How and Why to go Beyond the Discovery of the Higgs Boson

John Alison

University of Chicago

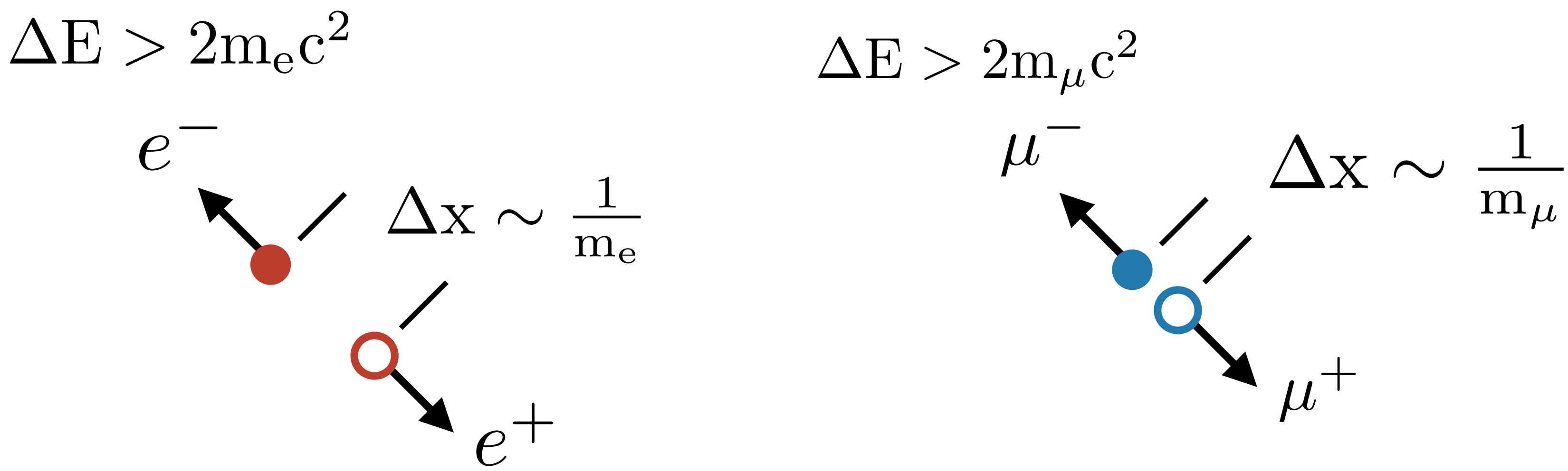
http://hep.uchicago.edu/~johnda/ComptonLectures.html

Reminder: Last Lecture

Combining Relativity and Quantum Mechanics

- To preserve causality needed to Anti-particle must exist

- In turn, major implications on the vacuum:



Reminder: Last Lecture

Combining Relativity and Quantum Mechanics

- Massive restrictions in types of theories possible

- Forced to talk particle spin:

  Integer spin = Bosons / Half-integer = Fermions

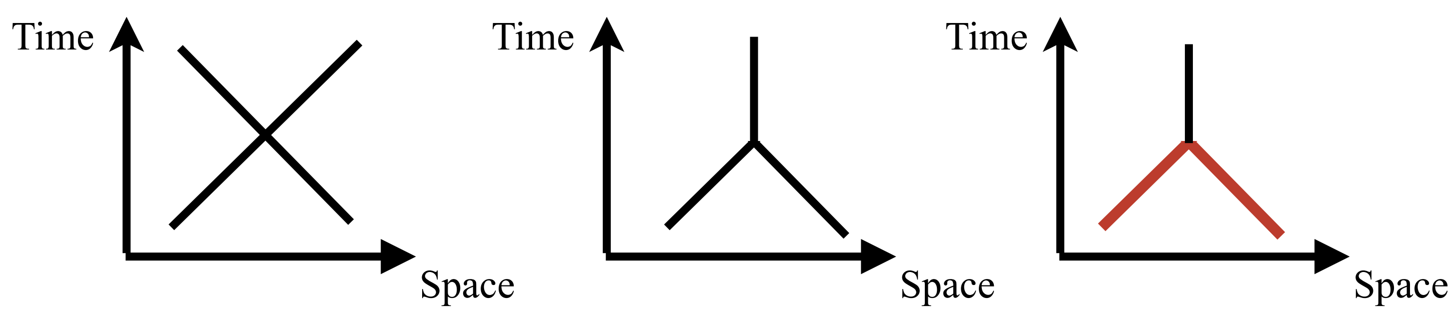
  Can only have: 0 1/2 1 3/2 2

- Major limits to possible interaction:

  Charge conservation / Local in space-time

  Only finite number of specific interactions allowed :

bosons
fermions



Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: **Mission Barely Possible: QM + SR**

April 15th: ***The Standard Model***

April 22nd: **Importance of the Higgs**

April 29th: **Guest Lecture**

May 6th: **The Cannon and**

May 13th: **The Discovery of**

May 20th: **Experimental Ch**

May 27th: **Memorial Day: N**

June 3rd: **Going beyond th**

Sources:

- **Nima Arkani-Hamed**
- **Steven Weinberg**
- …

I will keep this list up to date as we go along.

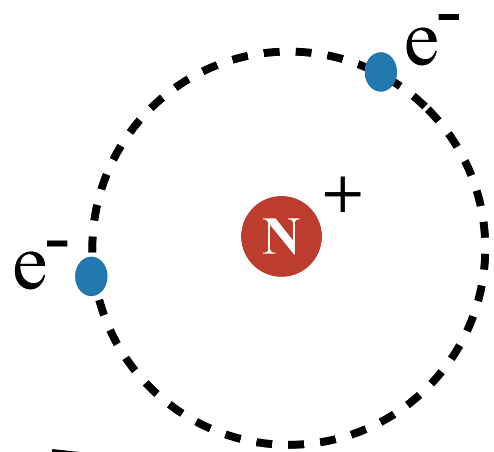
Today’s Lecture

The Standard Model:

What the world is made of

Matter

Stuff in the world made of atoms:



Atoms made of:

Electrons: Negatively ch
Responsible for volume of at
Thought to be fundamental

Matter particles (electrons/quarks) fermions
Large collections behave like classical particles

Nucleus: Positively charged
Responsible for the mass of an atom
Made of, protons and neutrons, which are made of quarks
Quarks also thought to be fundamental

Forces

All forces as important.
Look very different from one another

Gravity:
Known since antiquity / Inverse square law
Always attractive / Irrelevant for atomic/sub-atomic interactions

Electromagnetism:
Known since antiquity / Inverse square law
Attractive or repulsive / Holds electrons within atoms

Strong:
Discovered early 1900s / Short distances / No simple relationship
Responsible for holding together the nucleus

Weak:
Discovered just before turn of 20th century / Looks nothing like others
Radioactive decay. Heats the sun / earth

The Standard Model

Our world both Relativistic and Quantum Mechanical
$\Rightarrow$ described in terms of a Quantum Field Theory (QFT)

The particular version of QFT that was found to describe our universe developed in the 1960-70s.

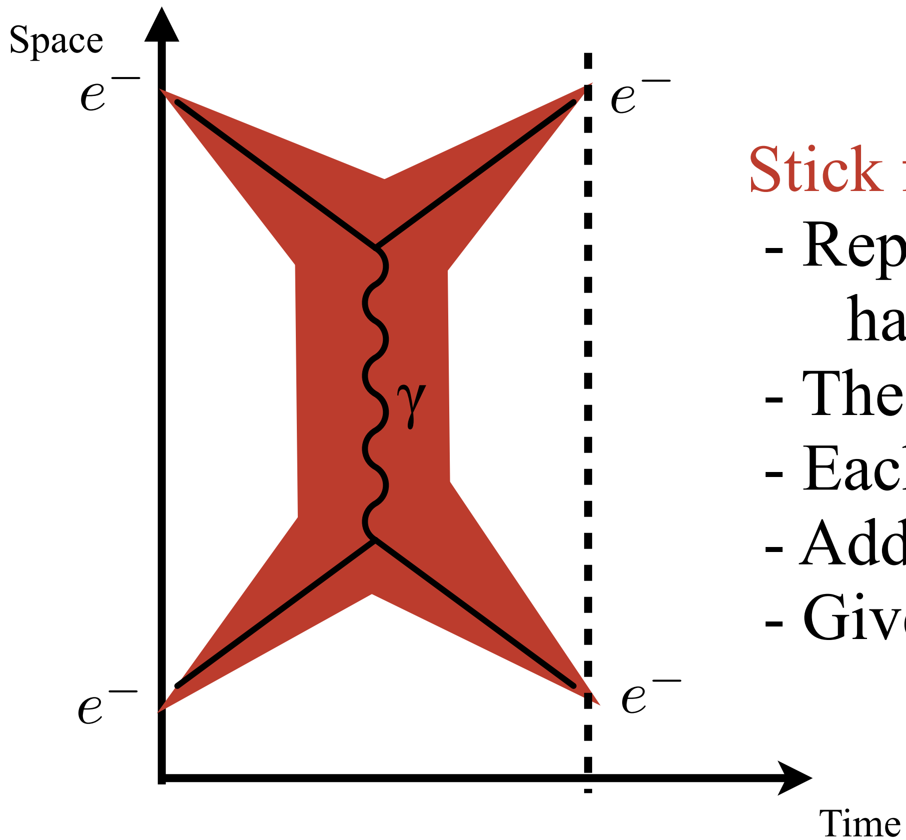
Describes all matter/interactions down to 10^-18m
(Distances 100 × smaller than proton)

Most accurate theory in all of science
Describes all particle interactions observed in laboratory

Output of the Theory

Predict probabilities for various things to happen

Example:



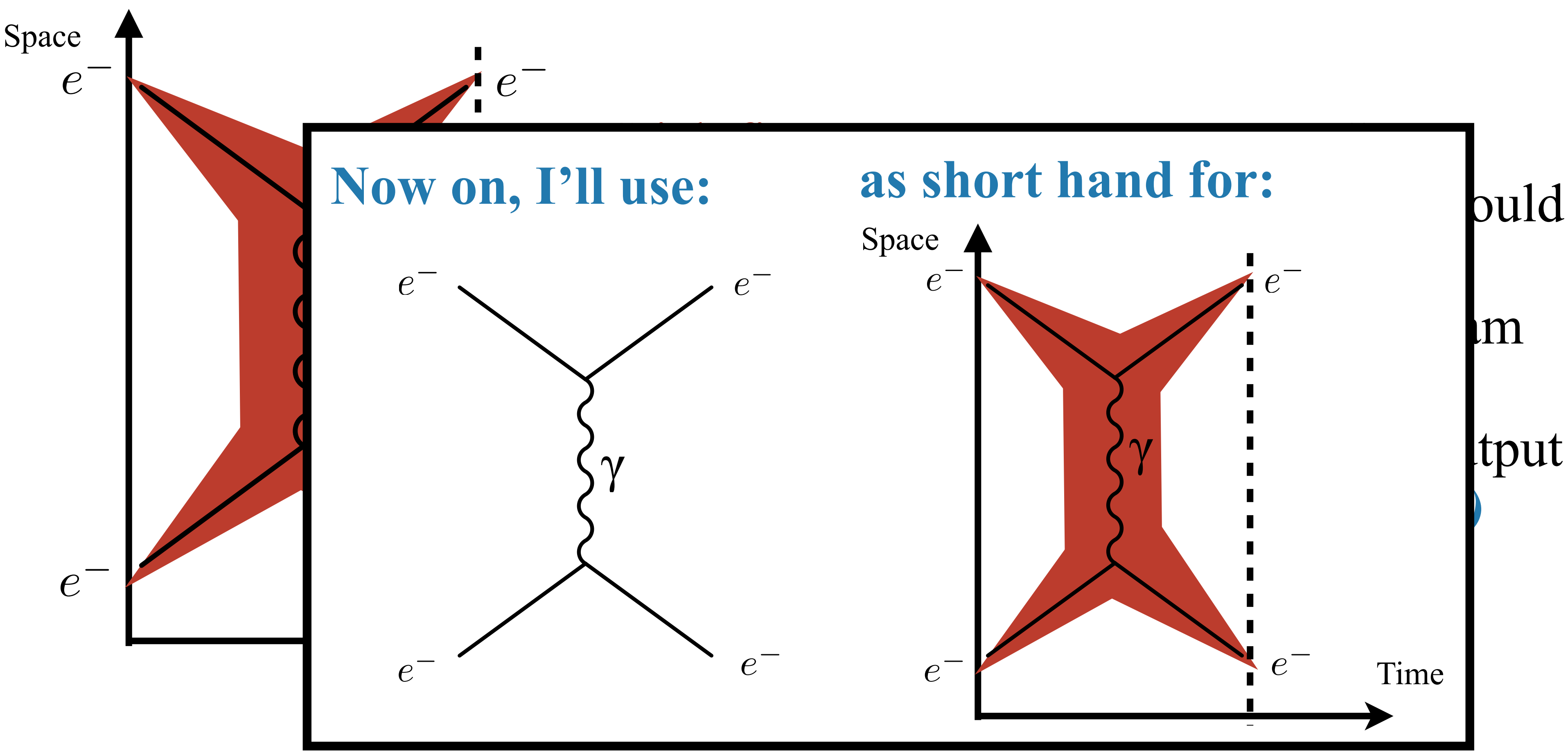
Stick figure: *"Feynman Diagram"*

- Represents one possible way things could have happened
- Theory assigns number to each diagram
- Each diagram only local interactions
- Add all paths consistent w/input & output
- Gives a contribution to ψ ***(more later)***

Output of the Theory

Predict probabilities for various things to happen

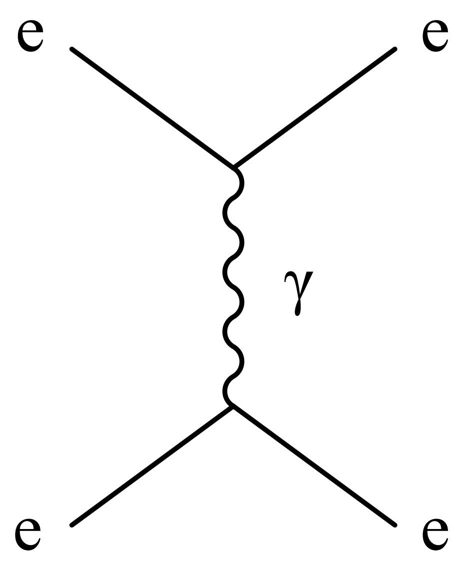
Example:



Forces from Interactions

Forces long-range manifestations of local interactions

No more action at a distance!

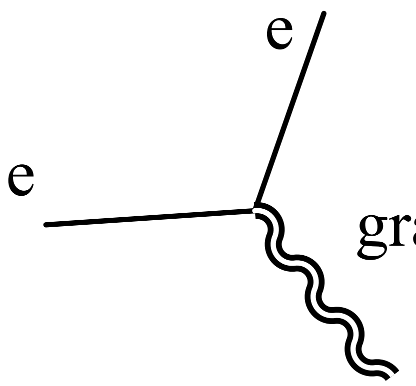


Electromagnetic force between two electrons result exchange of a photon

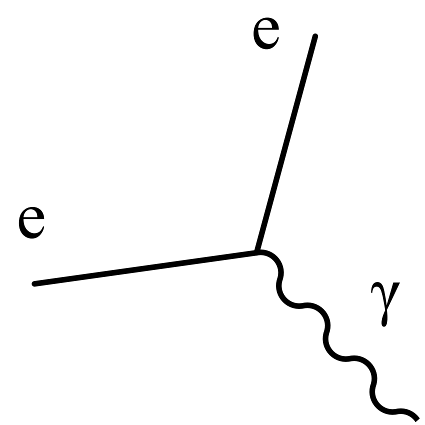
Exchange as local interactions two e-γ interactions

Forces from Interactions

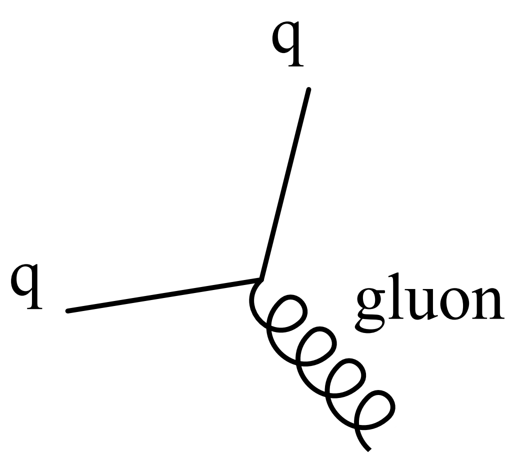
Gravitational Interaction



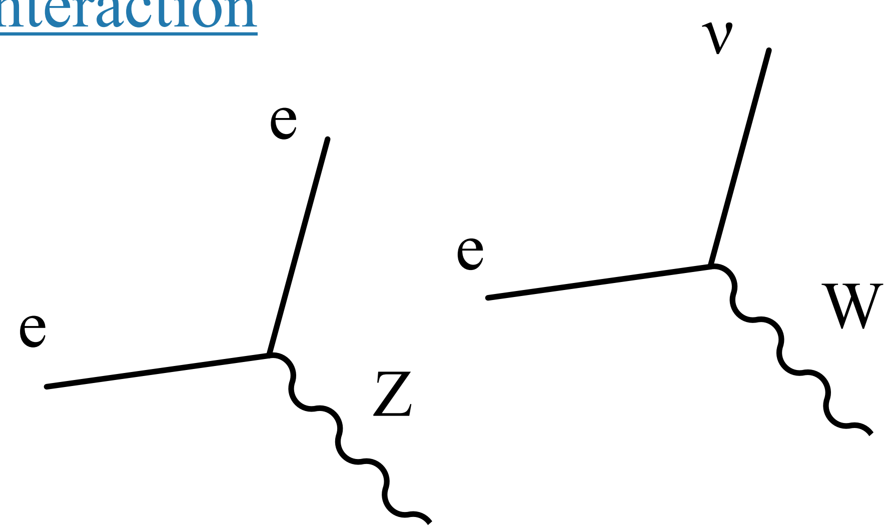
Electromagnetic Interaction



Strong Interaction

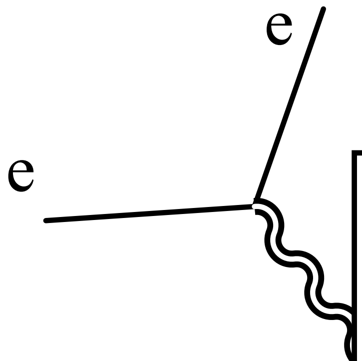


Weak Interaction

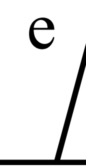


Forces from Interactions

Gravitational Interaction

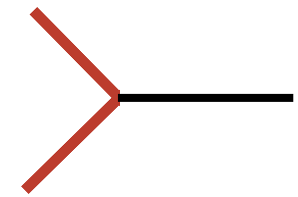


Electromagnetic Interaction



bosons

fermions

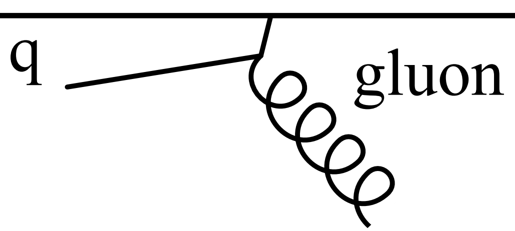


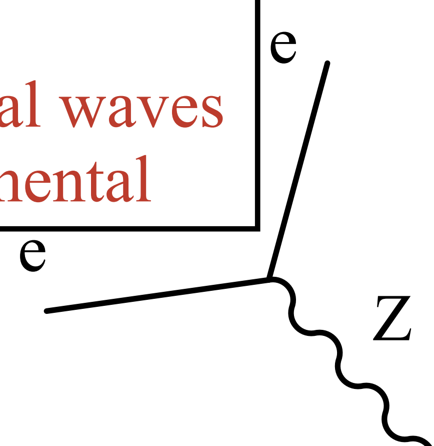
Neutrino (fermion)
- Needed describe week interactions
- Like electron w/no charge/~no mass
- Believed to be fundamental

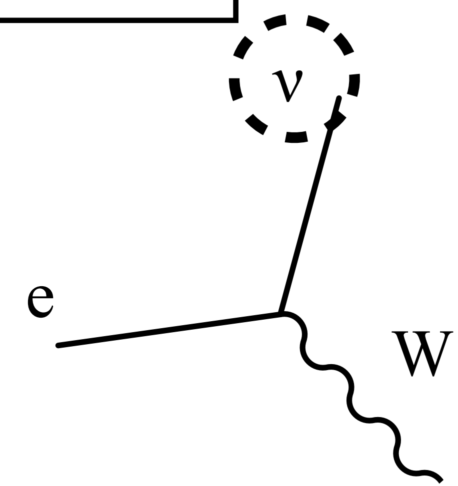
Strong Interaction

Weak Interaction

Force particles are bosons
Large collections behave like classical waves
Force particles believed to be fundamental







The Standard Model

<u>Matter Particles</u> (Fermions) Spin = 1/2

Leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

<u>Interactions</u> "Force carriers" (Bosons) Spin = 1

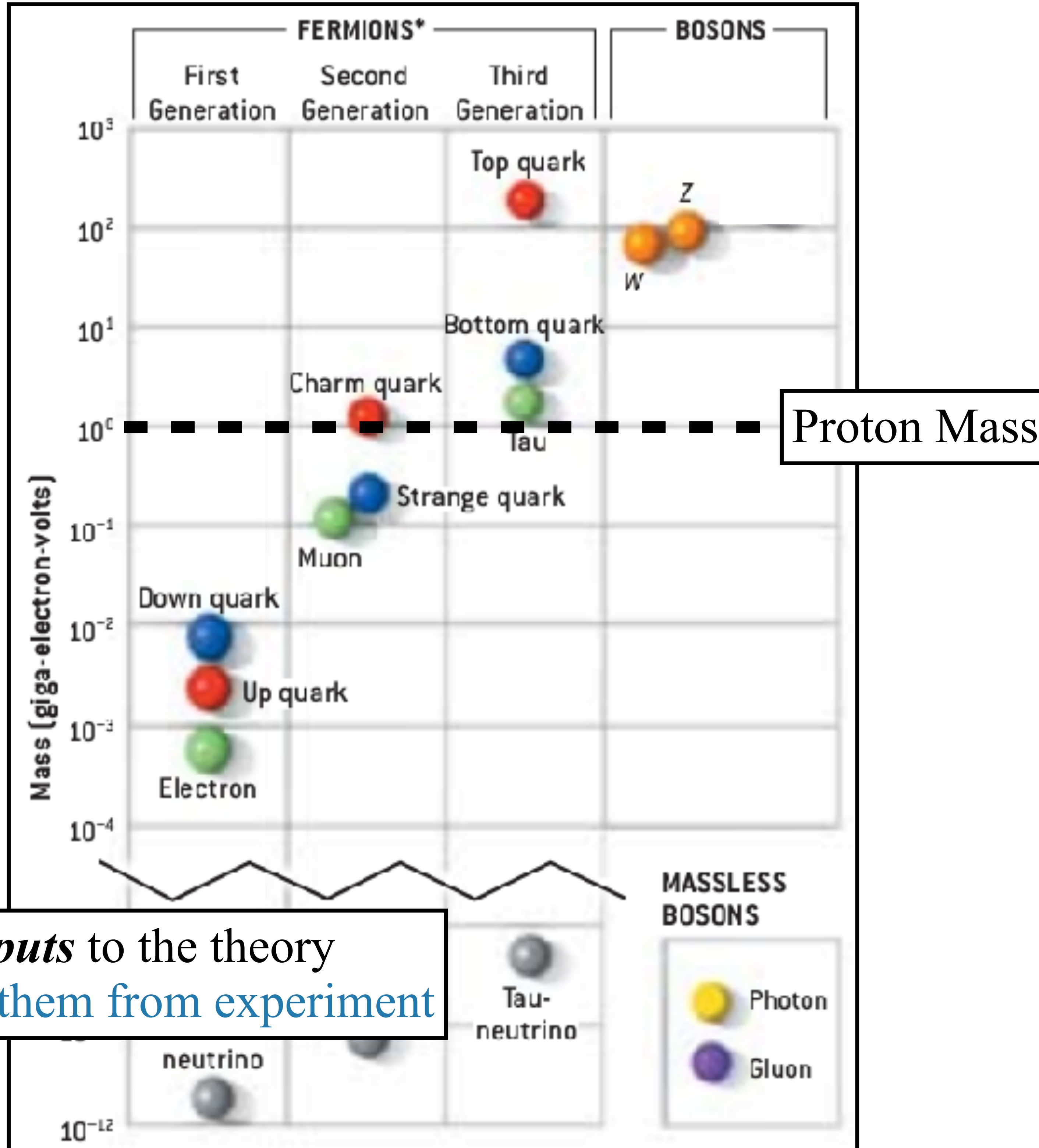
Gauge bosons:

γ W Z g

Beautiful (complicated) mathematics governs nature interactions

Dictated by principles of symmetry *(Much direct consequence QM + R)*

Masses

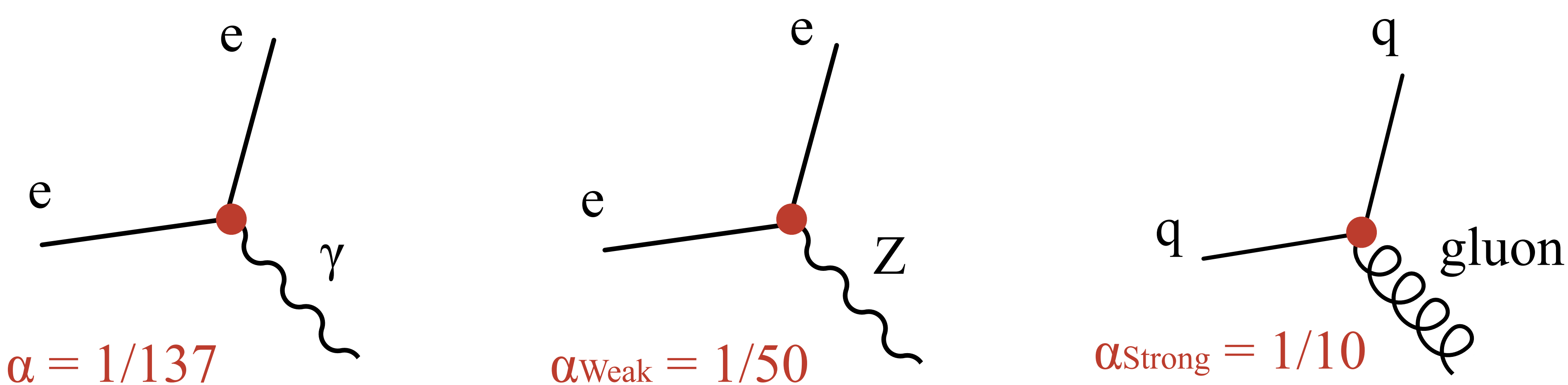


These masses are ***inputs*** to the theory

Need to determine them from experiment

Interaction Strengths

Each interaction vertex characterized by number:

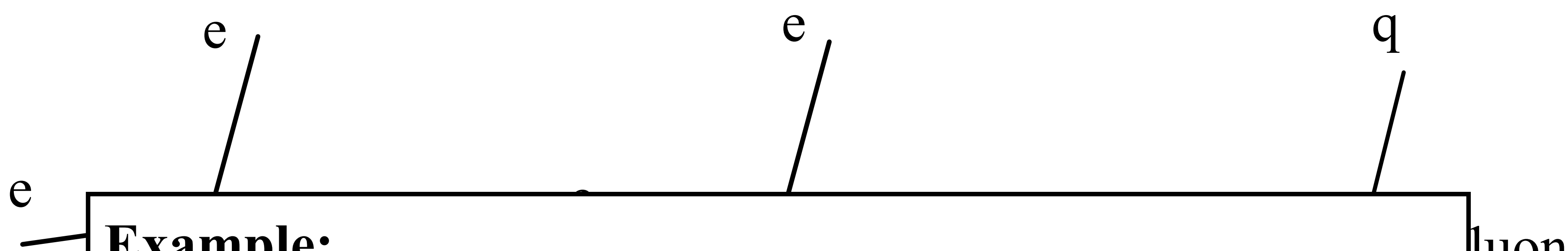


Sets the overall strength of the different interactions
- Directly related to the probability for the processes to occur

These numbers are ***inputs*** to the theory
- Need to determine them from experiment
- Then use them as input in other calculations.

Interaction Strengths

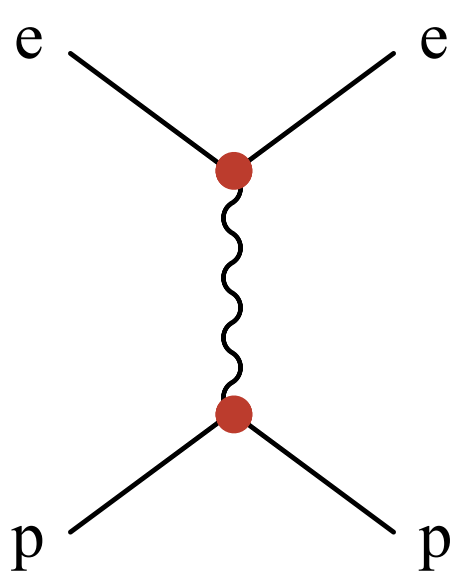
Each interaction vertex characterized by number:



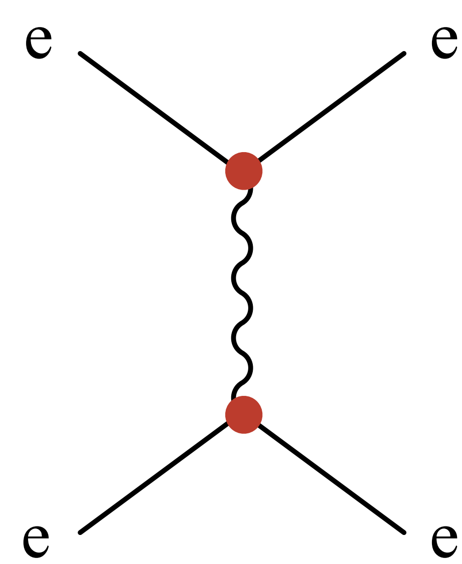
$\alpha = 1$

Example:

Fix α from measuring properties of atoms, given by:



Then predict all other EM probabilities (eg: how electrons (or anti-e) scatter)



Sets

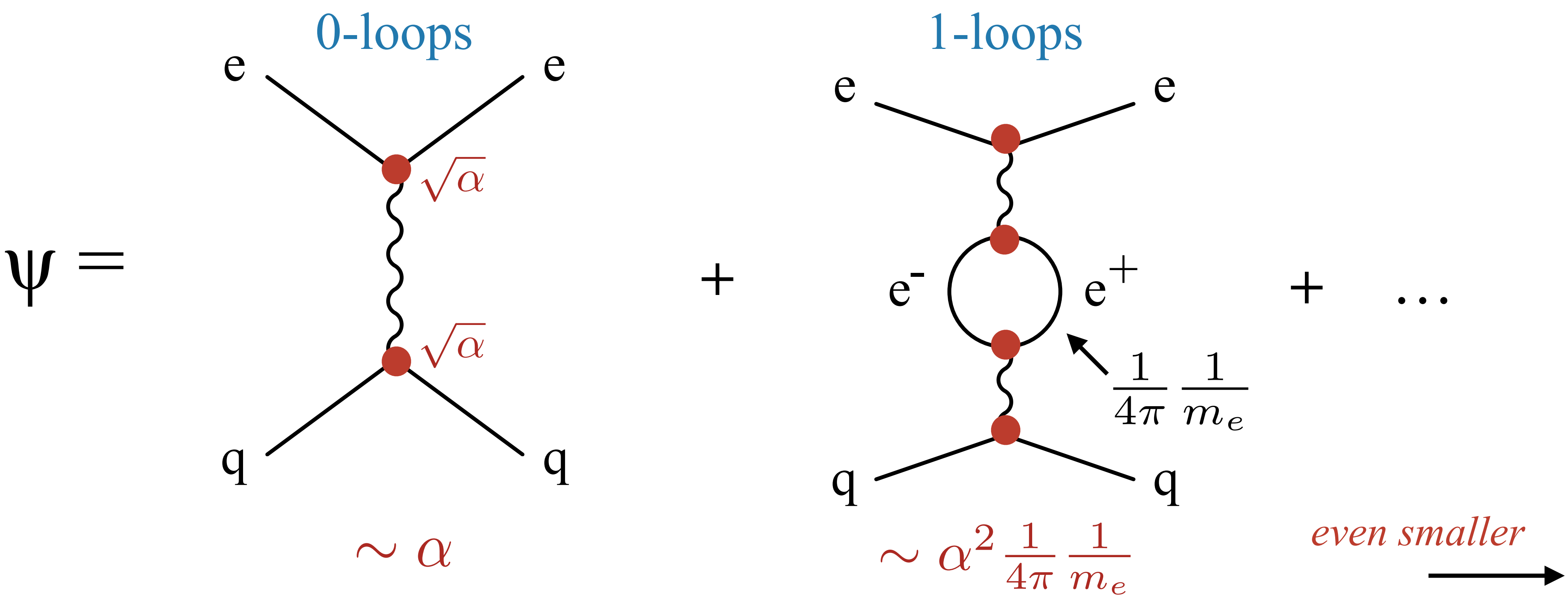
- D

Thes

- N
- T

Output of the Theory (Details)

Feynman Diagrams: Pictures of what happens
Invaluable Tool for calculation

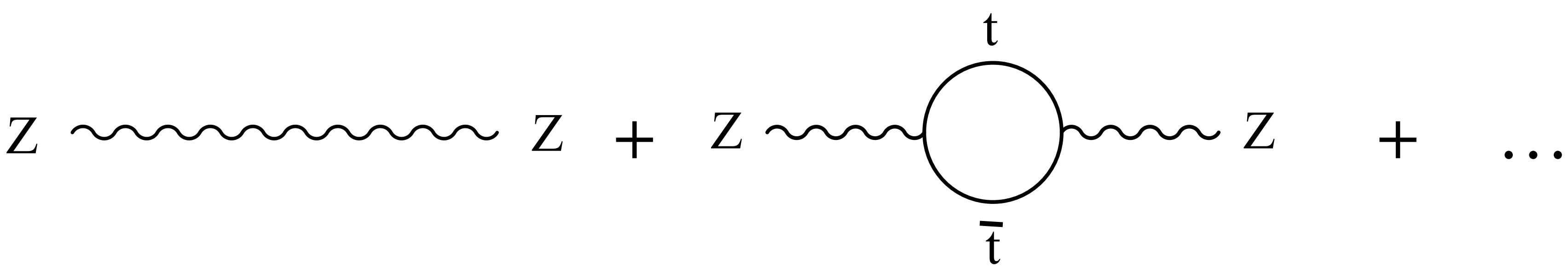


- Theory give prescription for assigning numerical value to diagram.
  Other rules associated to the lines / Sum overall possible configurations
- Sum of diagrams (# associated with diagrams) is ψ
- Really infinite sum. In practice, only the first few terms dominate

Output of the Theory (Details)

Just saw example of calculating interaction between particles
Can also calculate basic properties of particles

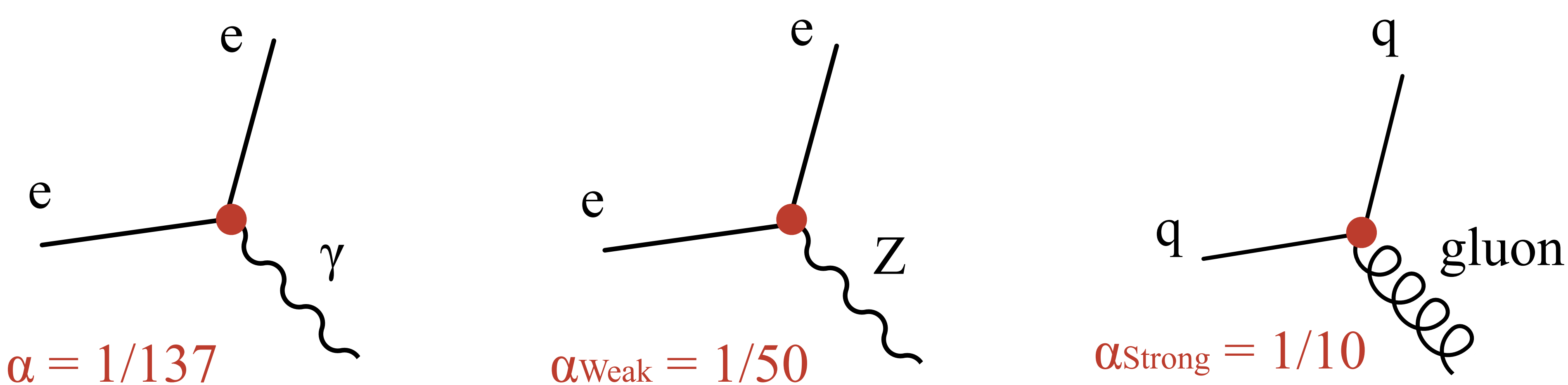
Example: *Contribution to mass Z boson*



- Seems impossible given mtop > mZ
- Allowed by Quantum theory (Uncertainty principle $\Delta E \Delta t \geq h$)
- "Quantum Corrections" to mass
- Confirmed observable consequences

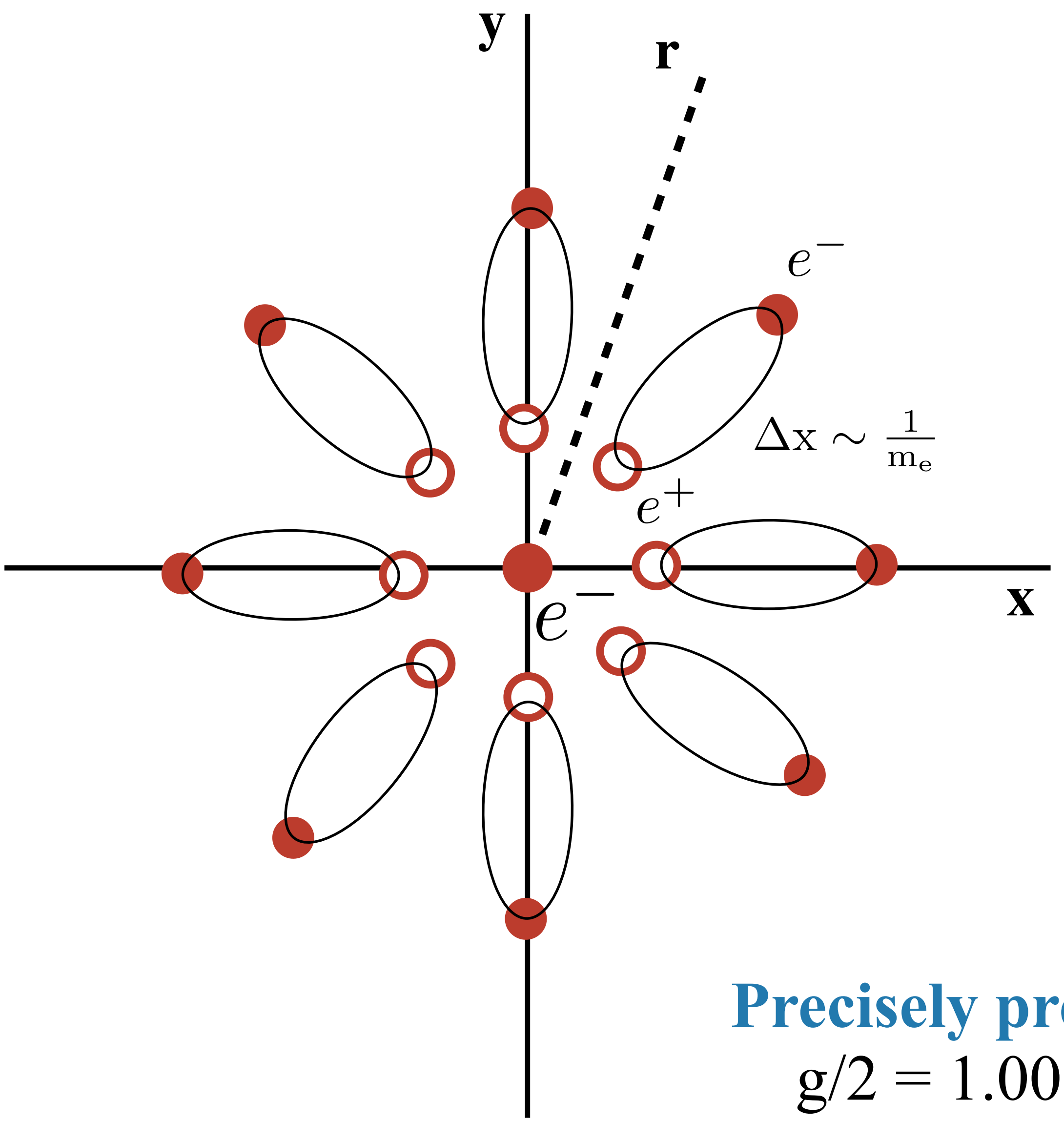
Forces Common Language

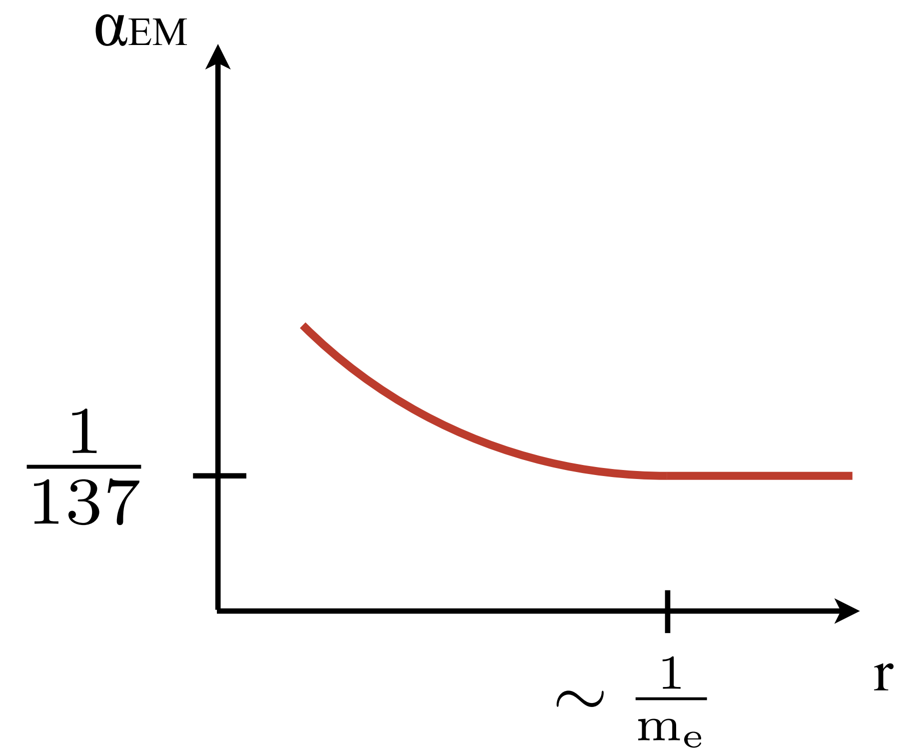
First time that we see that all forces described in same basic way.



Forces look very different to us…

EM Strength w/Distance





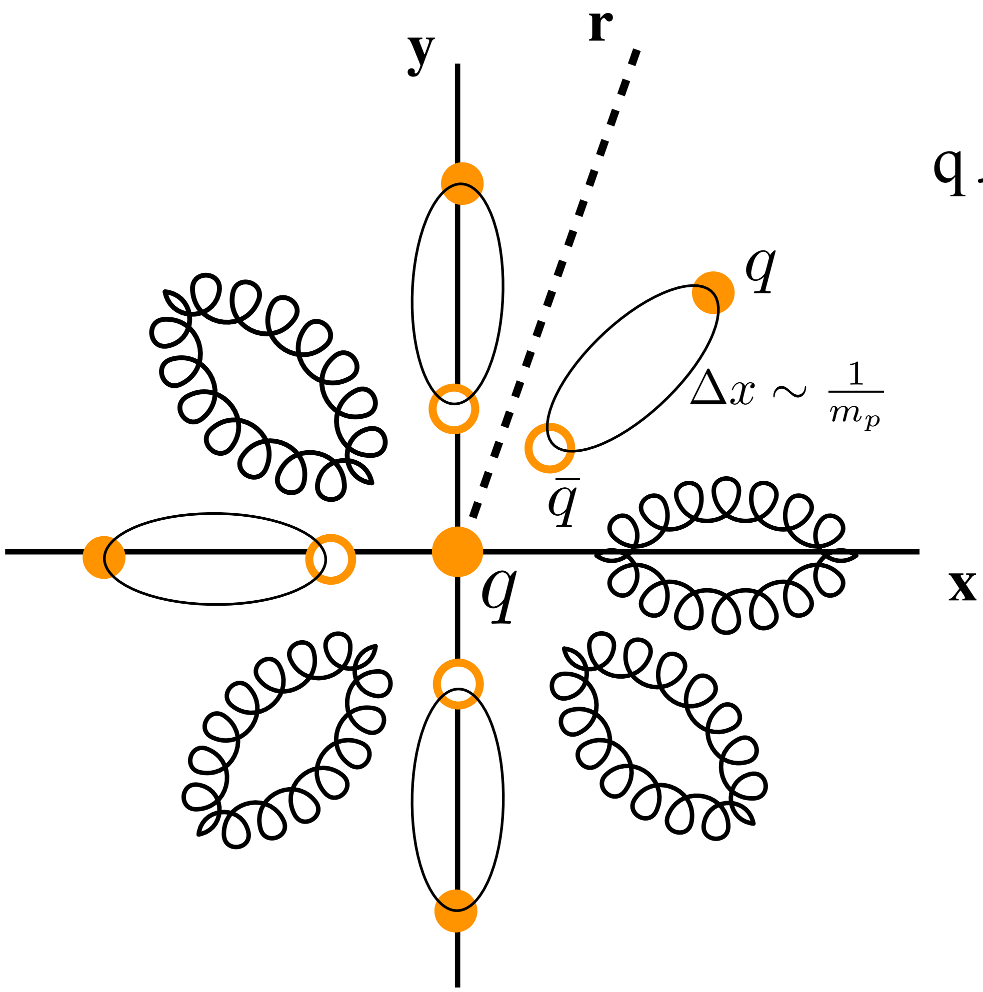
Precisely predict magnetic properties

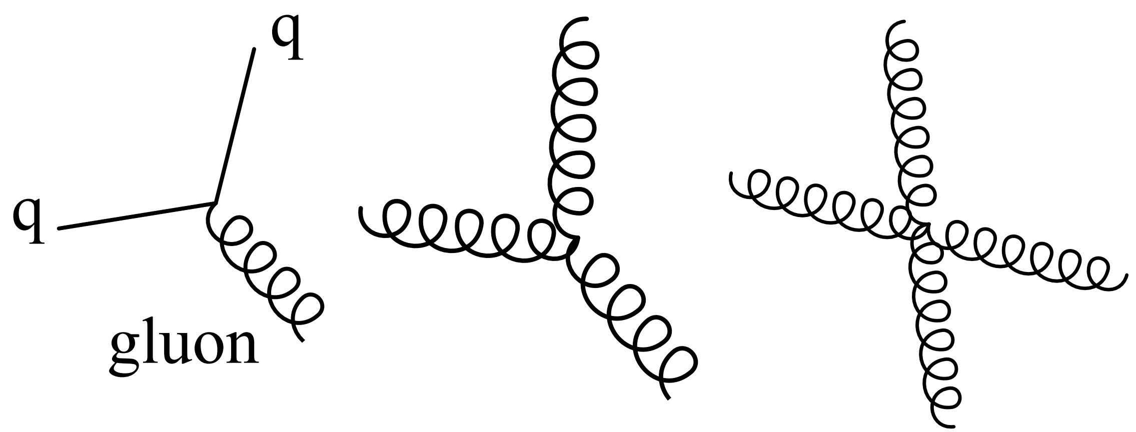
g/2 = 1.0011596521809(8),

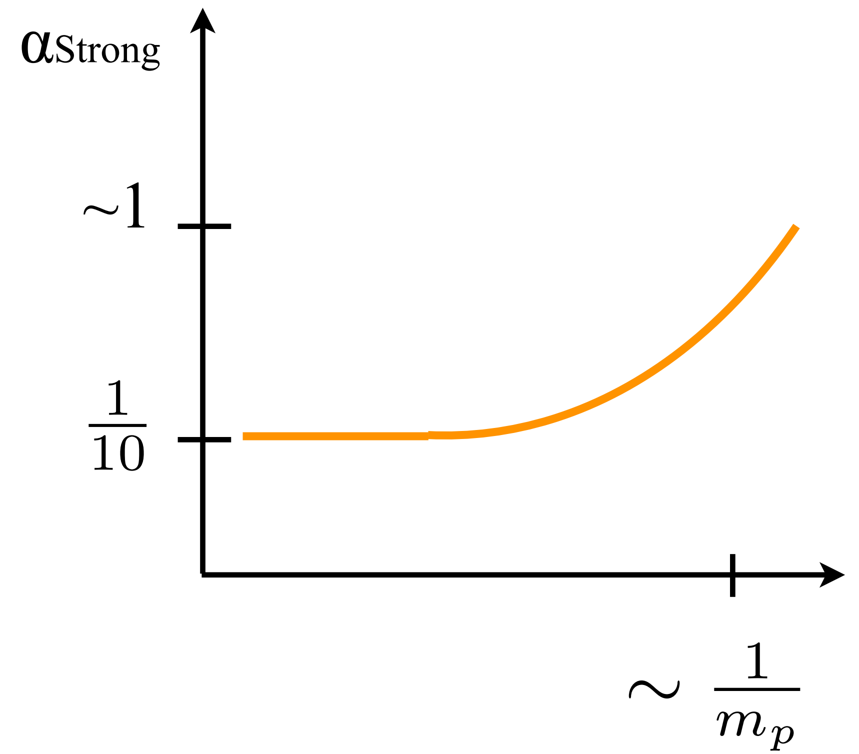
(Agree to better than one part in a trillion.)

Strong Interaction w/Distance

Unlike photons, gluons can self interact.

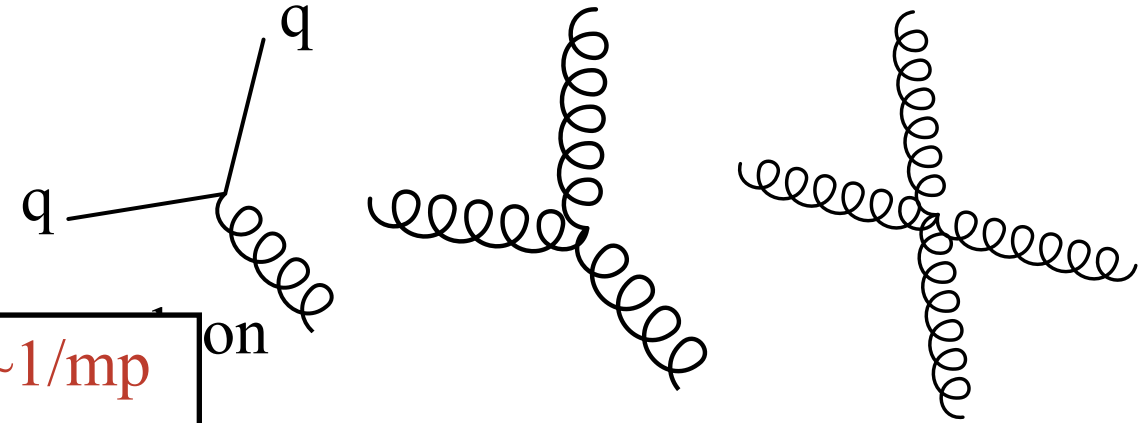


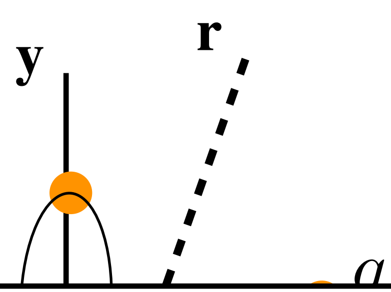




Strong Interaction w/Distance

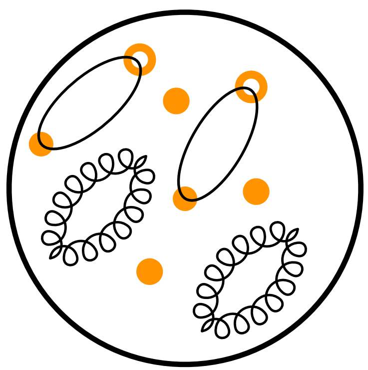
Unlike photons, gluons can self interact.





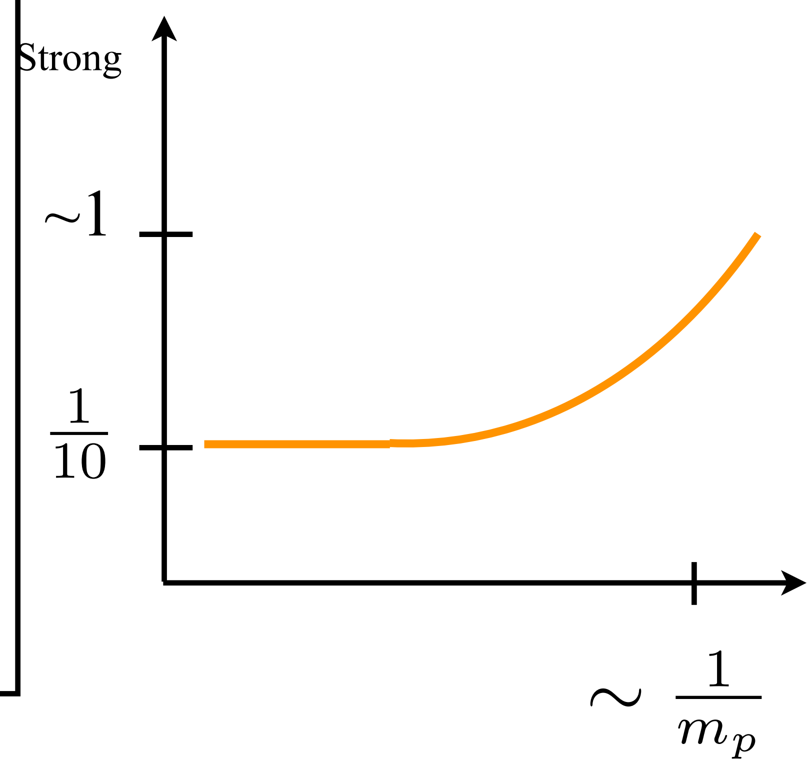
Interaction become very strong ~1/mp

Proton:



B/c force grows with distance:
- Cant pull them out of the proton
- q and gluons “confined “

Sets the size of protons (neutrons)



Weak Interaction

Electron high probability to emit γ when:

$E \times r < h/c$ *(consistent with $\Delta E \Delta t > h$)*

$r < h/Ec$

$r < h/pc^2$

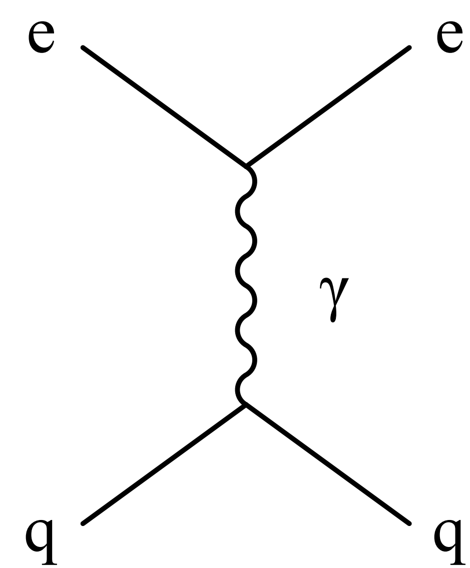
when $p \rightarrow 0$ then $r \rightarrow \infty$

F (= $-\Delta p$) on q can extends to $r = \infty$

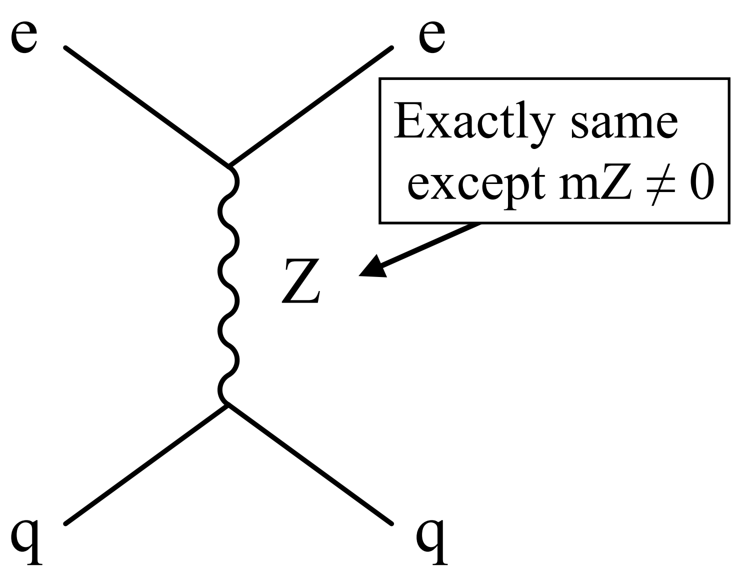
Of course, force get smaller ($p \rightarrow 0$)

(Gives precisely inverse square law)

Electro-magnetic Force



Weak Force



Electron high probability to emit **Z** when:

$E \times r < h/c$ *(consistent with $\Delta E \Delta t > h$)*

$r < h/Ec$

$r < h/\sqrt{(pc + m_Z c^2)}c$

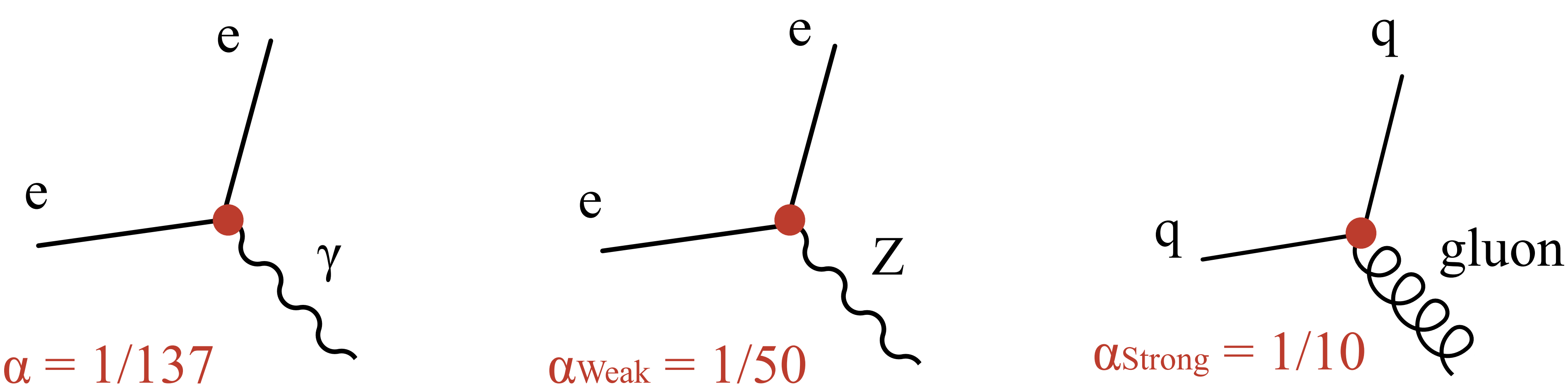
when $p \rightarrow 0$ then $r \rightarrow \sim 1/m_Z$

F (= $-\Delta p$) on q cannot extend to $r = \infty$

Mass of Z makes weak force short ranged.

Forces Common Language

First time that we see that all forces described in same basic way.



Forces look very different to us… **is a long distance illusion!**

- Strong force: anti-screening / confinement
- Weak force: massing force carriers

At short distance (~1/mZ) all look the forces start to look the same

This is the reason we build colliders! Unity at small scales.

The Standard Model

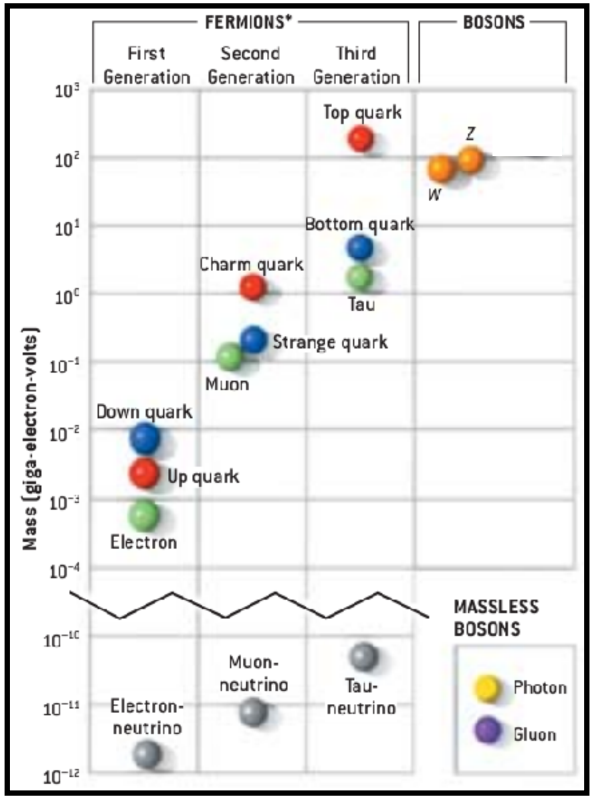
The Standard Model took on modern form in 60s - 70s.

Makes very precise predictions, shown to be highly accurate.

Consistent theory of electromagnetic, weak and strong forces ...
... provided **massless** *Matter* and *Force Carriers*

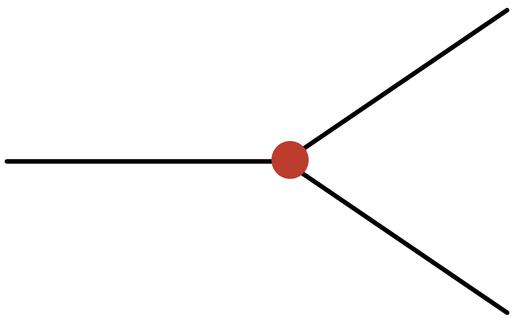
Serious problem as matter and W, Z known to be massive !

Pick up here next time.



Bonus

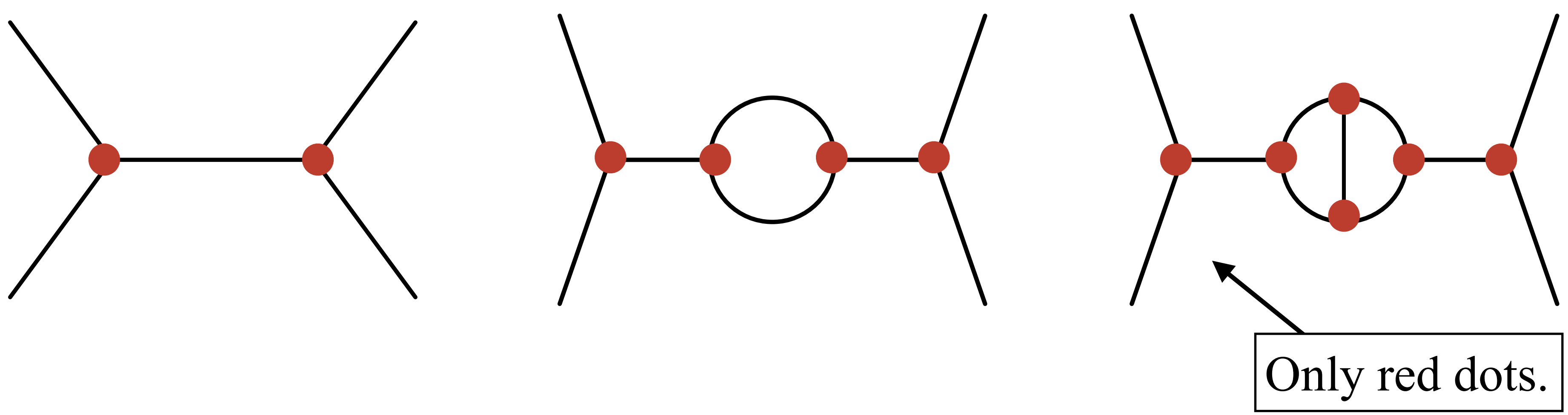
Number of Parameters



Vertex interaction strength input to the theory
- Taken from data

QFT ⇒ Only this “three point” interaction relevant

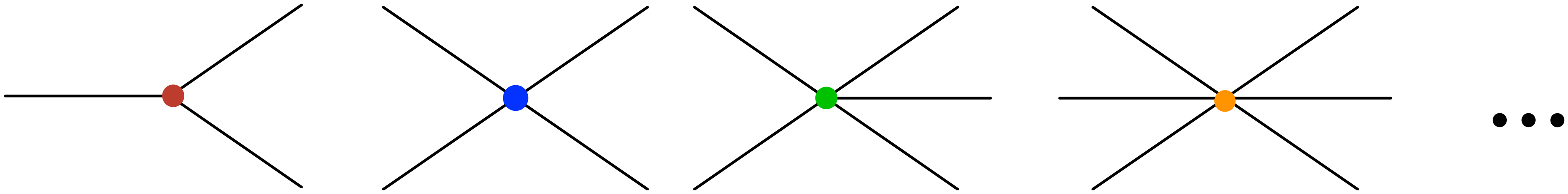
All calculations done by just stitch together this one basic vertex



One parameter (●) is enough to calculate all graphs

Number of Parameters

If all vertices relevant (as in NR QM)



Each term introduces a new unknown parameter.
Lose predictive power