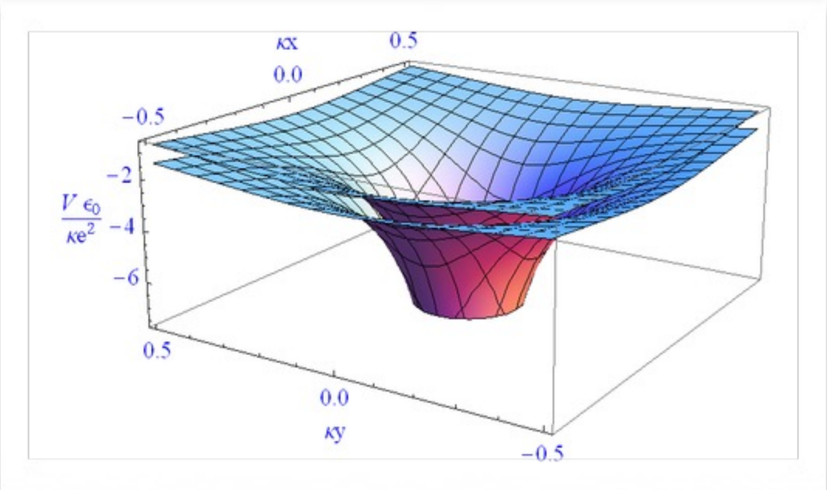




<u>Two major concepts associated with interactions:</u>

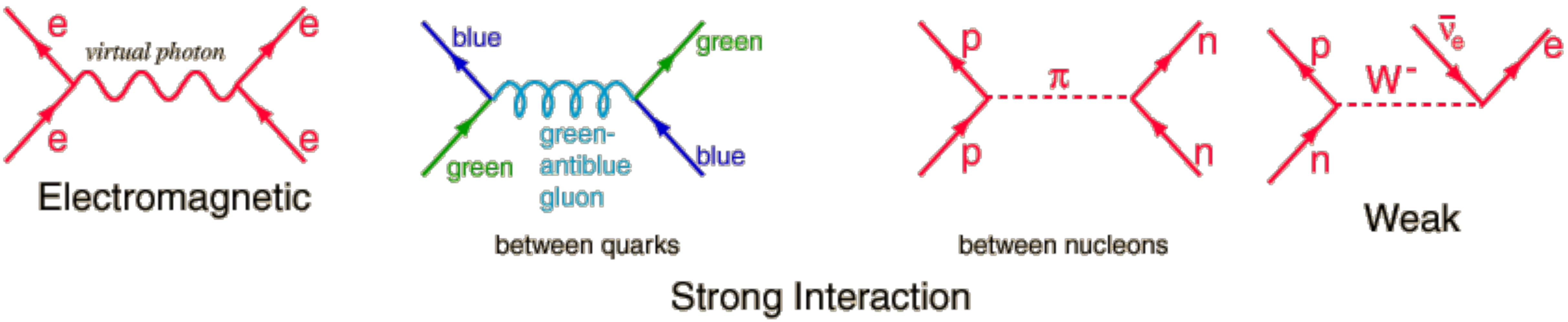
1) The interaction represents a potential acting on the field:
   Hamiltonian has the form H=KE+PE=T+V where V is non-zero.

2) This potential implies a force acting on a particle, and in quantum field theory, we manifest this force through **the exchange of force carriers.**

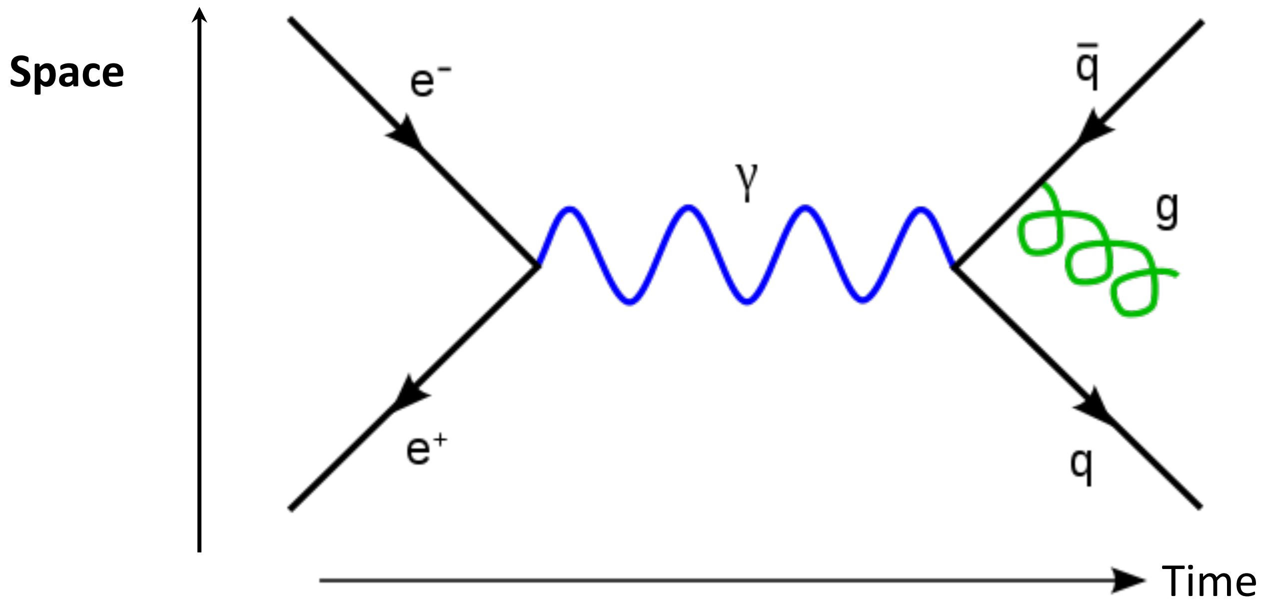
Interactions and Forces

Interaction	Current theory	Mediators	Relative strength[1]	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	1 (see discussion below)	10^{-15}
Electromagnetic	Quantum electrodynamics (QED)	photons	10^{36}	$\frac{1}{r^2}$	∞
Weak	Electroweak Theory	W and Z bosons	10^{25}	$\frac{1}{r}\ e^{-m_{W,Z}\ r}$	10^{-18}
Gravitation	General Relativity (GR)	gravitons (hypothetical)	1	$\frac{1}{r^2}$	∞

Standard Model

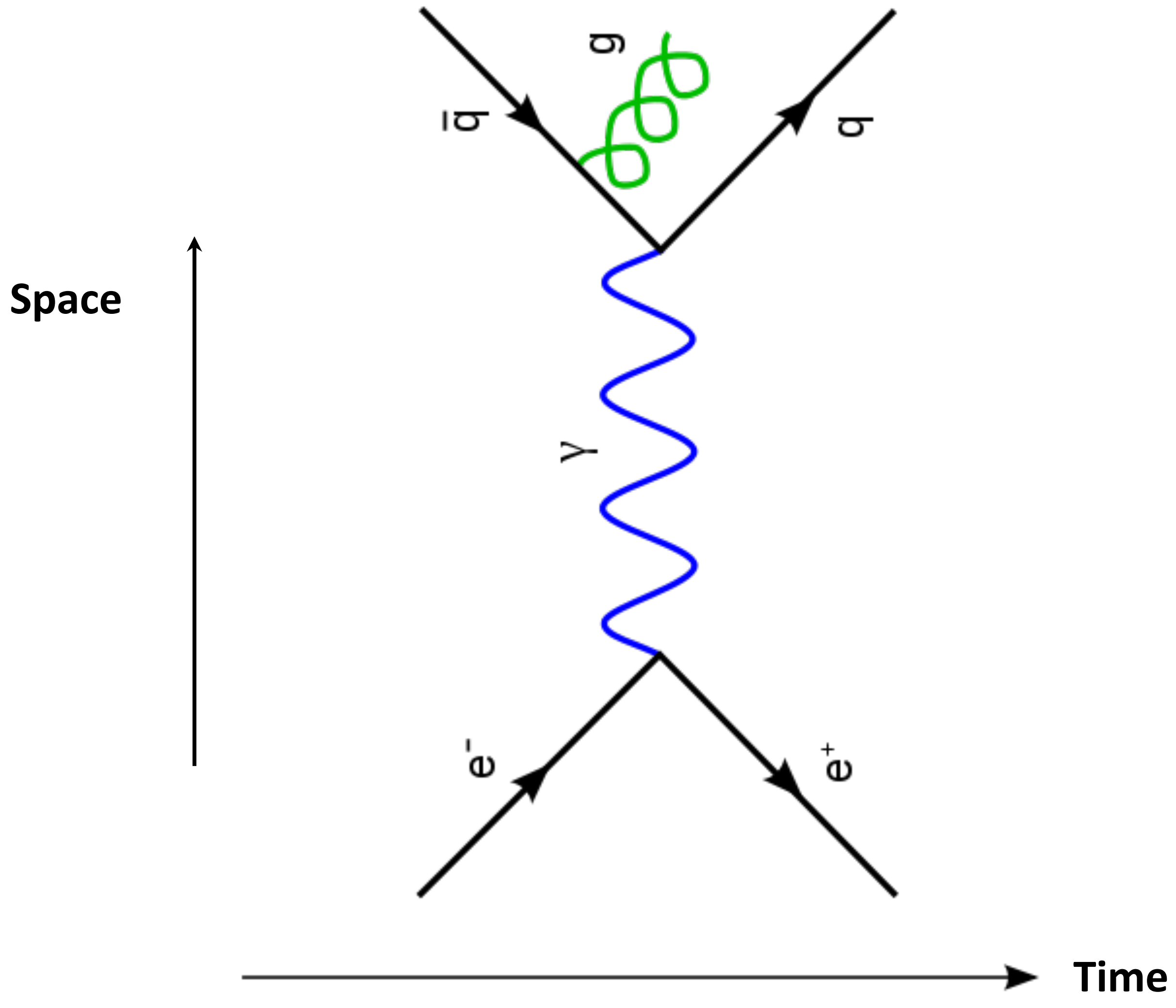


Feynman Diagrams



Note: diagrams can be rotated, but axes remain the same

Feynman Diagrams



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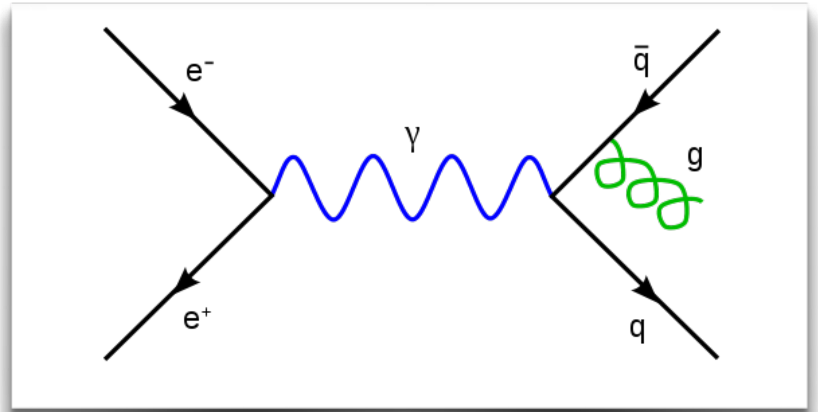
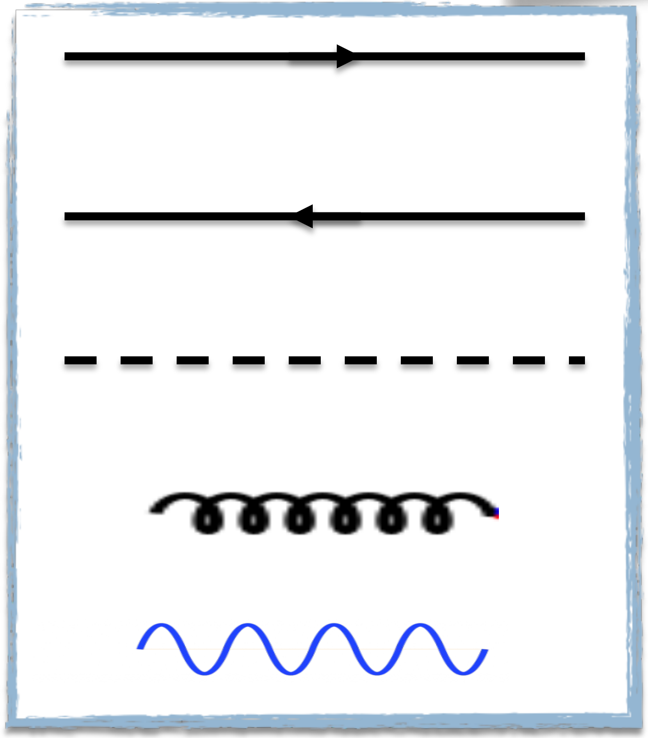
Elements of Feynman Diagrams





fermion line (eg, an electron or quark)

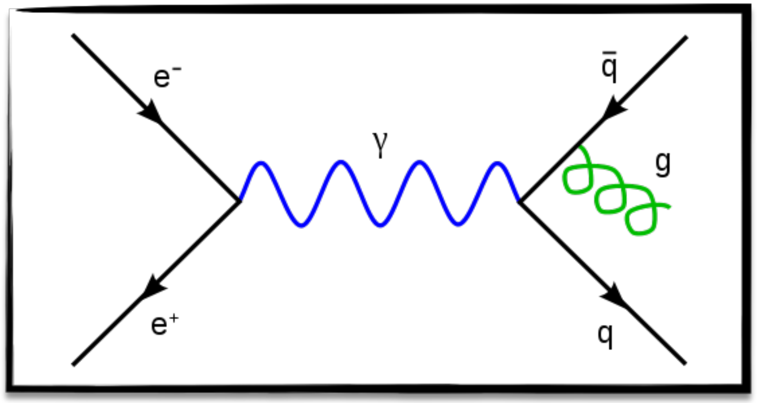
anti-fermion line (eg, a positron or anti-quark)

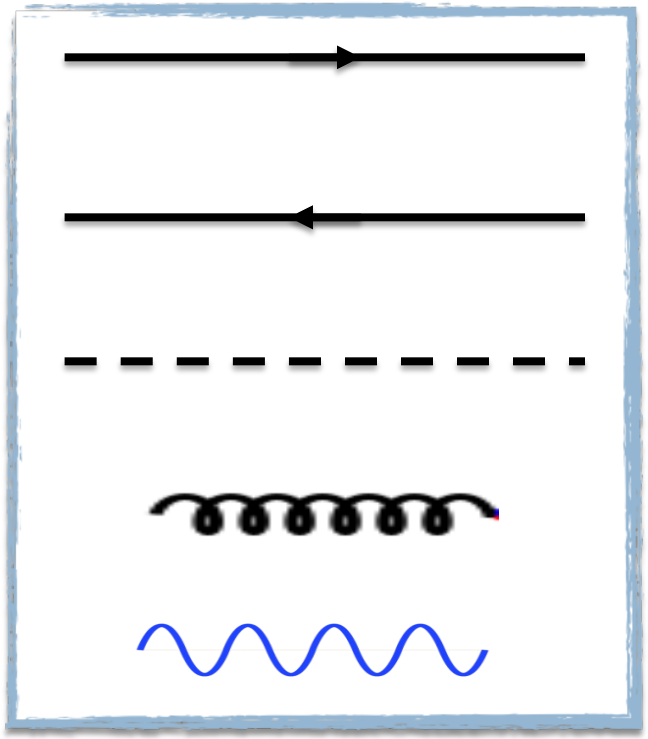
scalar line (eg, a Higgs boson)

gluon line

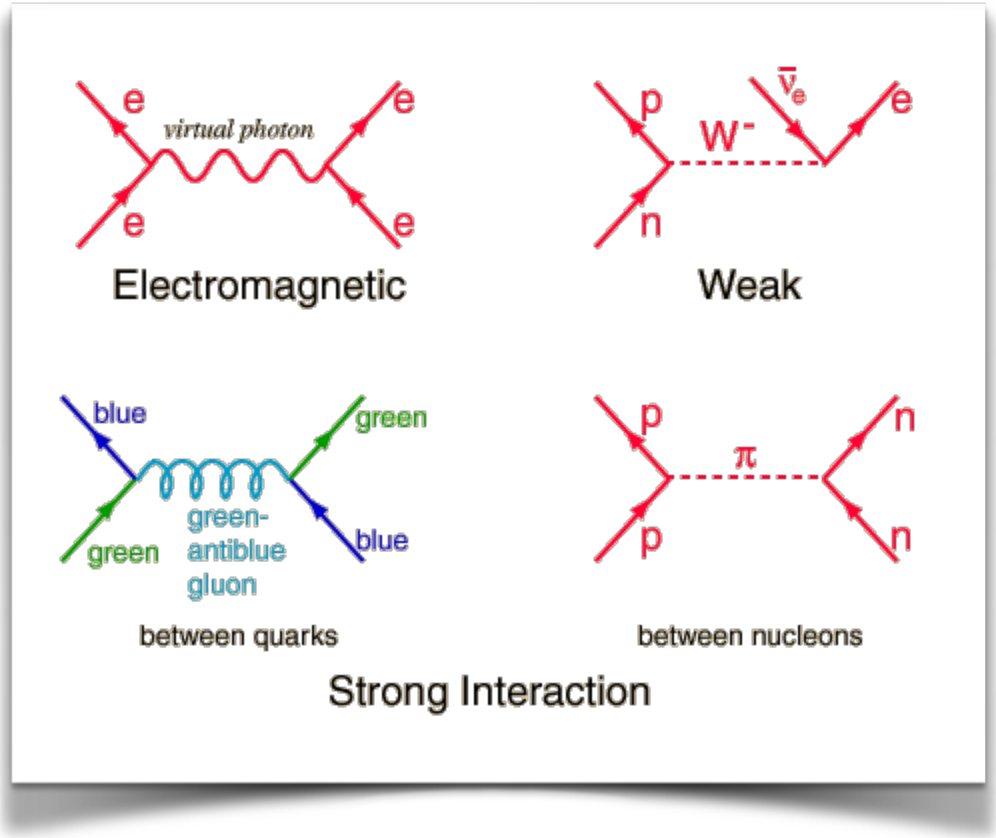
gauge boson line (eg, photon, W, or Z boson)

Feynman Diagrams





Note: people don't always follow these rules!



Feynman Diagram Rules

Rules for Feynman Diagrams

1. Initial state (left) and final state (right)
2. Lines are defined as earlier
3. Arrowhead pointing to the right (left) indicate particles (anti-particles)

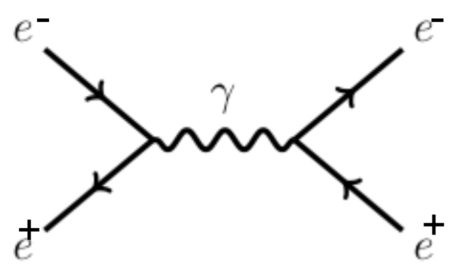
   Arrows do not indicate the particle's direction of motion!
4. Lines that end at boundaries are free particles
5. Vertices represent particle interactions

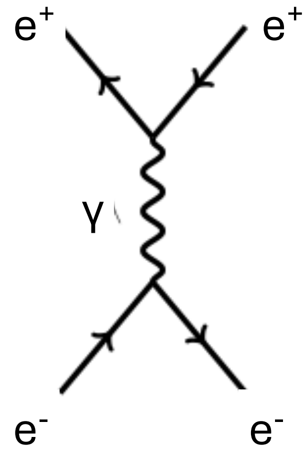
   5a. Energy (or momentum) is conserved at a vertex

   5b. Charge is conserved at a vertex

   5c. Fermion number is conserved at a vertex

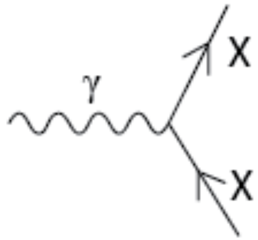
   5d. Quark number is conserved at a vertex
6. A rotation of a Feynman diagram must result in a valid diagram.
7. Internal propagator lines might not satisfy normal relativistic mass-energy relationships.





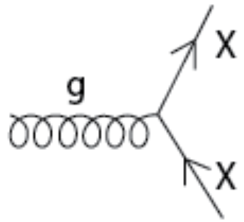
Basic Vertices

Electromagnetic

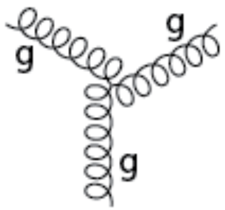


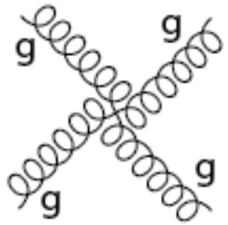
X is electrically charged.

Strong



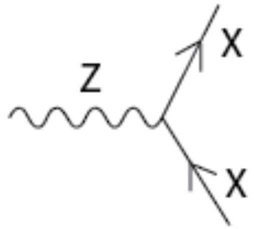
X is any quark.





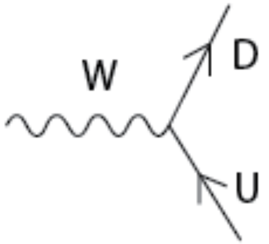
Weak

Neutral:

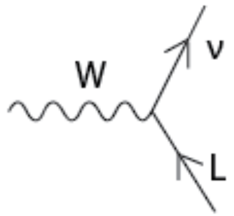


X is any fermion in the Standard Model.

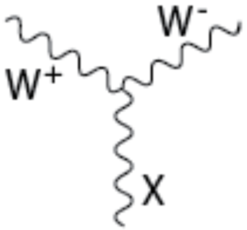
Charged:



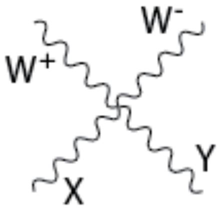
U is a up-type quark; D is a down-type quark.



L is a lepton and ν is the corresponding neutrino.



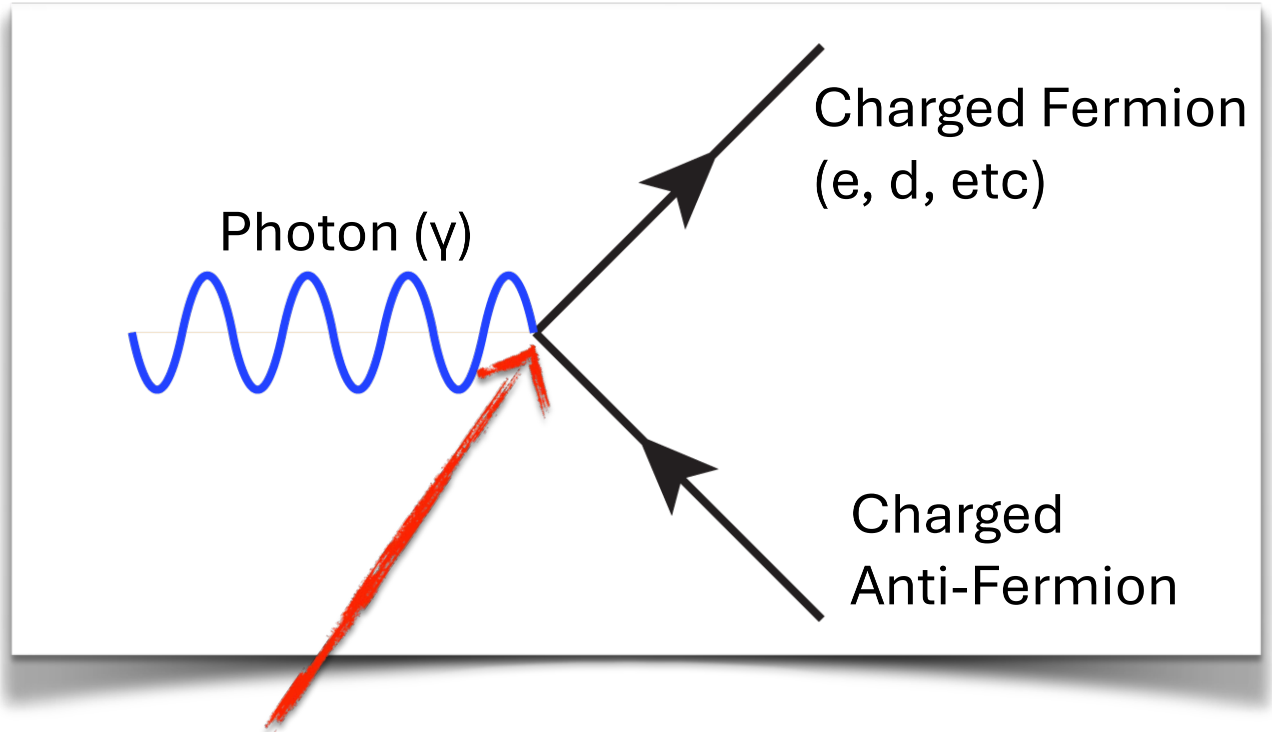
X is a photon or Z-boson.



X and Y are any two electroweak bosons such that charge is conserved.

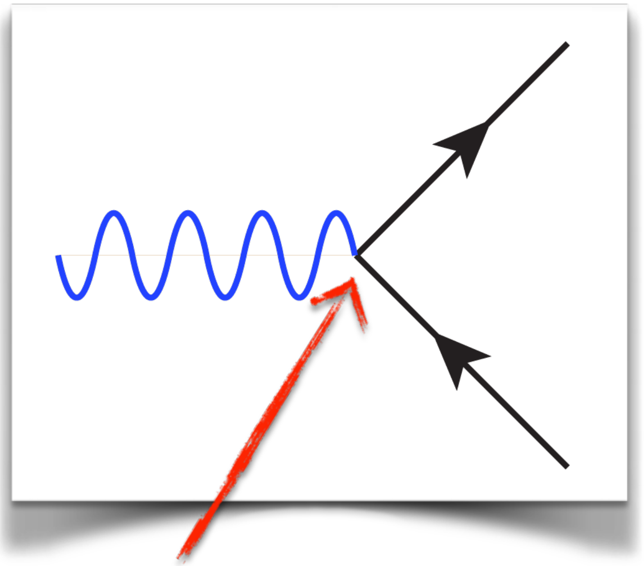
Quantum Electrodynamics (QED)

Electromagnetic force:



Vertex: the source/origin of the interaction.

Quantum Electrodynamics (QED)



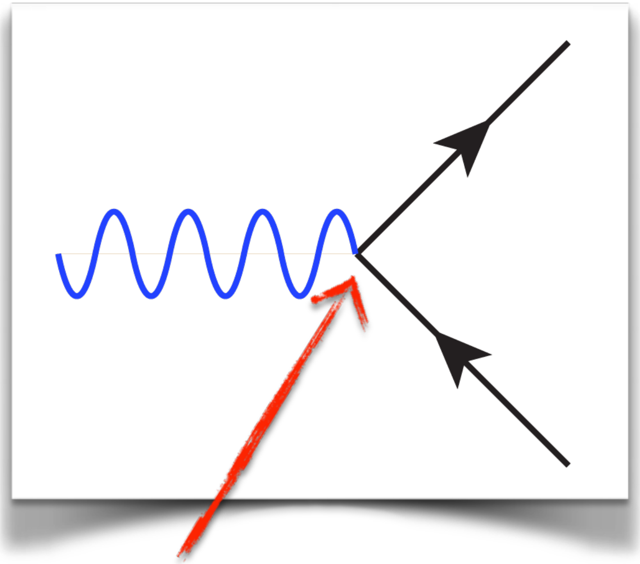
<u>Vertex:</u> the source/origin of the interaction.

The dynamics of the interaction are determined by:

1) The generator of the interaction. Also known as the "coupling".
   - In this context, the generator is electric charge.
   - **"The photon couples to electric charge."**

2) The quantities that are conserved at the vertex.
   - QED conserves most quantities!
     - Charge, fermion number, quark flavor, weak isospin, spin, parity

Quantum Electrodynamics (QED)



<u>Vertex:</u> the source/origin of the interaction.

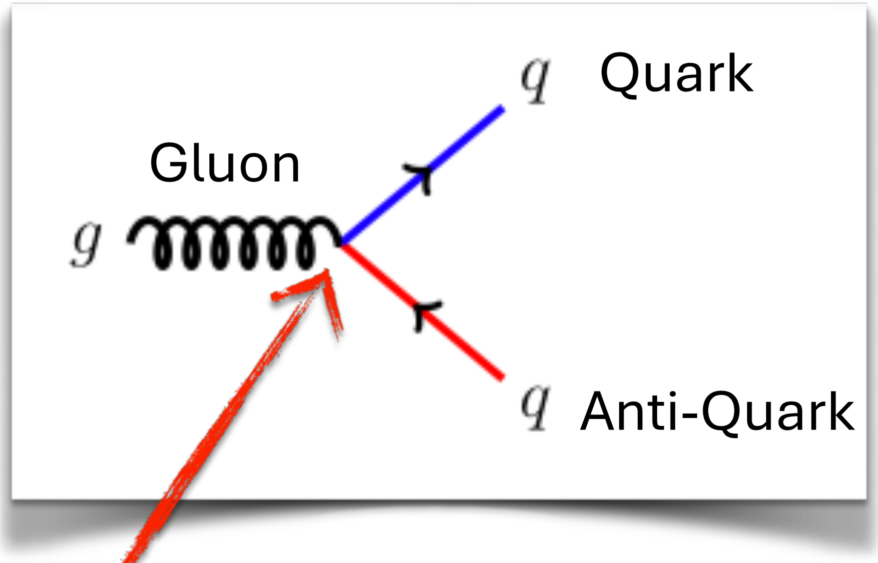
The probability for a process to occur (the cross section) depends on properties of the vertex.

- The "strength" of the QED coupling depends on the squared magnitude of the generator quantity
    - Electrons ($Q=\pm1$) couple more strongly to photons than quarks ($Q=\pm2/3$ or $\pm1/3$)
- Vertices that do not satisfy required conservation laws do not happen.
    - The QM probability to occur is 0.

More on how this is calculated later in the course!

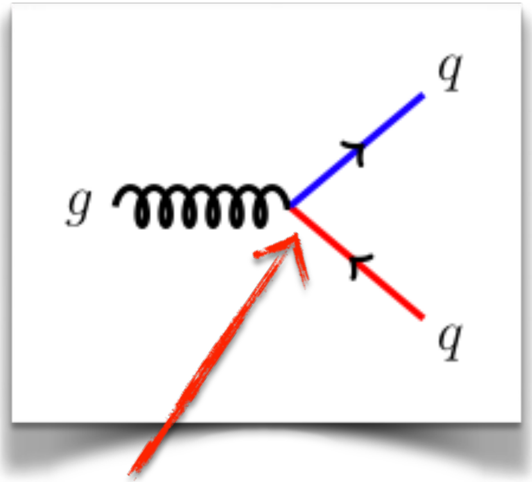
Quantum Chromodynamics (QCD)

Strong force



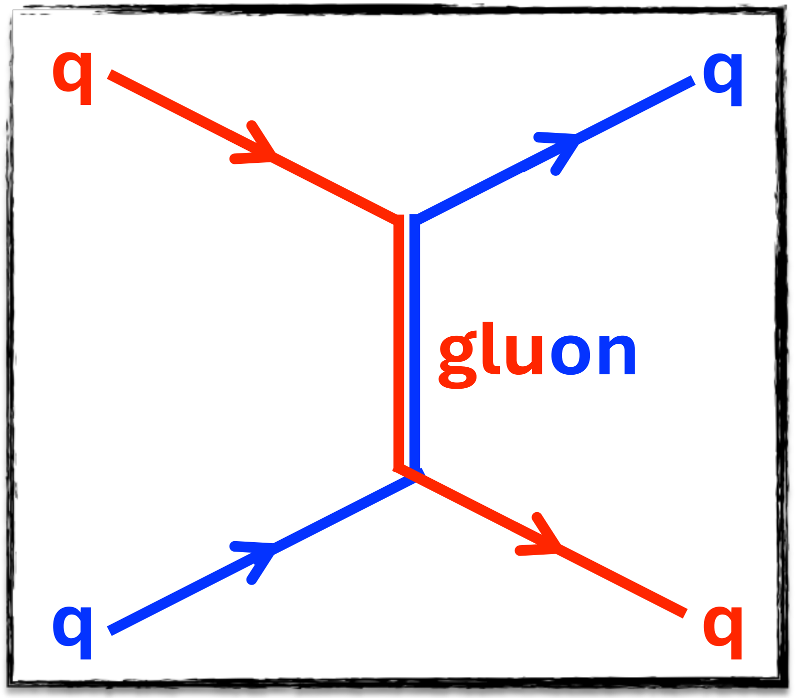
The generator for the QCD vertex is color. Only particles that carry color participate.

Quantum Chromodynamics (QCD)



The generator for the QCD vertex is color. Only particles that carry color participate.

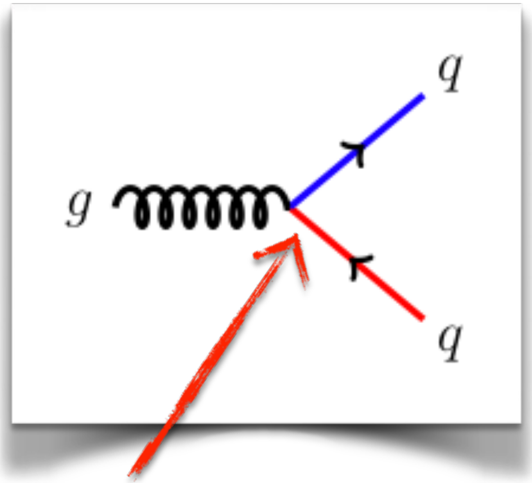
Recall, gluons have color!



Vertices conserve color

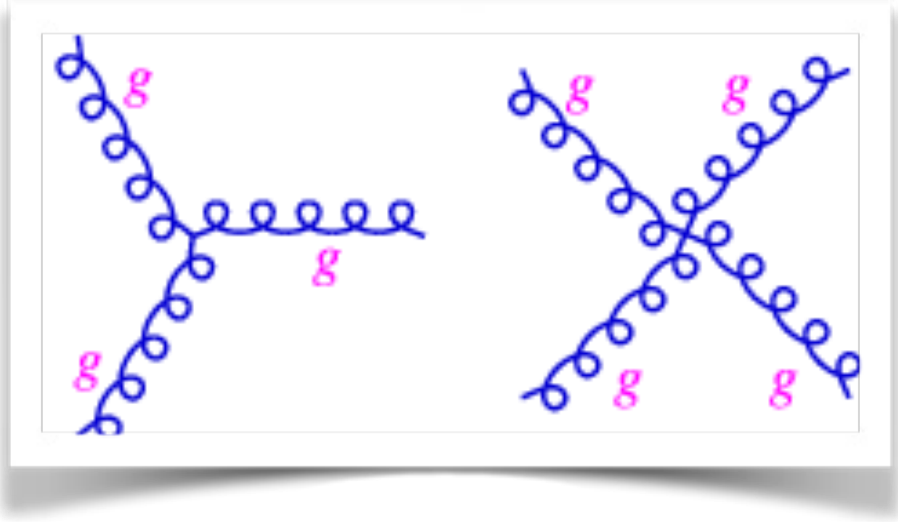
Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD):



The generator for the QCD vertex is color. Thus, only particles that carry color quanta participate.

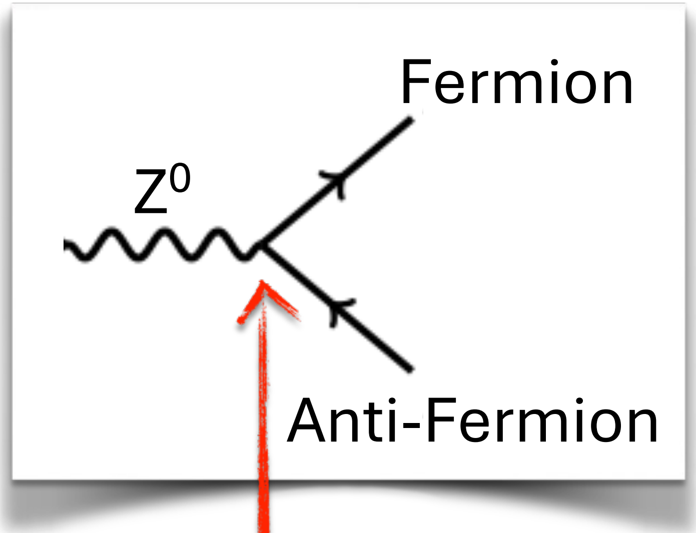
Recall, **gluons have color**!



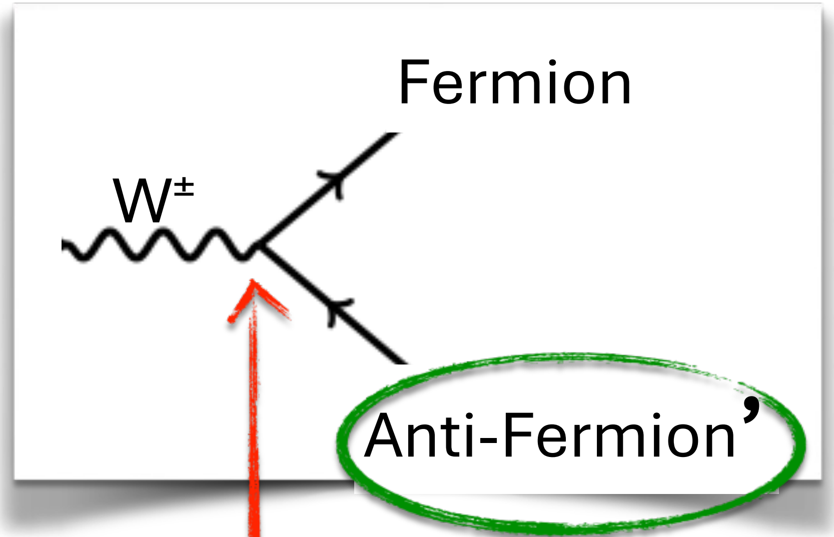
Quantum Flavor Dynamics (QFD)

Weak Force

Neutral "Current"



Charged "Current"



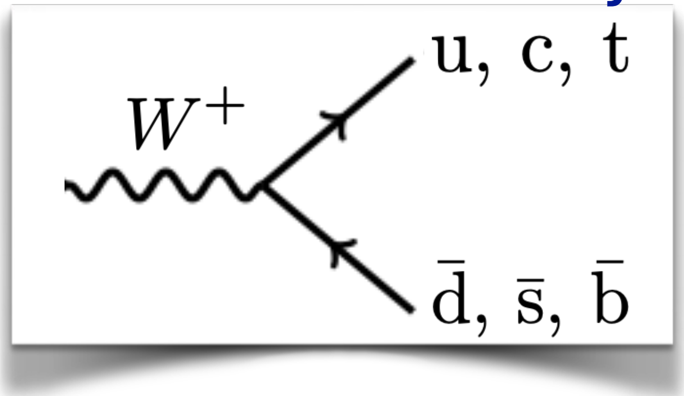
Not any anti-fermion!

The generator for the QFD vertex is a combination of weak hyper-charge and weak isospin.

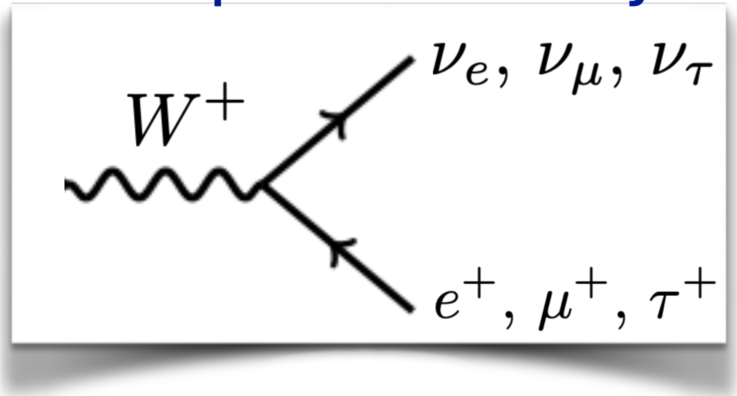
Charge conservation -> means cannot have fermion-anti-fermion pair (ie. e+ e-)

More on Charged Current Interactions

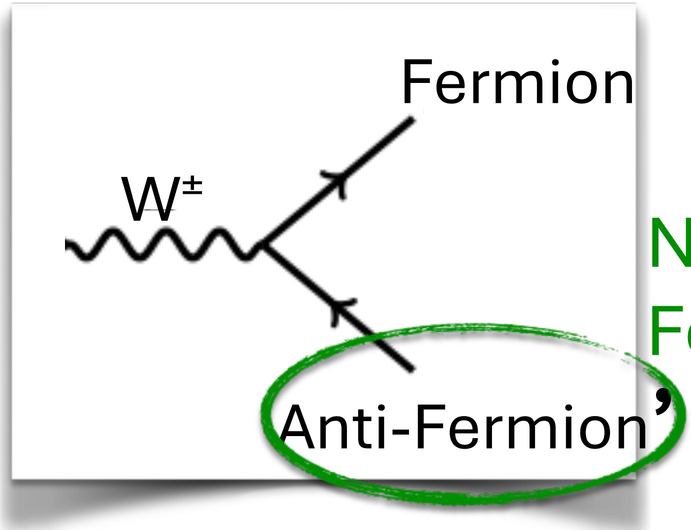
Hadronic Decay*



Leptonic Decay*



*For W boson sign change, flip particle/anti-particle assignments



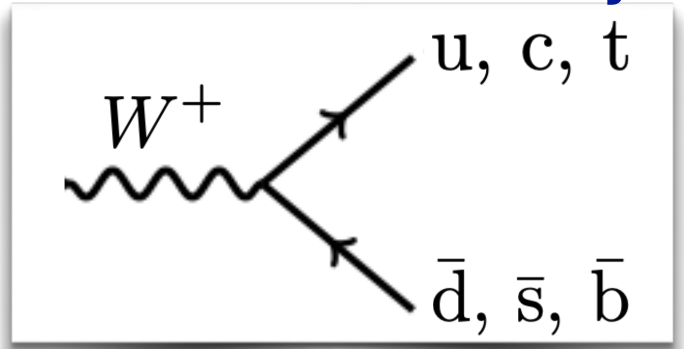
Not any anti-Fermion!

Total number of quarks conserved, but quark flavor is not conserved in weak interactions

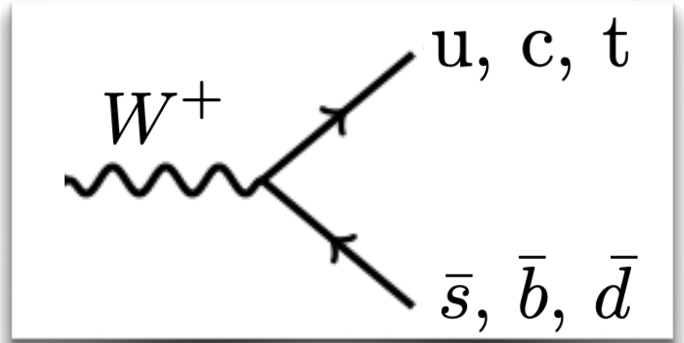
Lepton flavor is conserved by the weak interaction

More on Charged Current Interactions

Hadronic Decay*

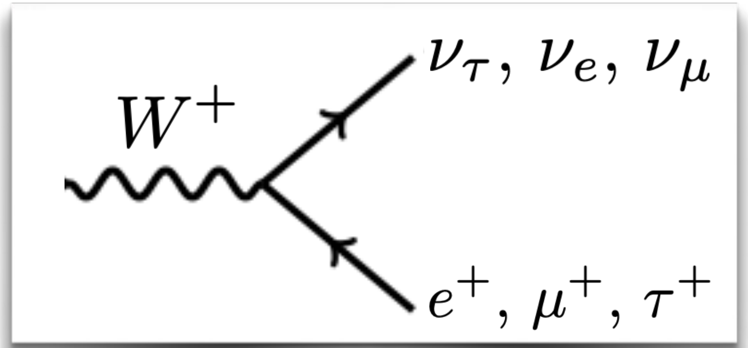


A Twist in the Story:



Allowed

Quark generation can also be crossed!

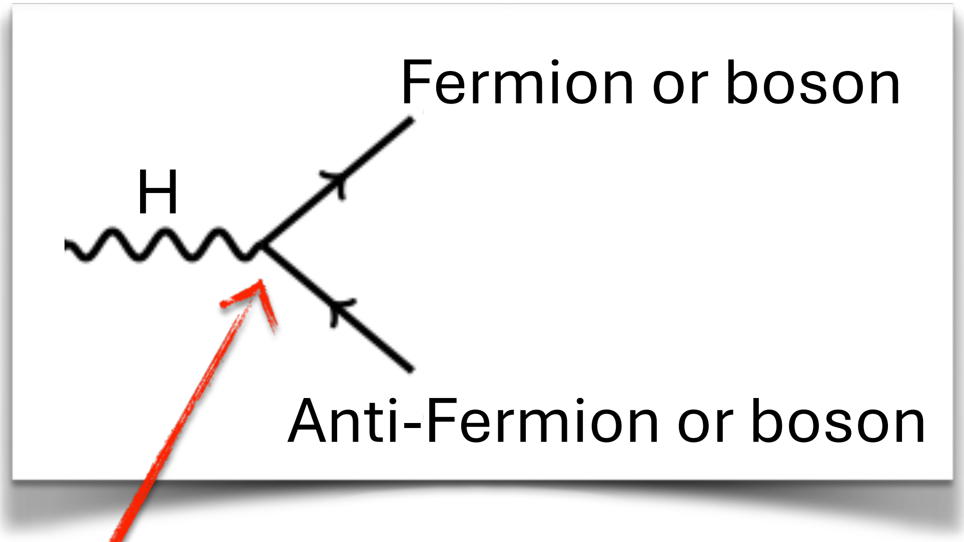


NOT Allowed!

There are flavor-changing charged current reactions.

- But only for quarks, not for leptons!
- ***And there are no flavor-changing neutral currents. The Z cannot do this!***

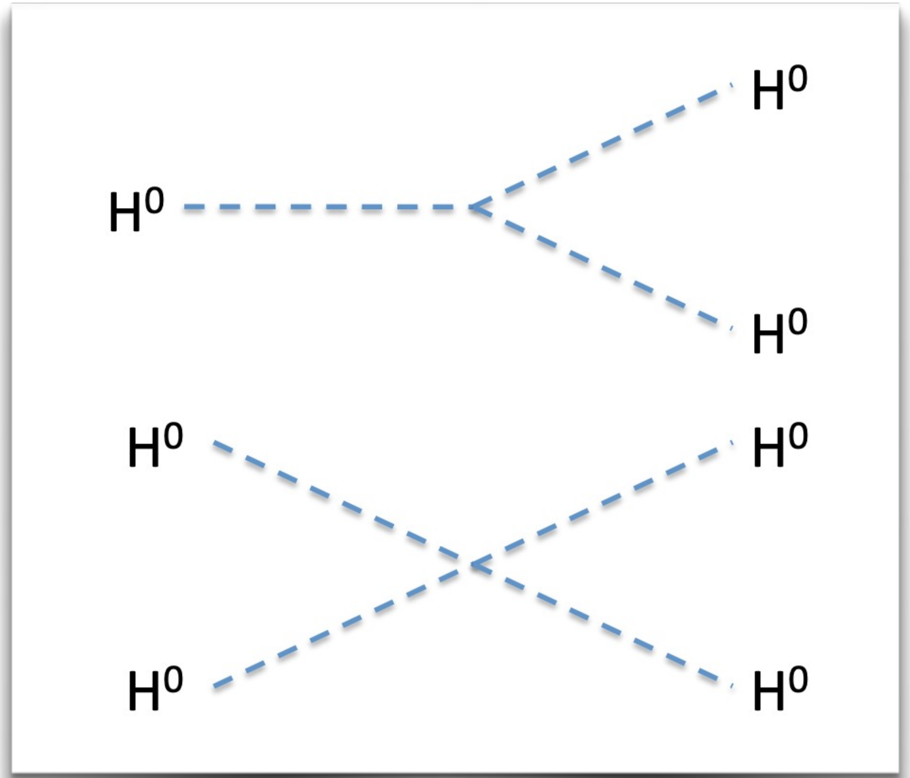
Higgs interactions



The generator for the Higgs vertex is the particle mass

- The generator for the Higgs vertex is mass
    - Only particles that have mass participate
    - The heavier the particle, the stronger its Higgs interaction
- Higgs interaction conserves most quantities
    - Charge, fermion number, quark flavor, weak isospin, spin, parity, color

Higgs self-coupling



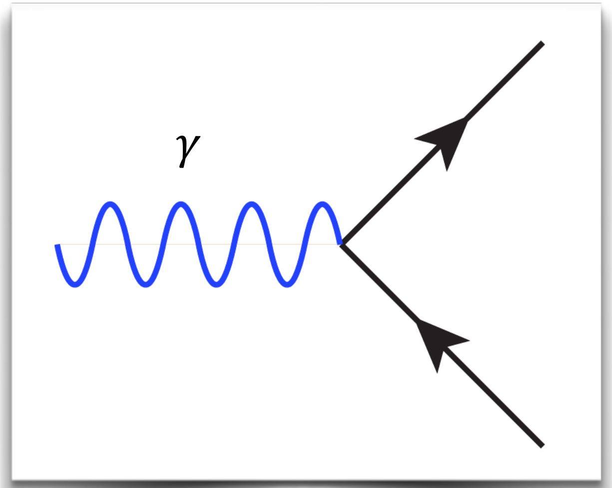
Higgs tri-linear coupling
Higgs quartic coupling

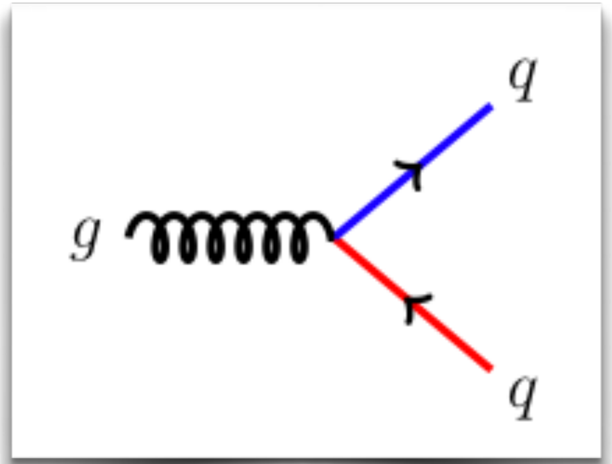
Both probe the structure of the Higgs potential

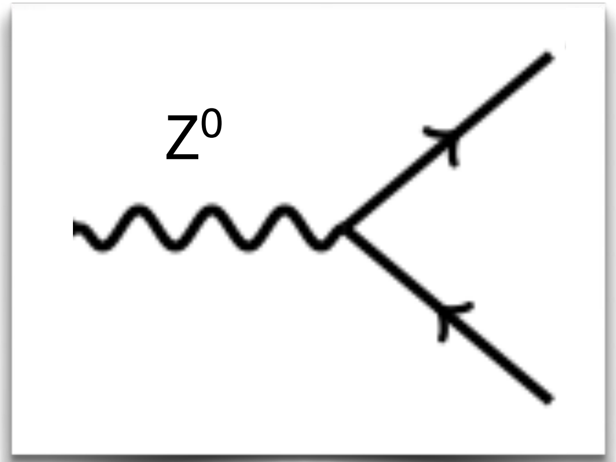
Vertex Building Blocks

These vertex building blocks are just that: pieces of larger puzzles

- They do not exist in nature: something has to emit the boson
  - The boson must be virtual - its mass must be equal to the total final state energy



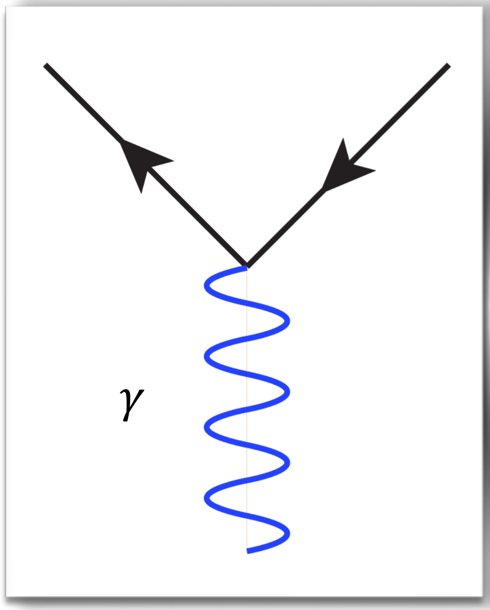


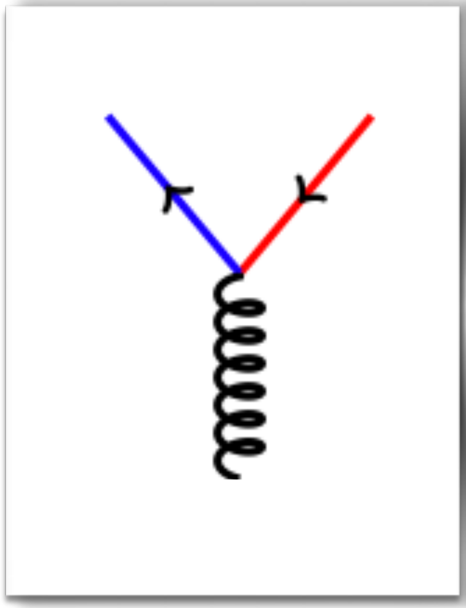


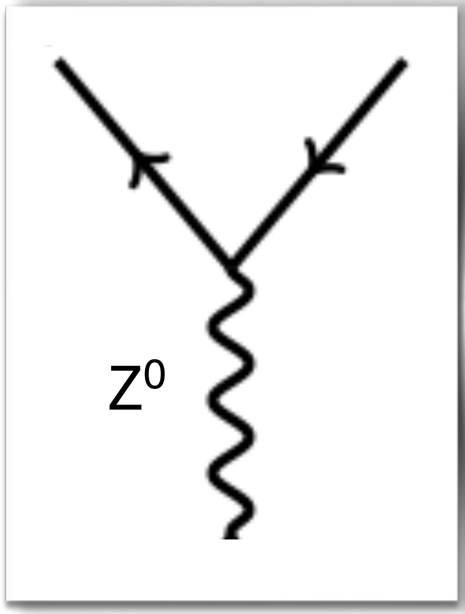
Vertex Building Blocks

Rotations of the building blocks result in new, valid building blocks.

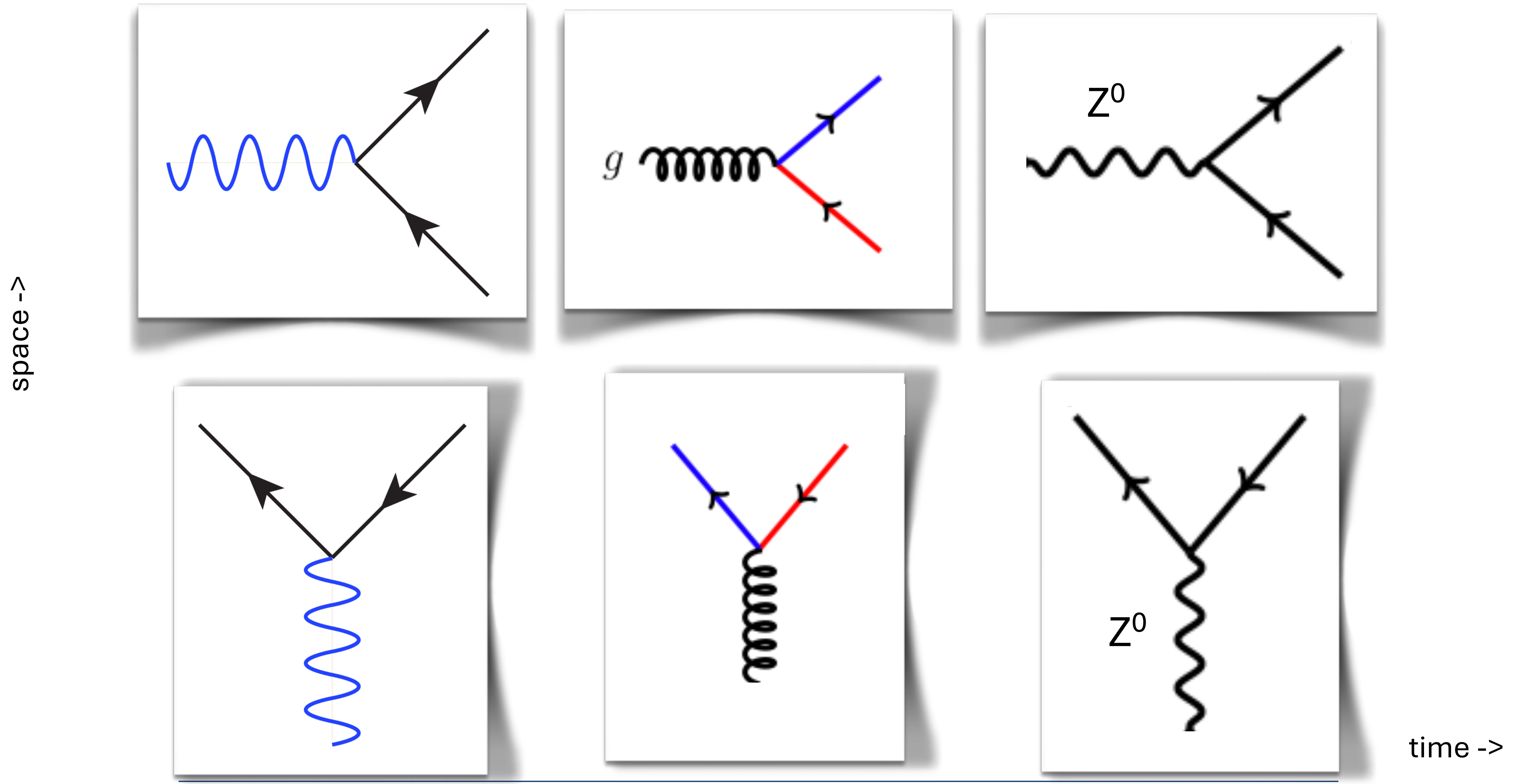
- Be careful about the arrow directions!





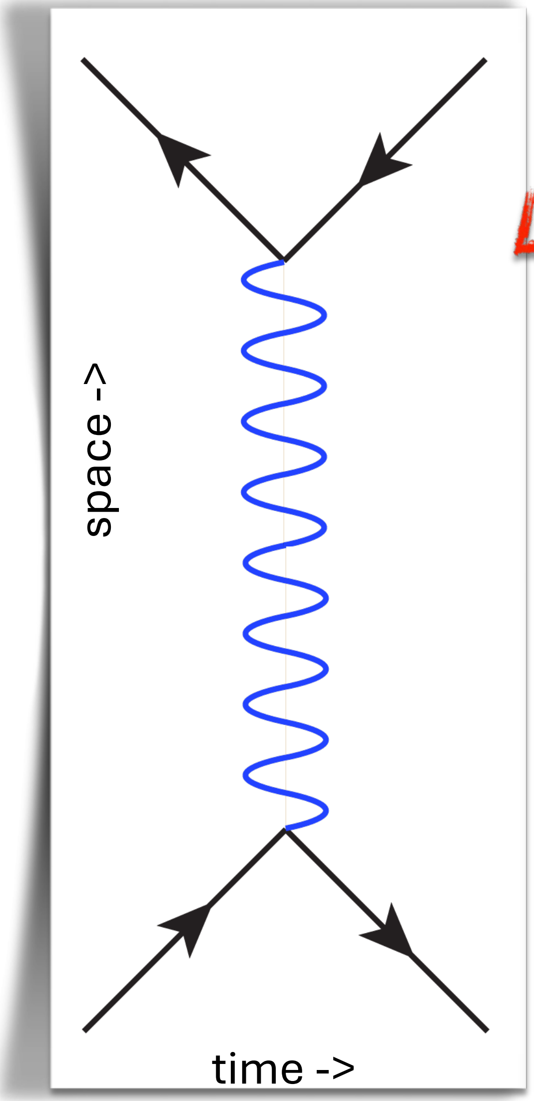


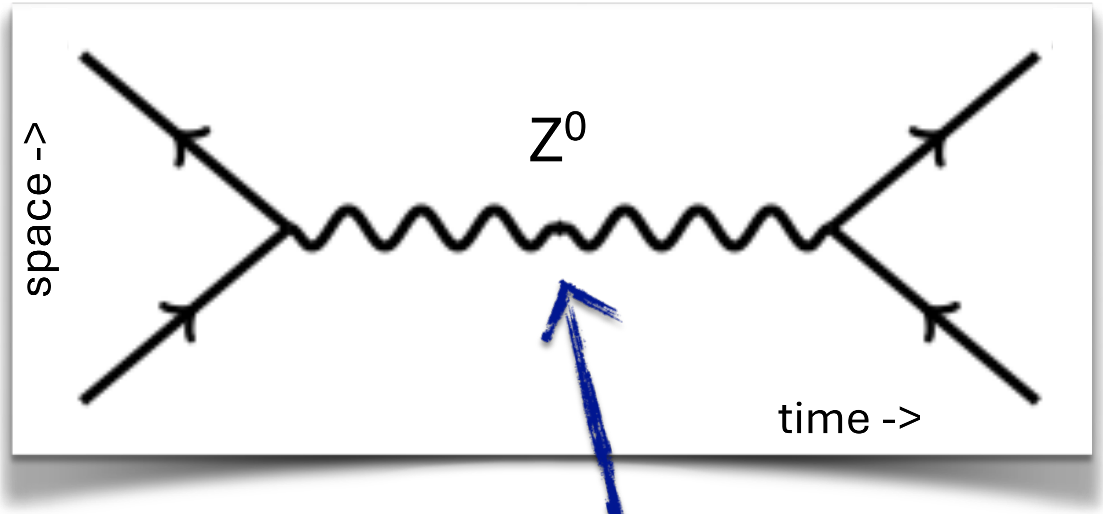
Vertex Building Blocks: Valid in both directions



Vertex Building Blocks

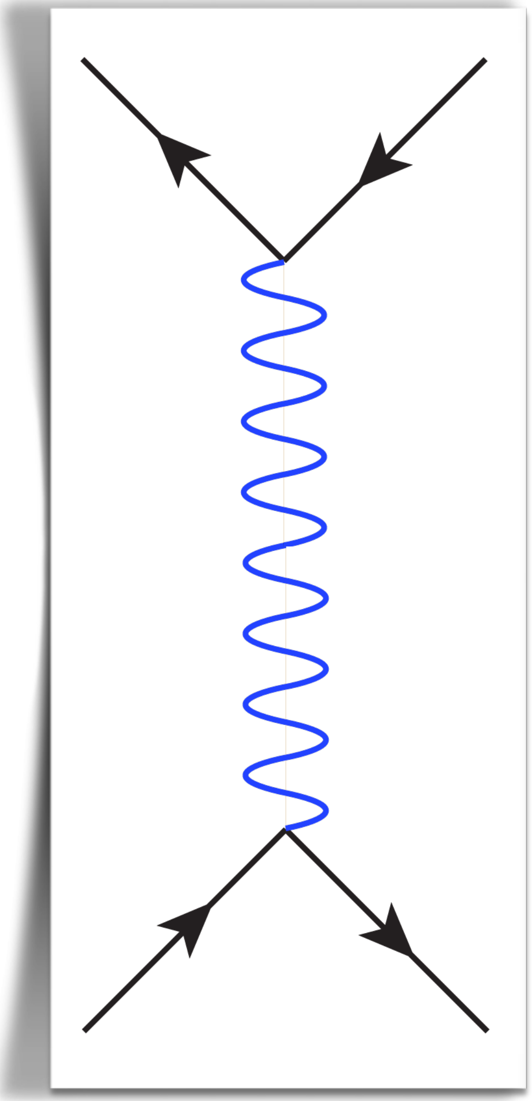
"t-channel" diagram (time-like): describes an interaction happening at a fixed time.





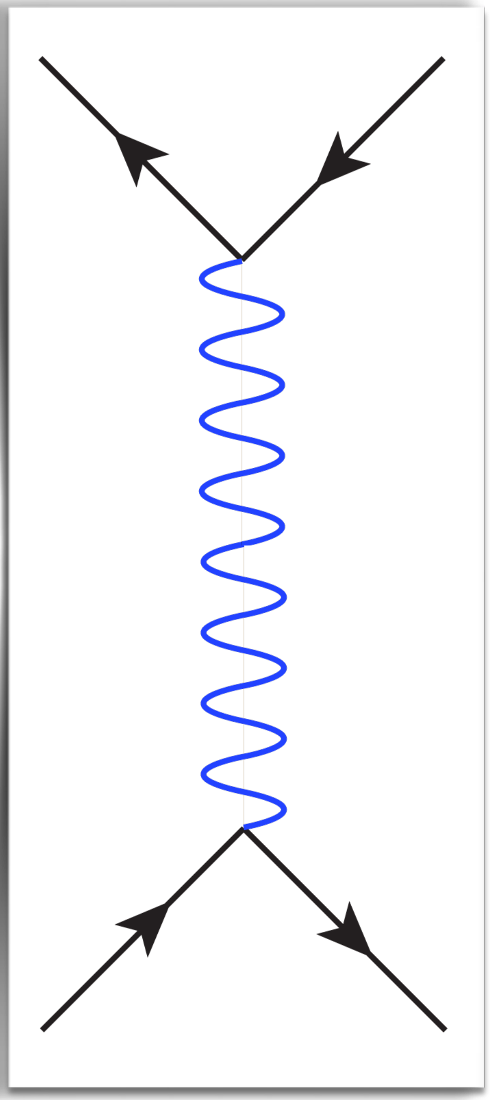
s-channel diagram (space-like): describes an interaction happening at a fixed point in space.

A Question:



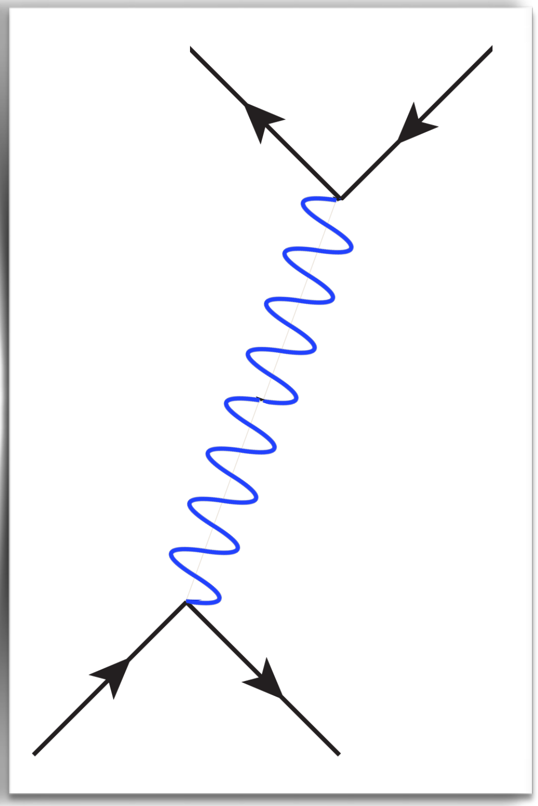
In the time-like diagram, which particle is doing the emitting and which is doing the absorbing?

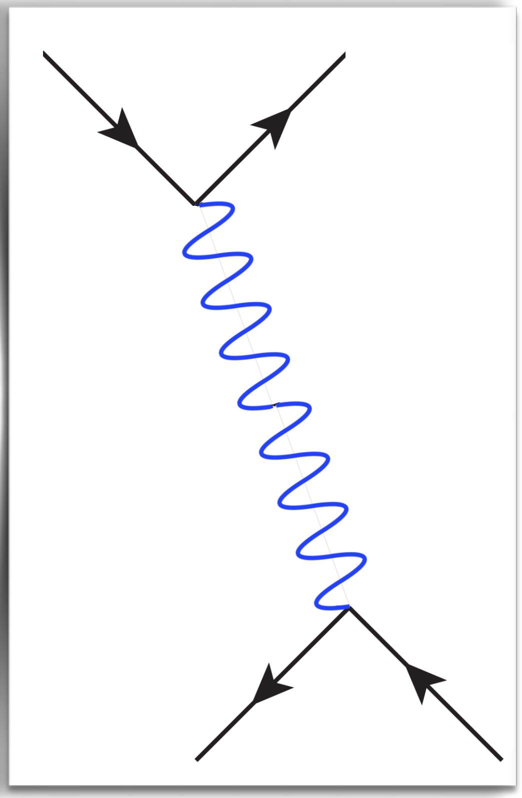
Answer:



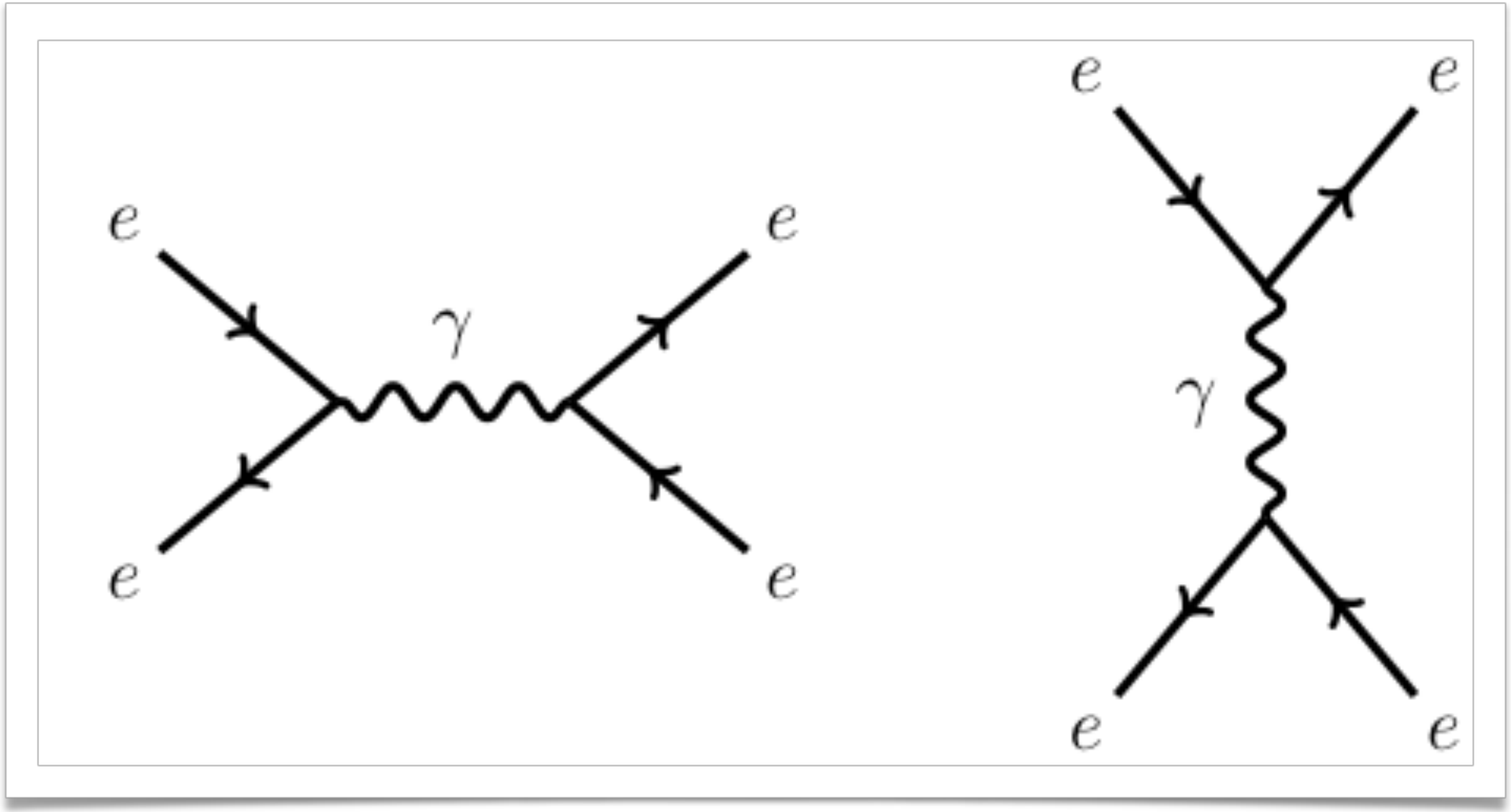
In the time-like diagram, which particle is doing the emitting and which is doing the absorbing?

Answer: We don't know, so the diagram must represent both possibilities!

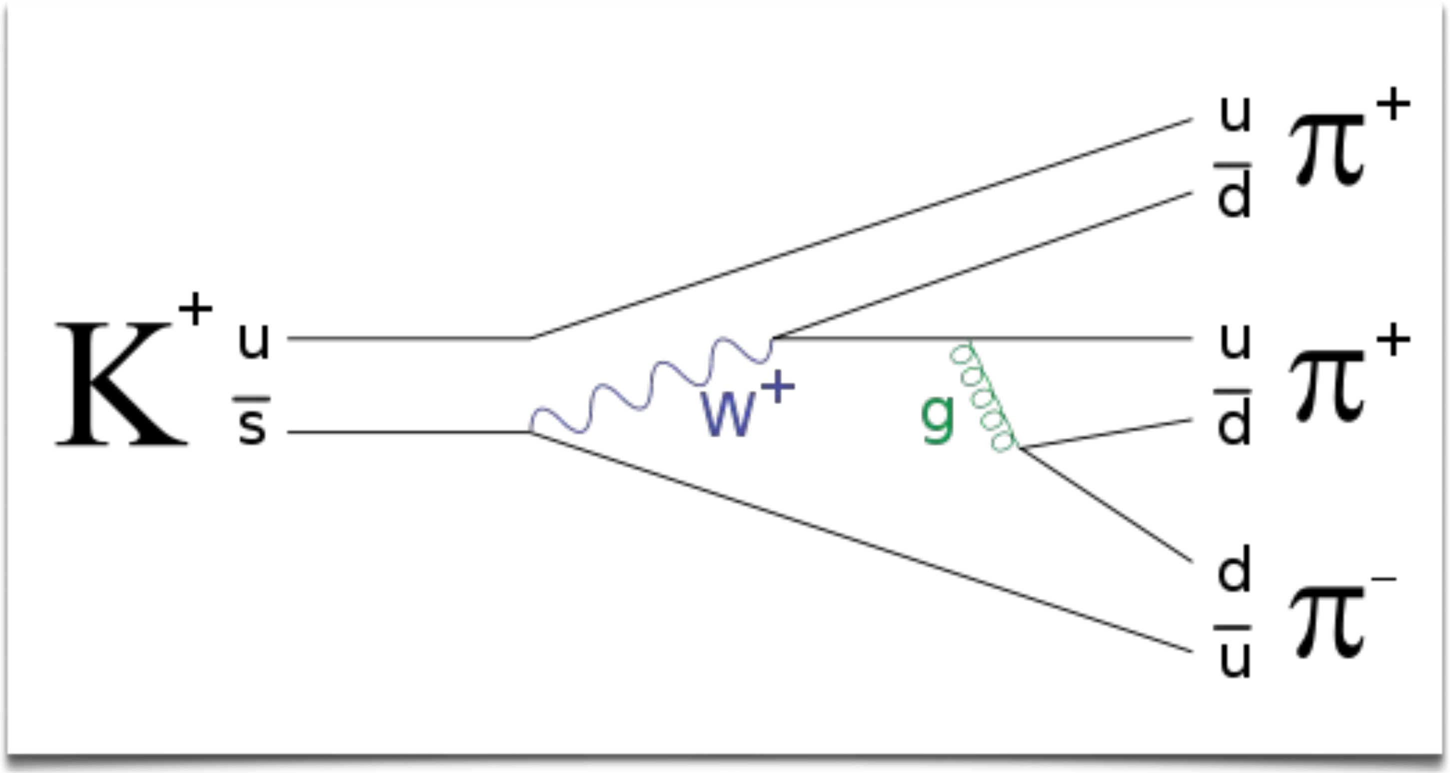




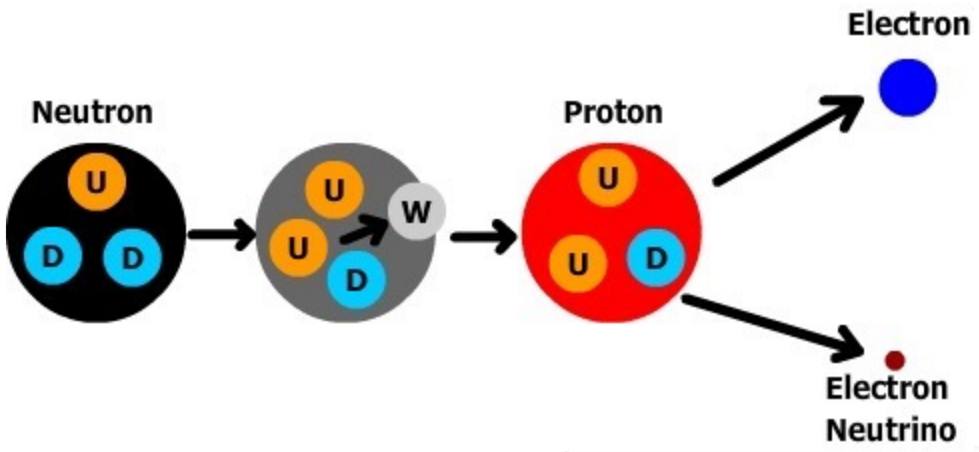
Example Diagrams

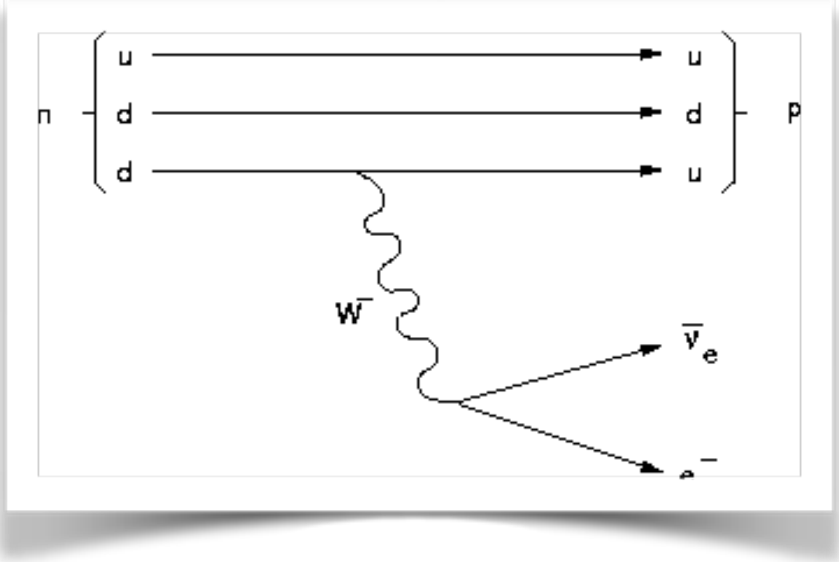


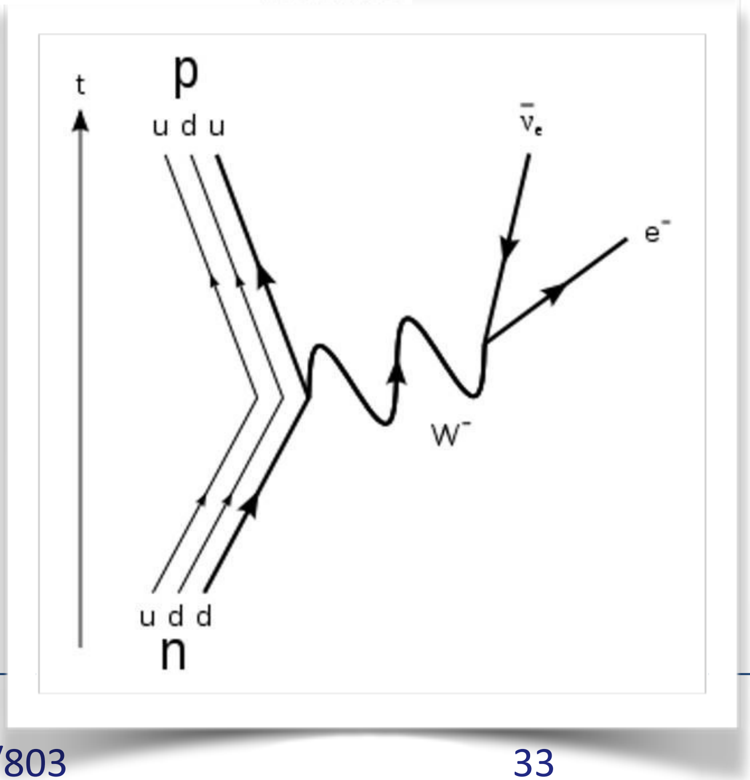
Composite Particle Example



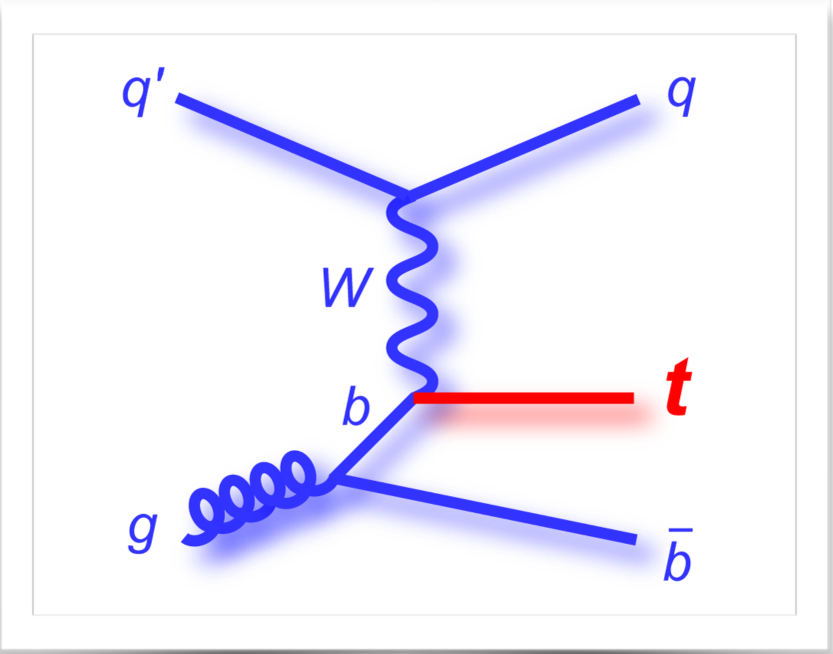
Neutron Beta Decay Representations



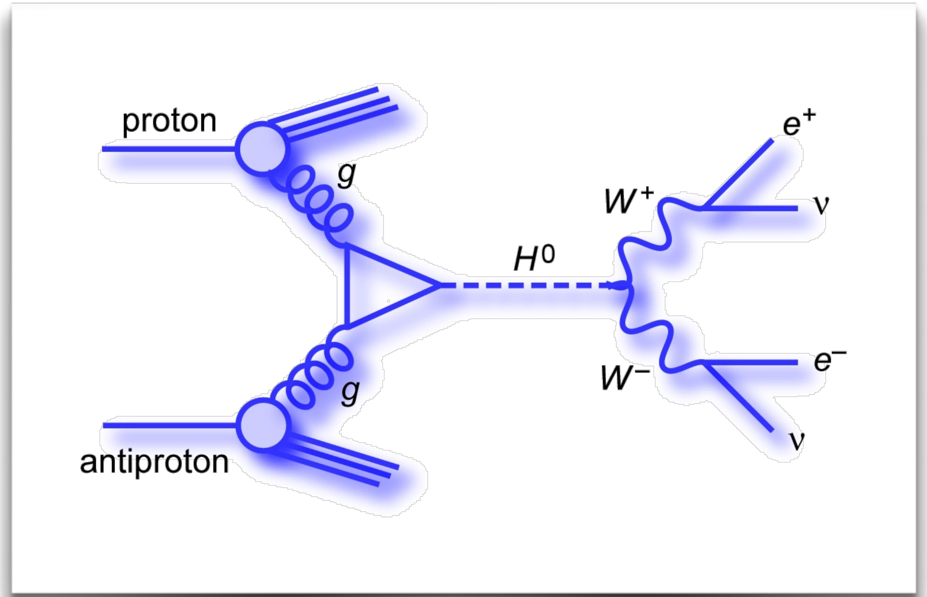




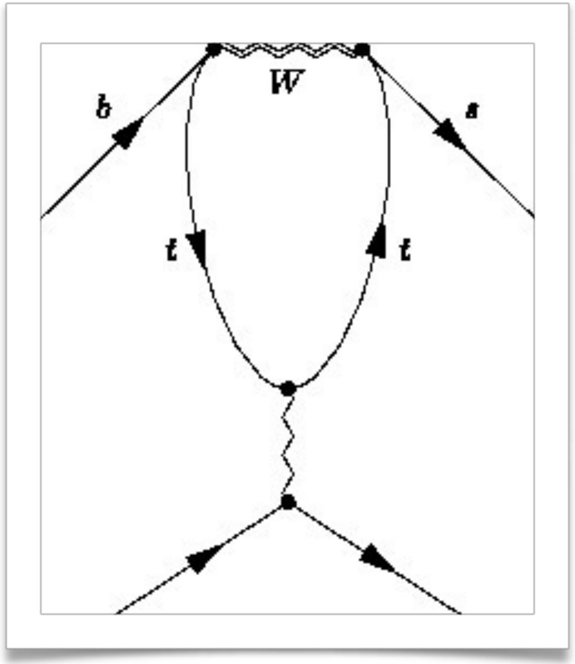
More complicated examples



proton – anti-proton collision:



Penguins?



W
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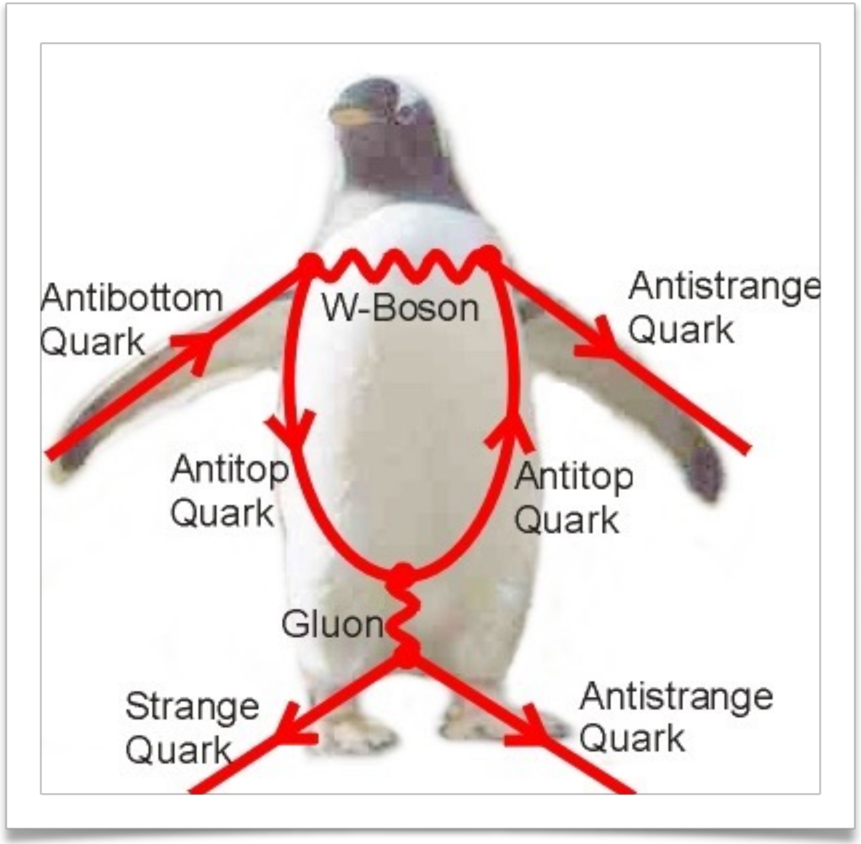


Antibottom Quark
W-Boson
Antistrange Quark
Antitop Quark
Antitop Quark
Gluon
Strange Quark
Antistrange Quark

Virtual Particles

Quantum mechanics allows for a very interesting effect for the lifetime and behavior of particles.

Consider Heisenberg's uncertainty principle:

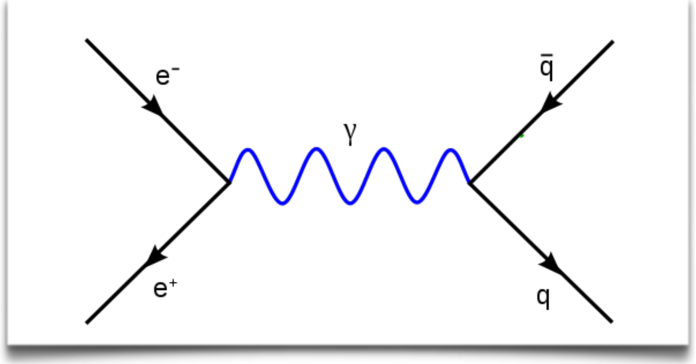
$$\Delta E \Delta t \geq \hbar/2$$

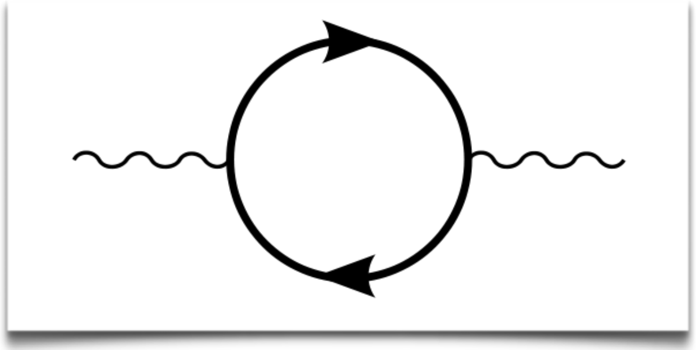
Propagators might not satisfy the normal energy-mass relationship

$$m^2 = E^2 - p^2$$

Any particle that violates this relationship ("off mass shell") is referred to as a virtual particle.

- Virtual particles may have zero or even negative "mass".
- Virtual particles don't manifest in reality, so they can only be internal lines





Loops!

Loops make things more interesting!