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

John Alison

University of Chicago

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

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 the Camera**

May 13th: **The Discovery of the Higgs Boson**

May 20th: **Experimental Challenges**

May 27th: **Memorial Day: No Lecture**

June 3rd: **Going beyond the Higgs: What comes next ?**

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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.

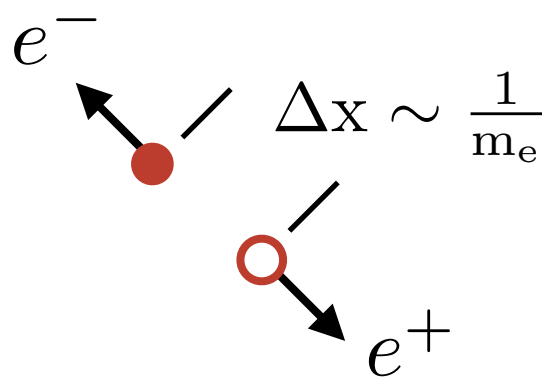
Reminder: Last Lecture

Combining Relativity and Quantum Mechanics

- To preserve causality needed to Anti-particle must exist

- In turn, major implications on the vacuum:

$\Delta E > 2m_e c^2$



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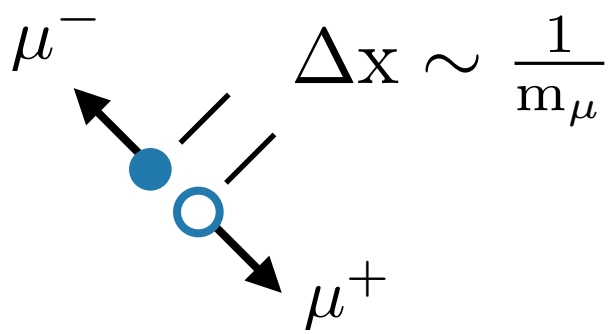


Reminder: Last Lecture

Combining Relativity and Quantum Mechanics

- Massive restrictions in types of theories possible

- Forced to talk particle spin:

  Integer spin = Bosons / Half-integer = Fermions

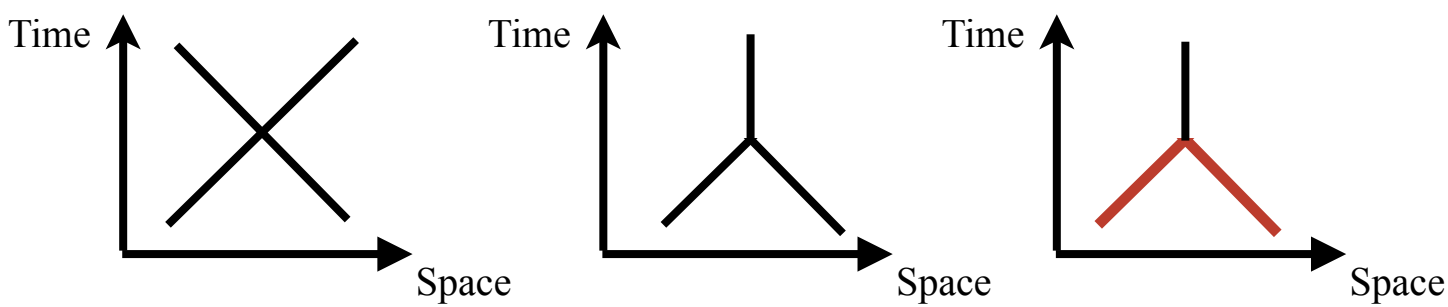
  Can only have: 0 1/2 1 3/2 2

- Major limits to possible interaction:

  Charge conservation / Local in space-time

  Only finite number of specific interactions allowed :

bosons
fermions



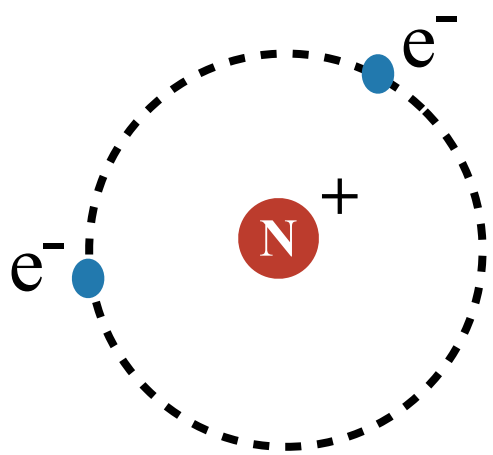
Today's Lecture

The Standard Model:

What the world is made of

Matter

Stuff in the world made of atoms:



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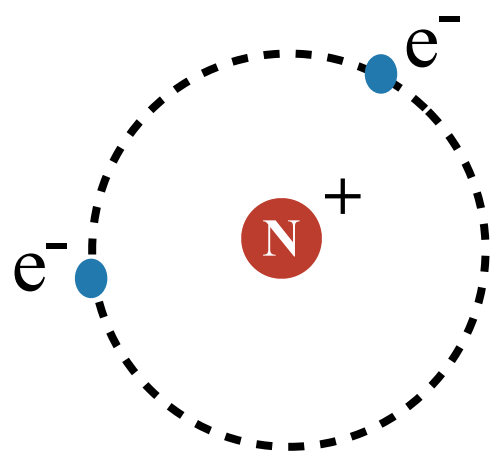

Atoms made of:

Electrons:

Nucleus:

Matter

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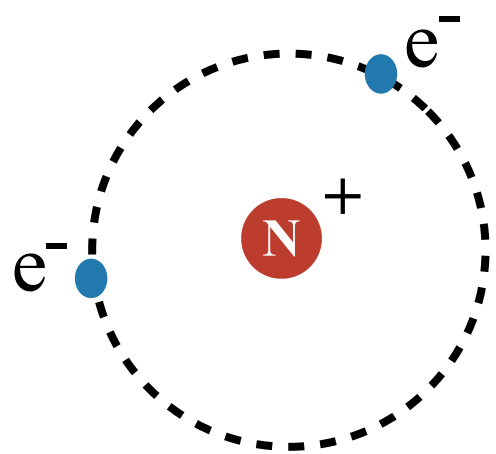

Atoms made of:

Electrons: Negatively charged
Responsible for volume of atom
Thought to be fundamental

Nucleus:

Matter

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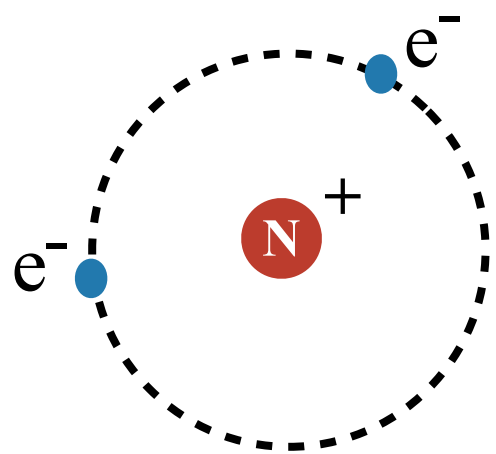

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Responsible for the mass of an atom
Made of, protons and neutrons, which are made of quarks
Quarks also thought to be fundamental

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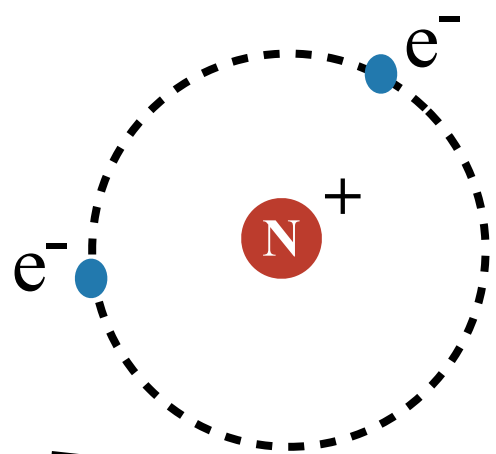

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Matter particles (electrons/quarks) fermions
Large collections behave like classical particles

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Forces

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Known since antiquity / Inverse square law

Always attractive / Irrelevant for atomic/sub-atomic interactions

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Discovered early 1900s / Short distances / No simple relationship

Responsible for holding together the nucleus

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

Forces

All forces as important.
Look very different from one another

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$\Rightarrow$ described in terms of a Quantum Field Theory (QFT)

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

The Standard Model

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

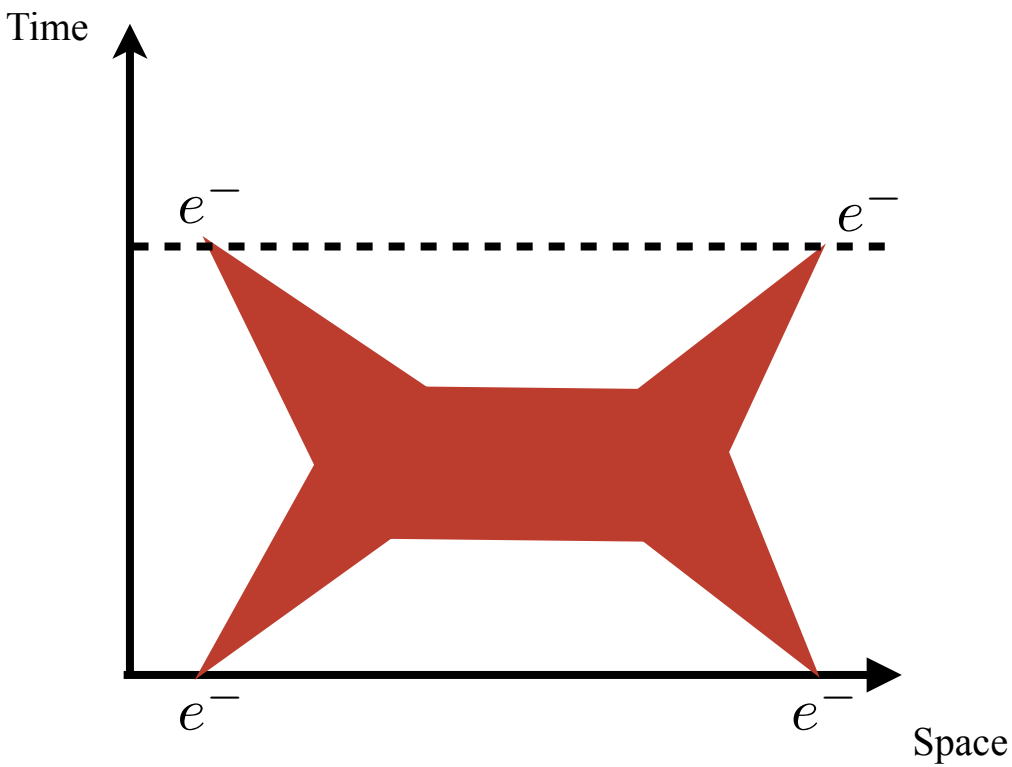
The particular version of QFT that was found to describe our universe developed in the 1960-70s.

Most accurate theory in all of science
- Describes all matter/interactions down to 10^-18m
  (Distances 100 × smaller than proton)
- Accurate/precise description all observed particle interactions

Output of the Theory

Predict probabilities for various things to happen

Example:



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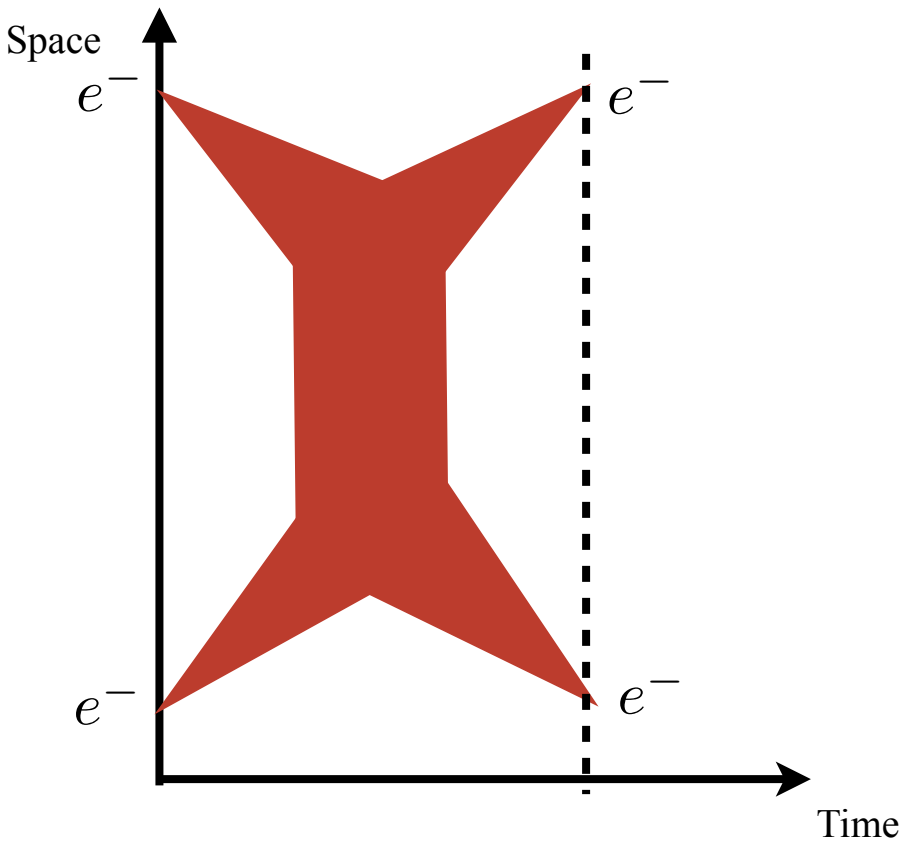

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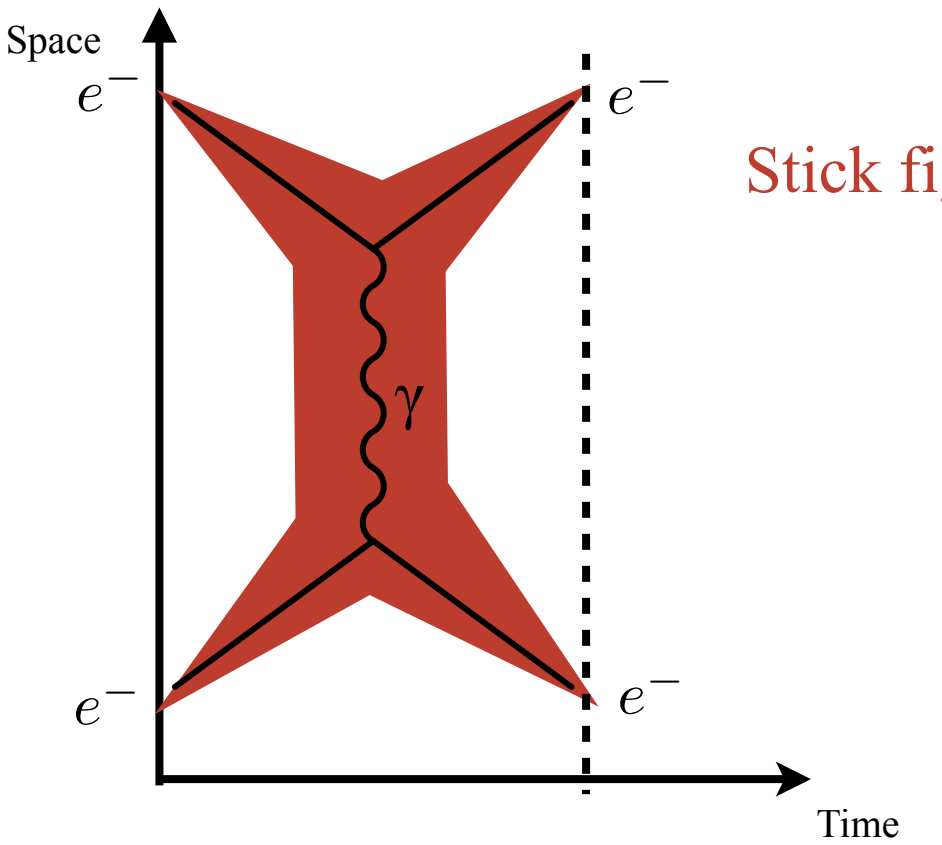

Stick figure: *"Feynman Diagram"*

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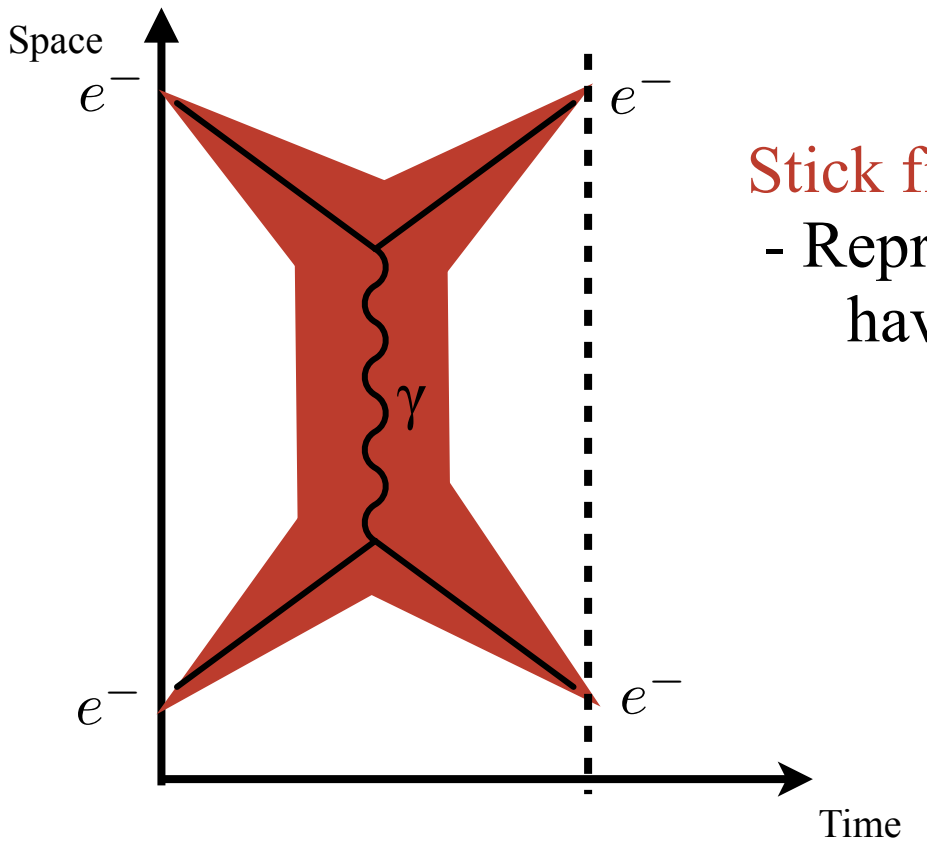

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- Represents one possible way things could have happened

Output of the Theory

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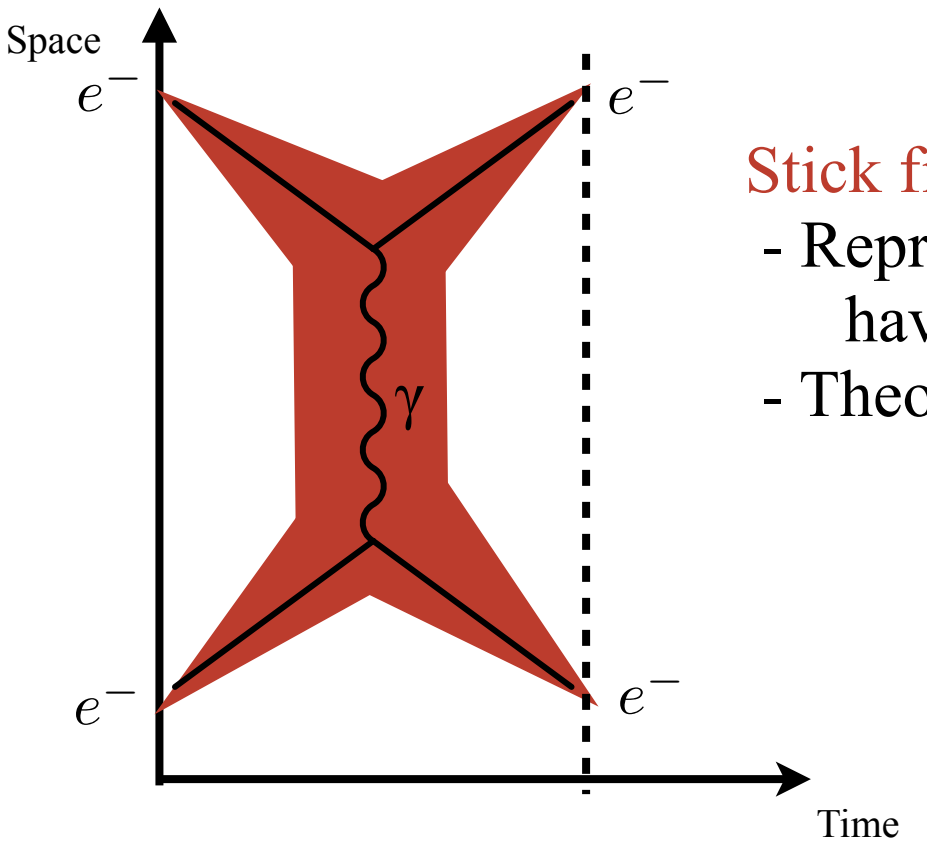


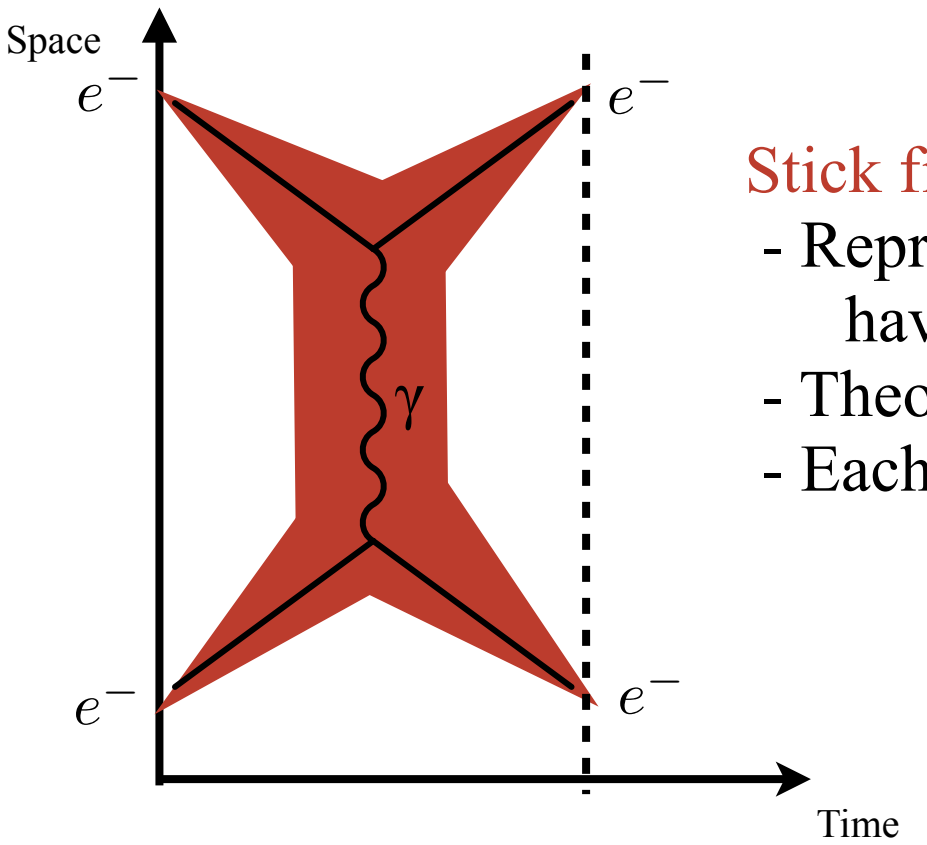
Stick figure: *"Feynman Diagram"*

- Represents one possible way things could have happened
- Theory assigns number to each diagram

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

Output of the Theory

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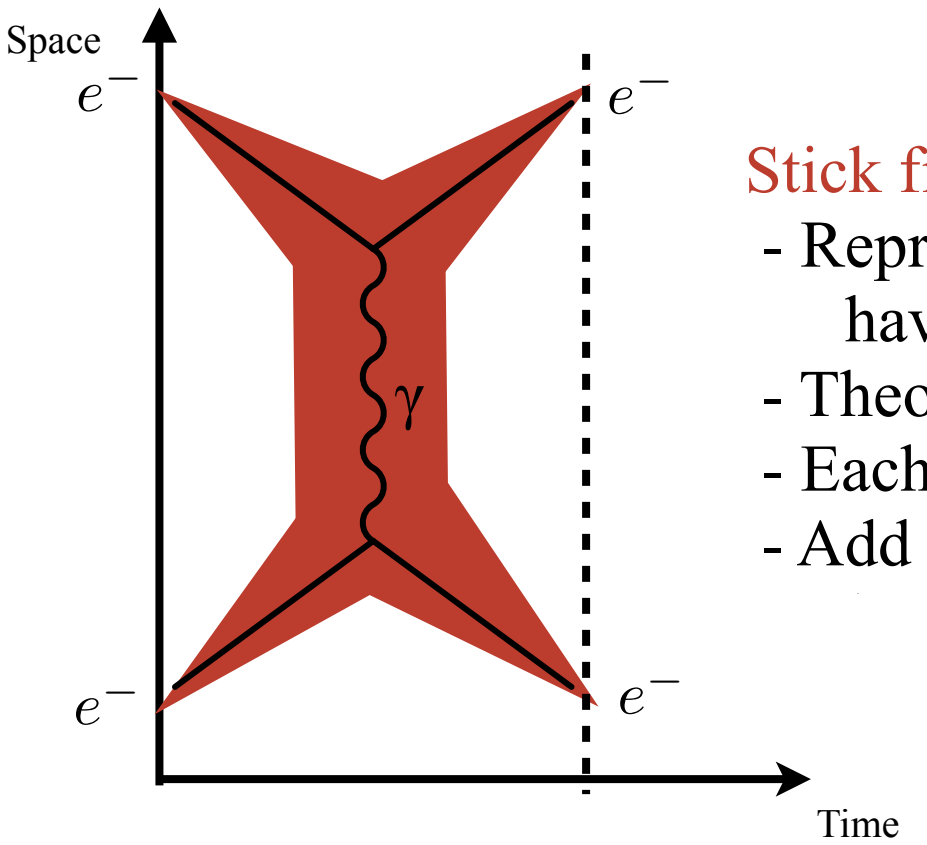

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- Add all paths consistent w/input & output

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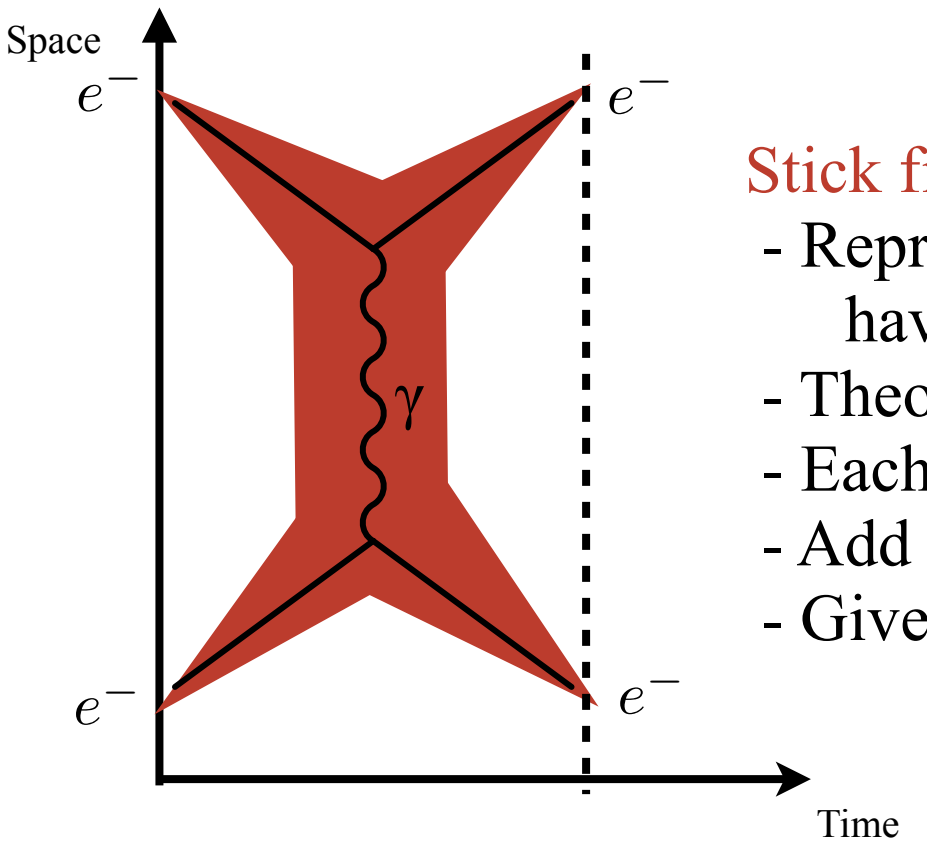

Stick figure: *"Feynman Diagram"*

- 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

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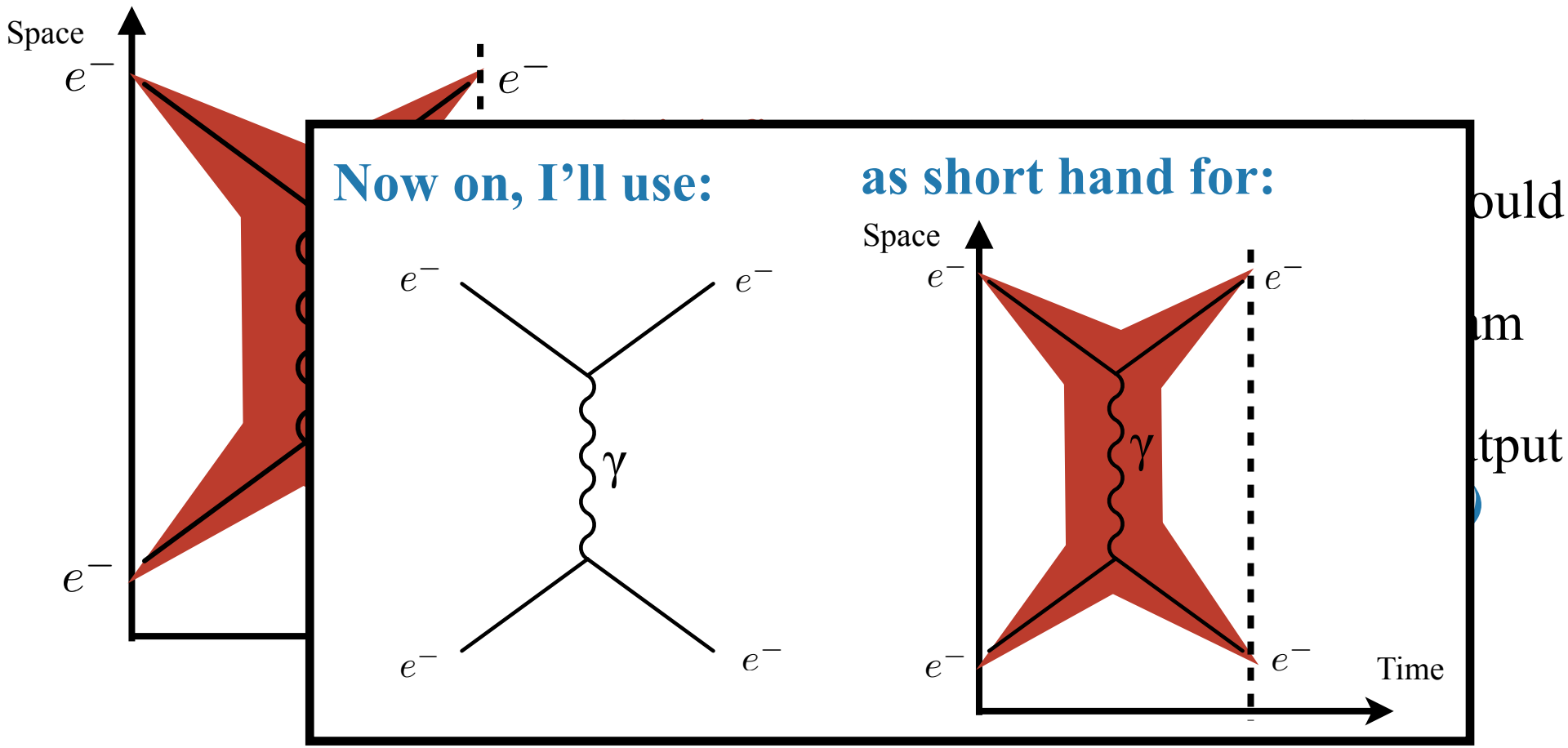
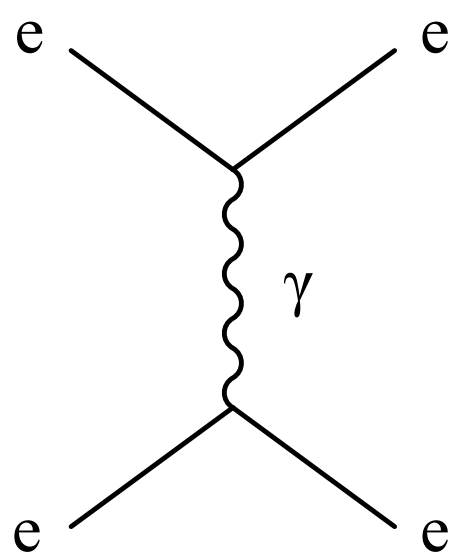


Forces from Interactions

Forces long-range manifestations of local interactions

No more action at a distance!

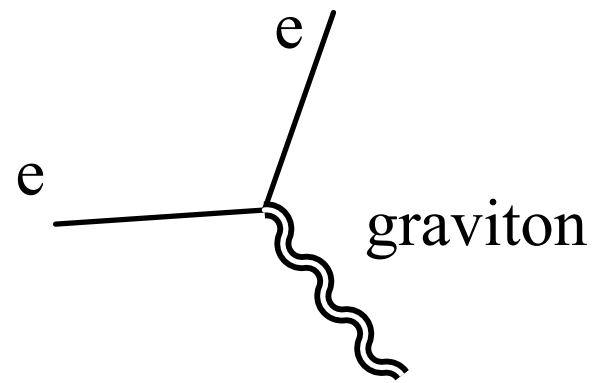


Electromagnetic force between two electrons result exchange of a photon

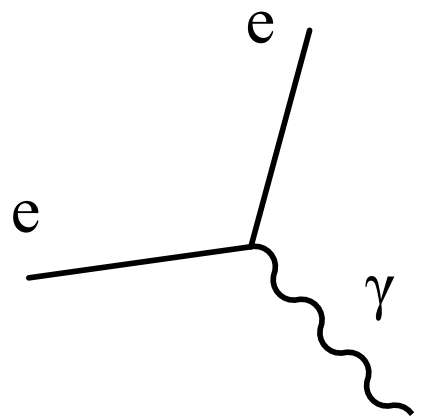
Exchange as local interactions two e-γ interactions

Forces from Interactions

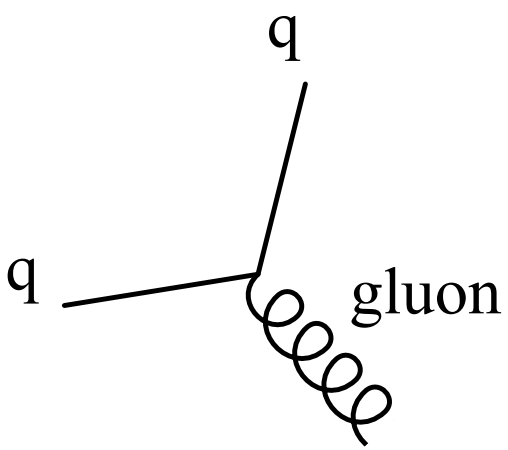
Gravitational Interaction



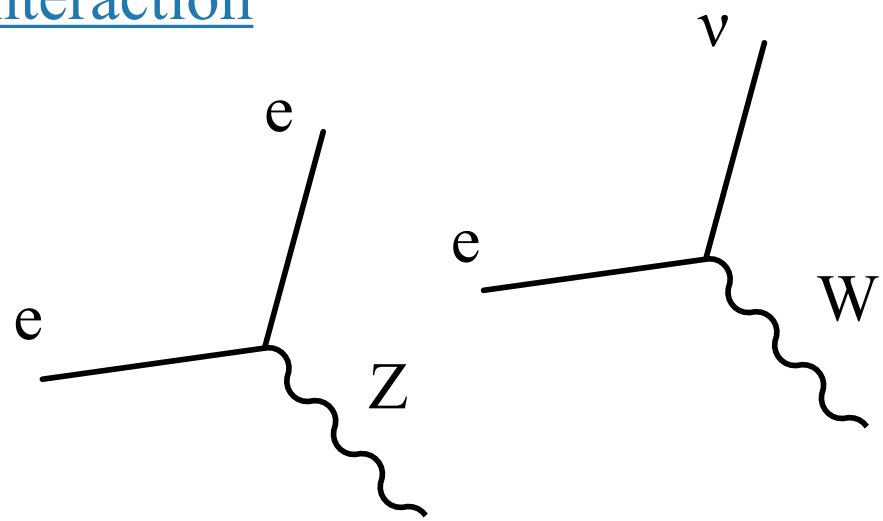
Electromagnetic Interaction



Strong Interaction



Weak Interaction



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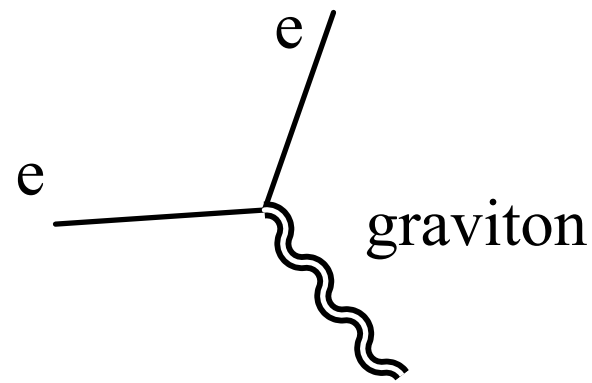
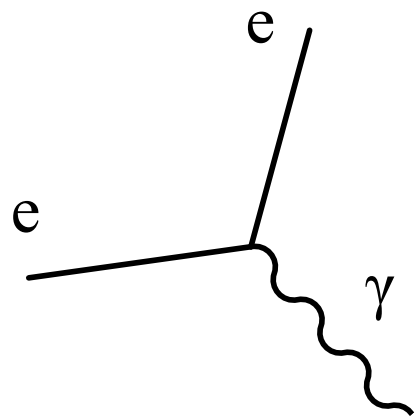


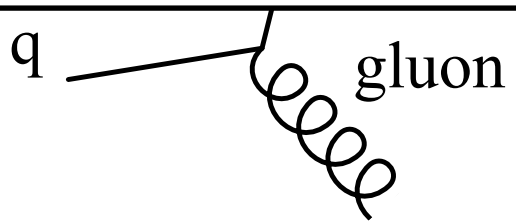
Electromagnetic Interaction

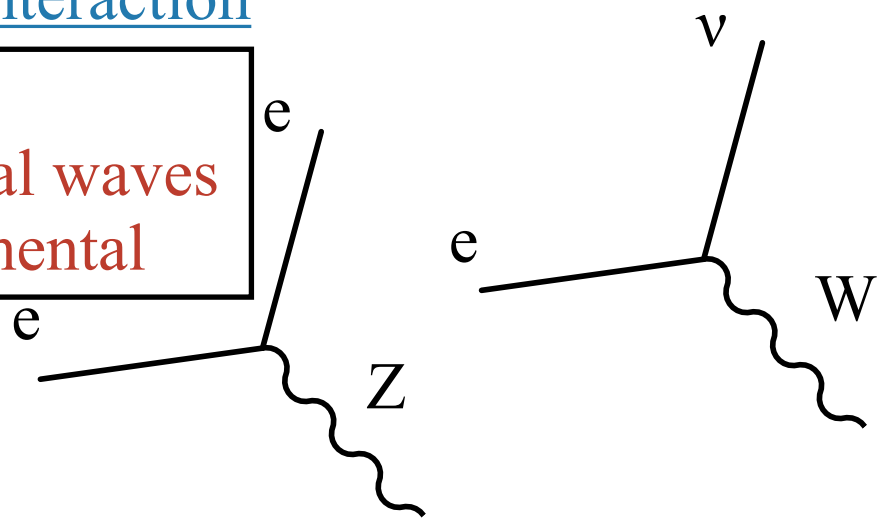


Strong Interaction

Weak Interaction

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





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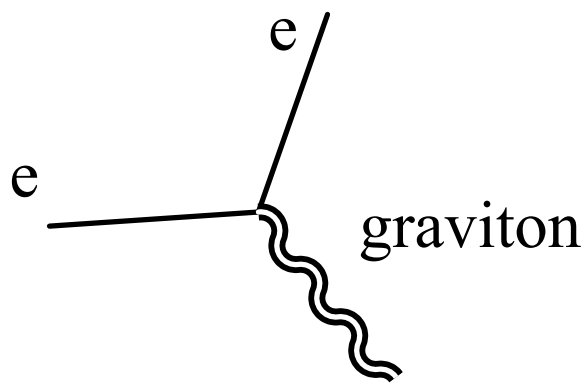

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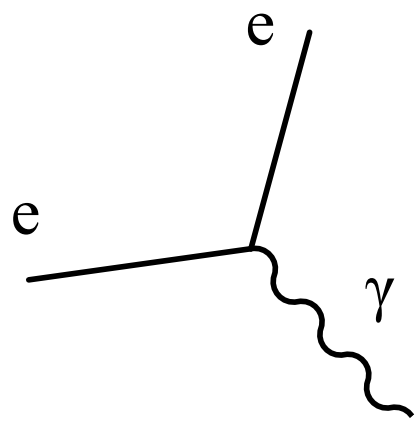

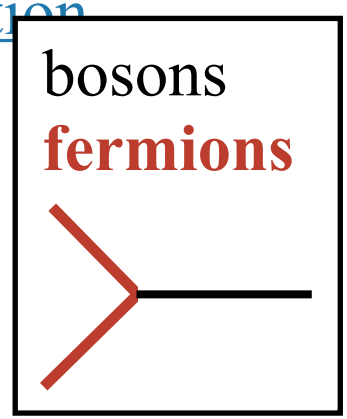

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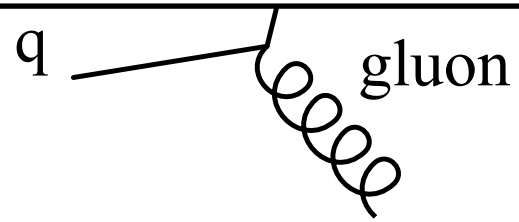

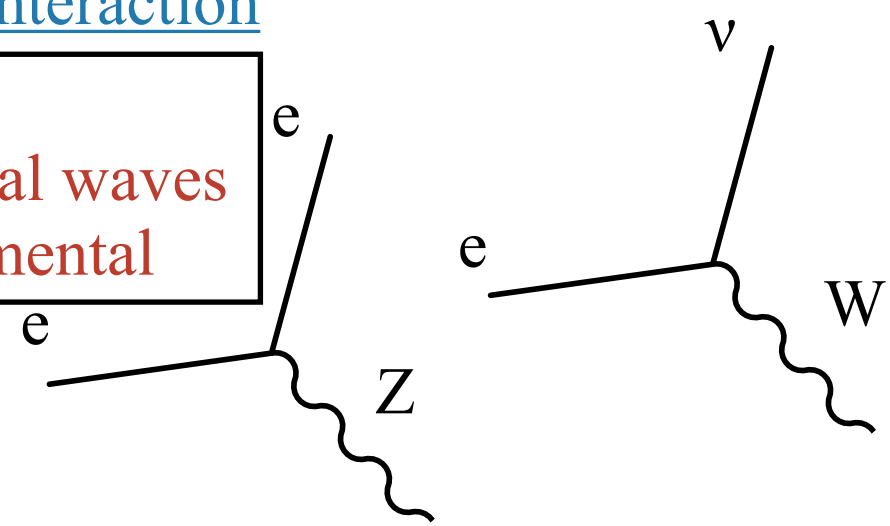

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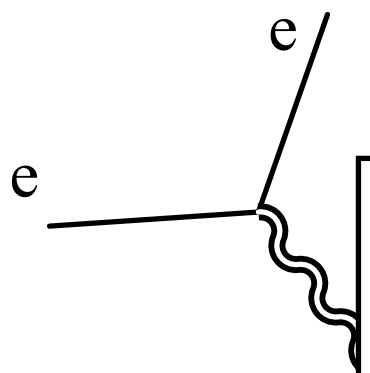
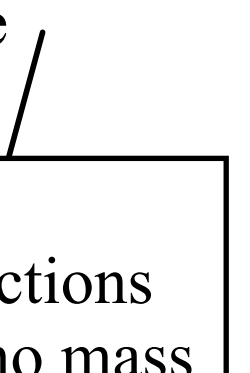
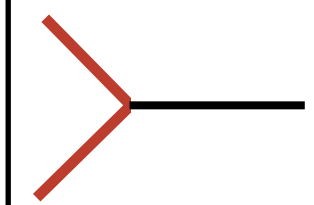




bosons
fermions



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

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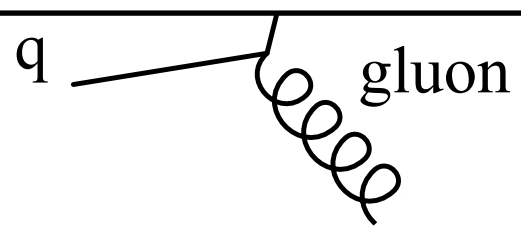

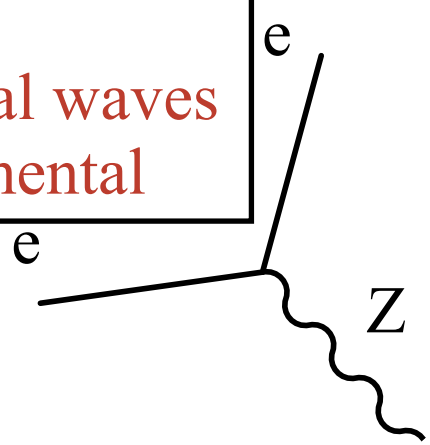

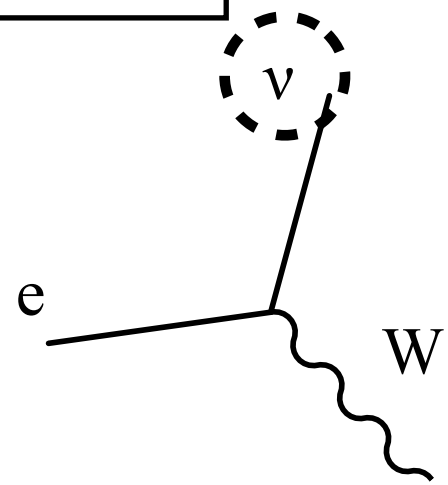

The Standard Model

Matter Particles (Fermions) Spin = 1/2

Leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

Quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

Interactions "Force carriers" (Bosons) Spin = 1

Gauge bosons:

γ W Z g

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Beautiful (complicated) mathematics governs nature interactions
Dictated by principles of symmetry *(Much direct consequence QM + R)*

The Standard Model

Matter Particles (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:

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

Interactions "Force carriers" (Bosons)

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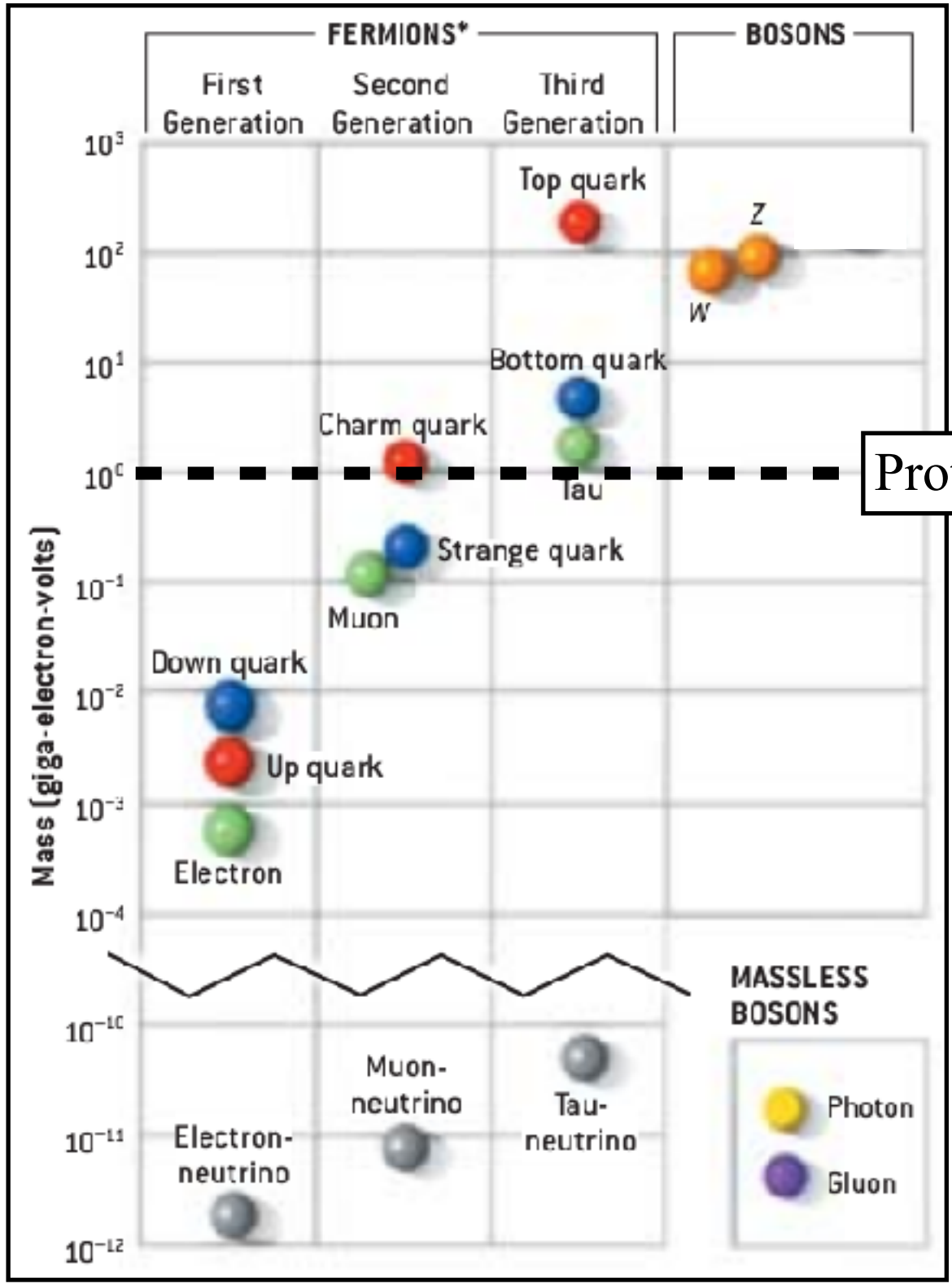
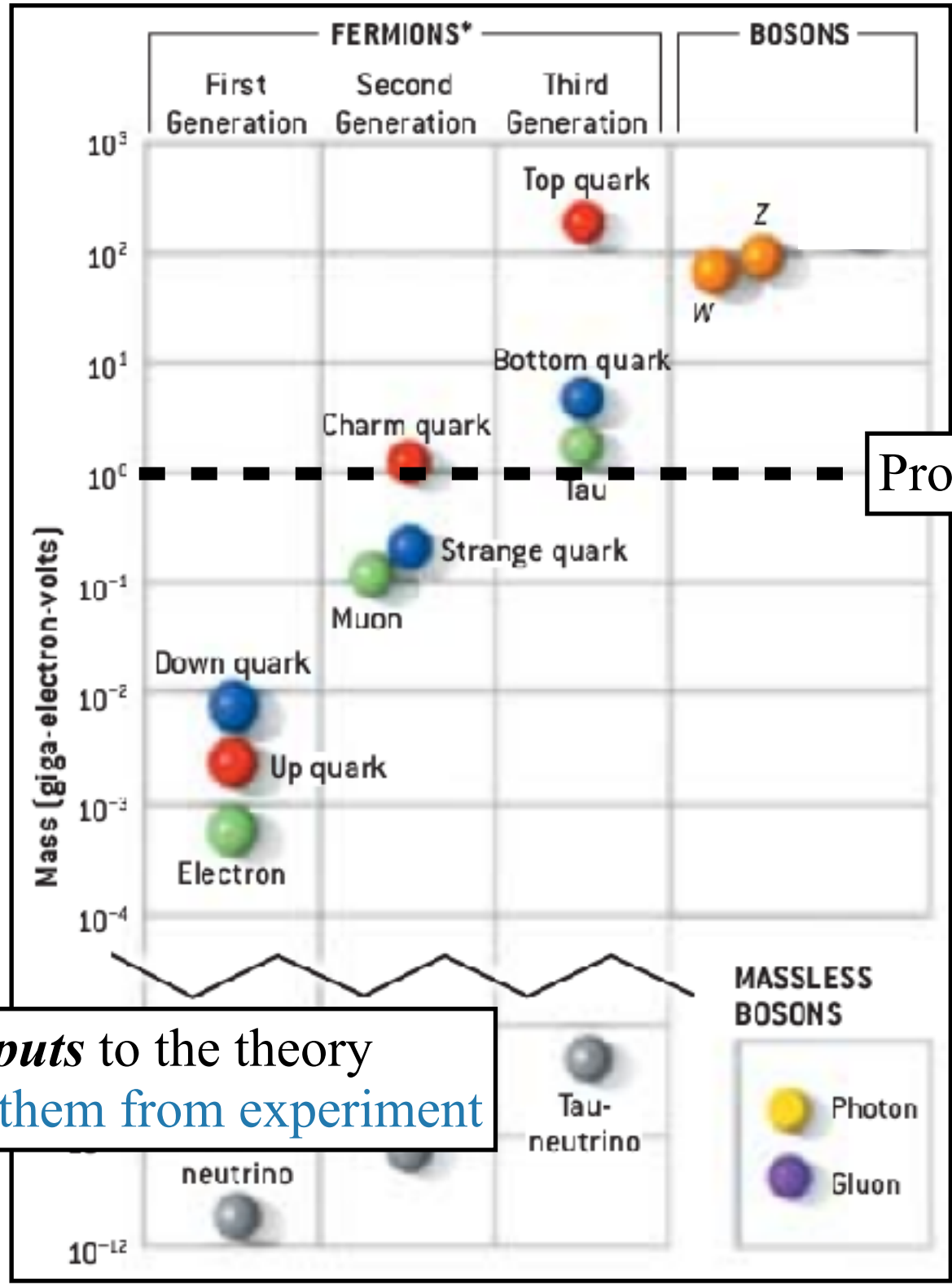
Masses


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
Top quark
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
Proton Mass
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

Masses

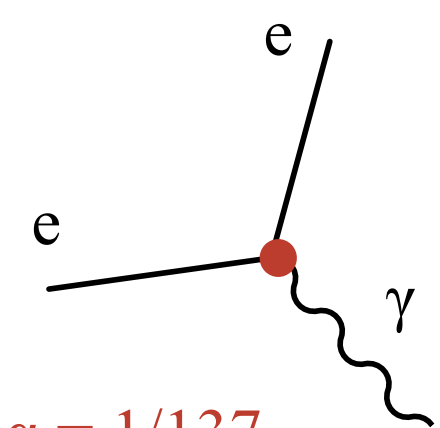


These masses are ***inputs*** to the theory

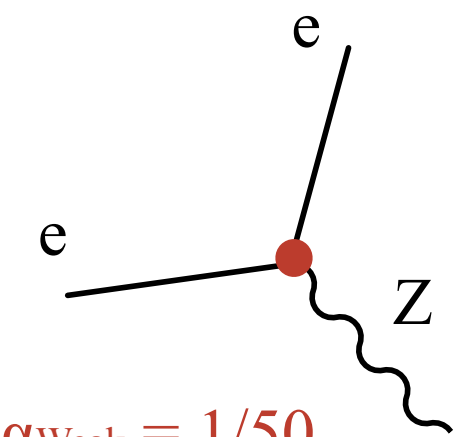
Need to determine them from experiment

Interaction Strengths

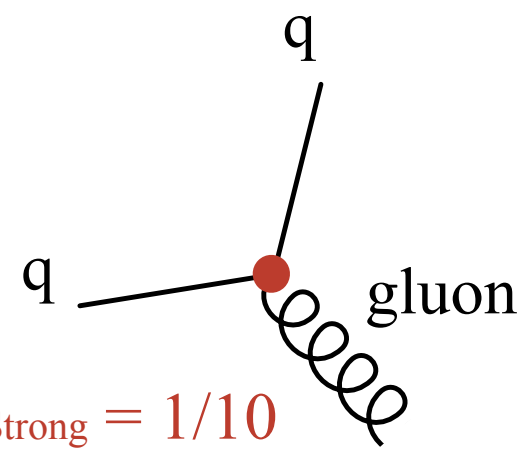
Each interaction vertex characterized by number:



$\alpha = 1/137$



$\alpha_{Weak} = 1/50$



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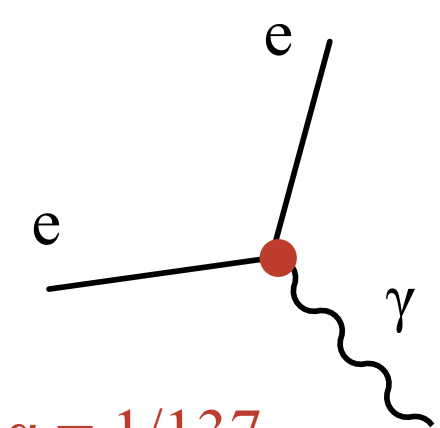
Sets the overall strength of the different interactions

- Directly related to the probability for the processes to occur

Interaction Strengths

Each interaction vertex characterized by number:



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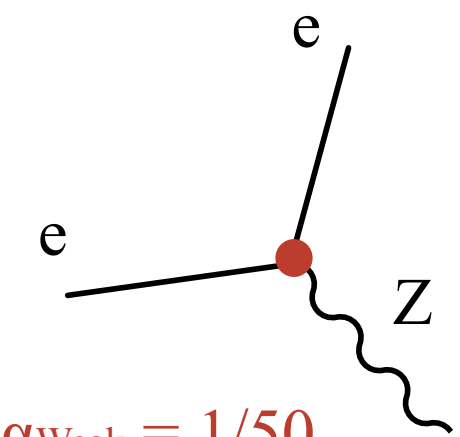

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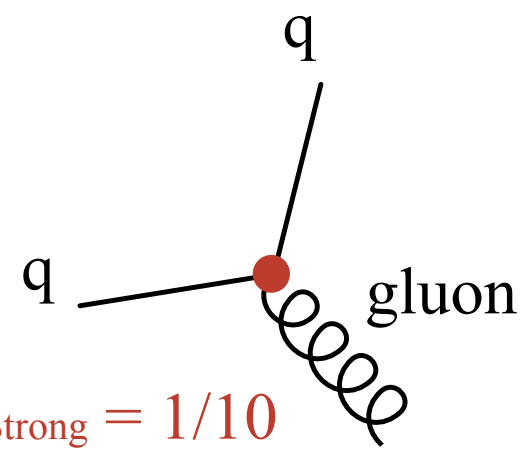

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Sets the overall strength of the different interactions

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These numbers are ***inputs*** to the theory

- Need to determine them from experiment
- Then use them as input in other calculations.

Interaction Strengths

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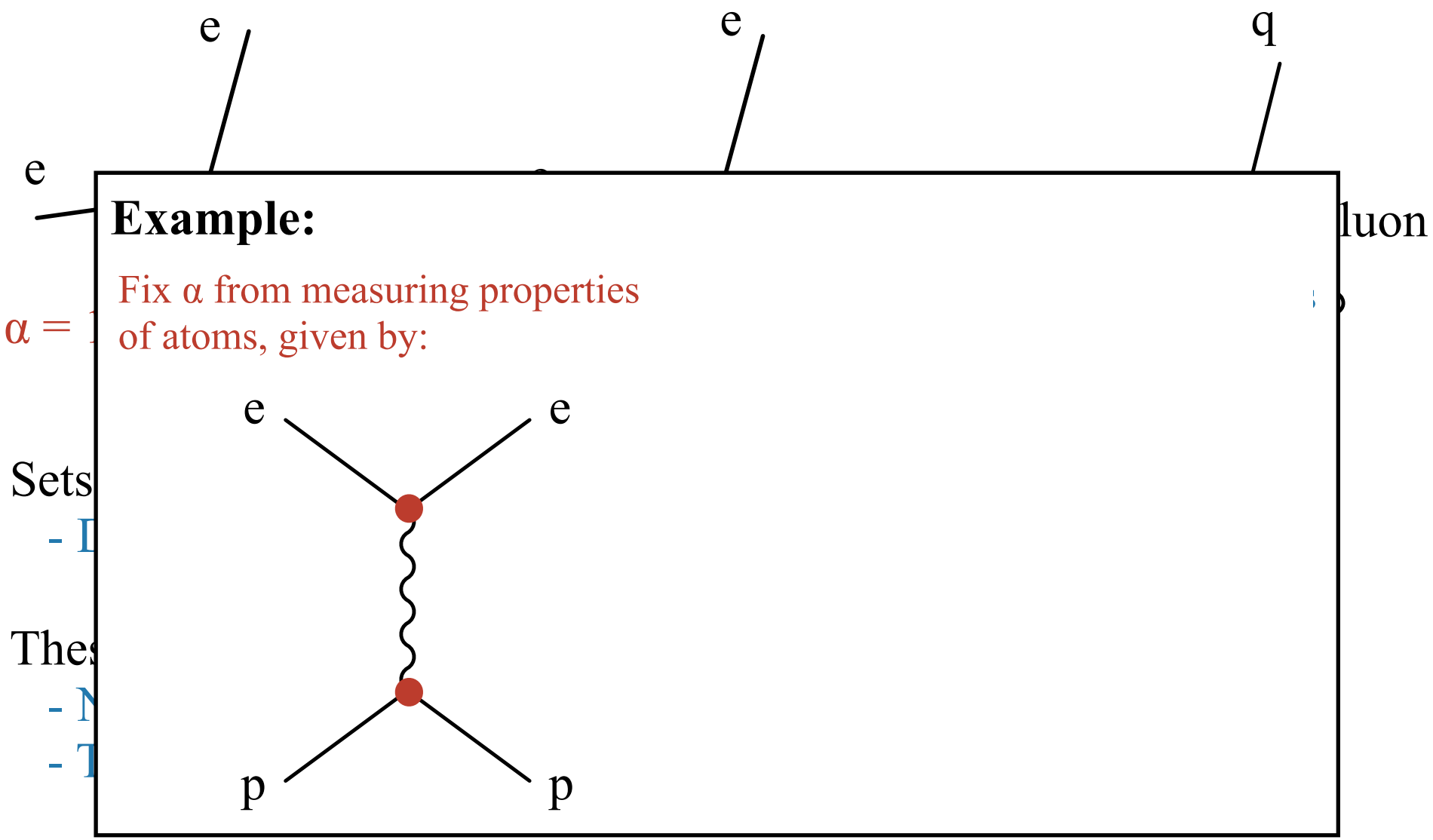

Example:

Fix α from measuring properties of atoms, given by:

Interaction Strengths

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e e q e luon

$\alpha =$

Sets

- E

Thes

- N
- T

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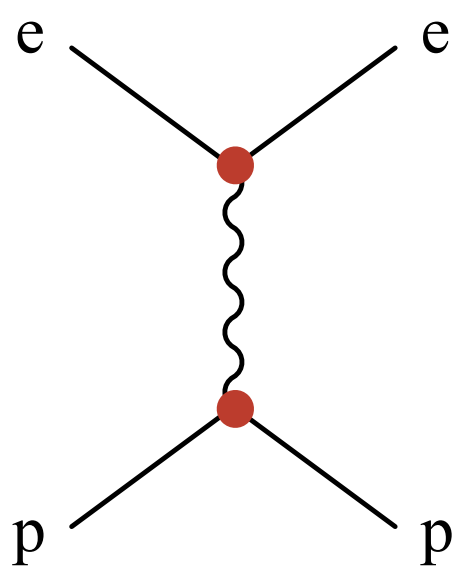
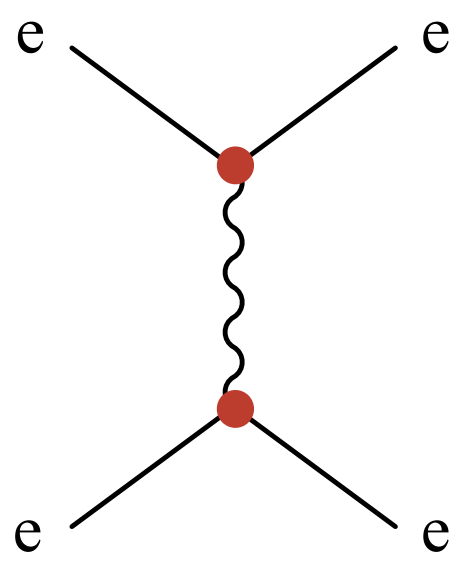
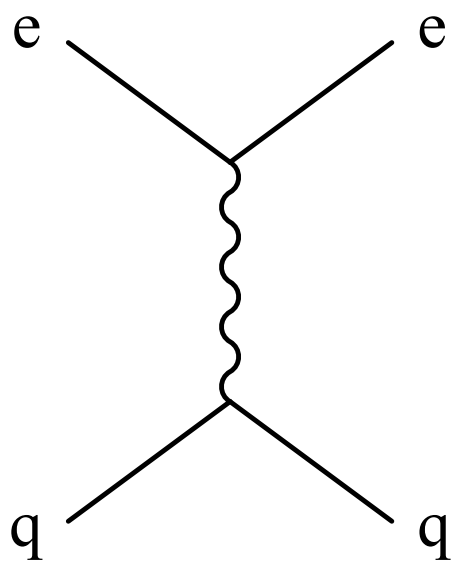


Then predict all other EM probabilities (eg: how electrons (or anti-e) scatter)



Output of the Theory (Details)

Feynman Diagrams: Pictures of what happens
Invaluable Tool for calculation



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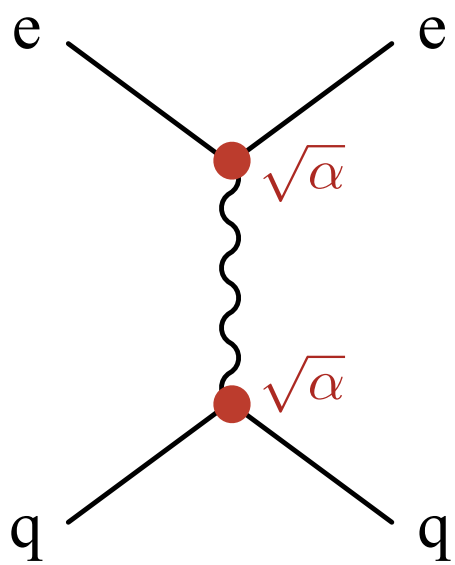

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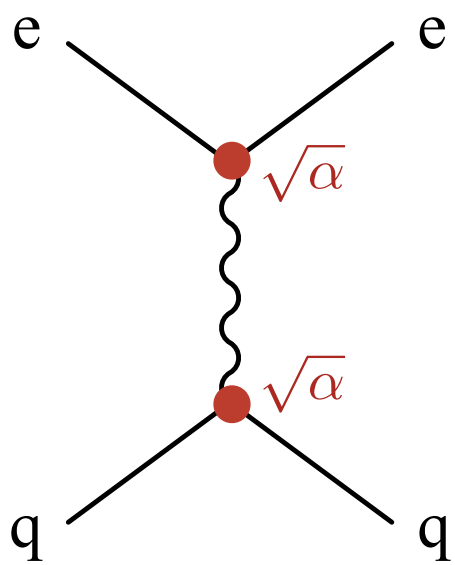
$\psi =$



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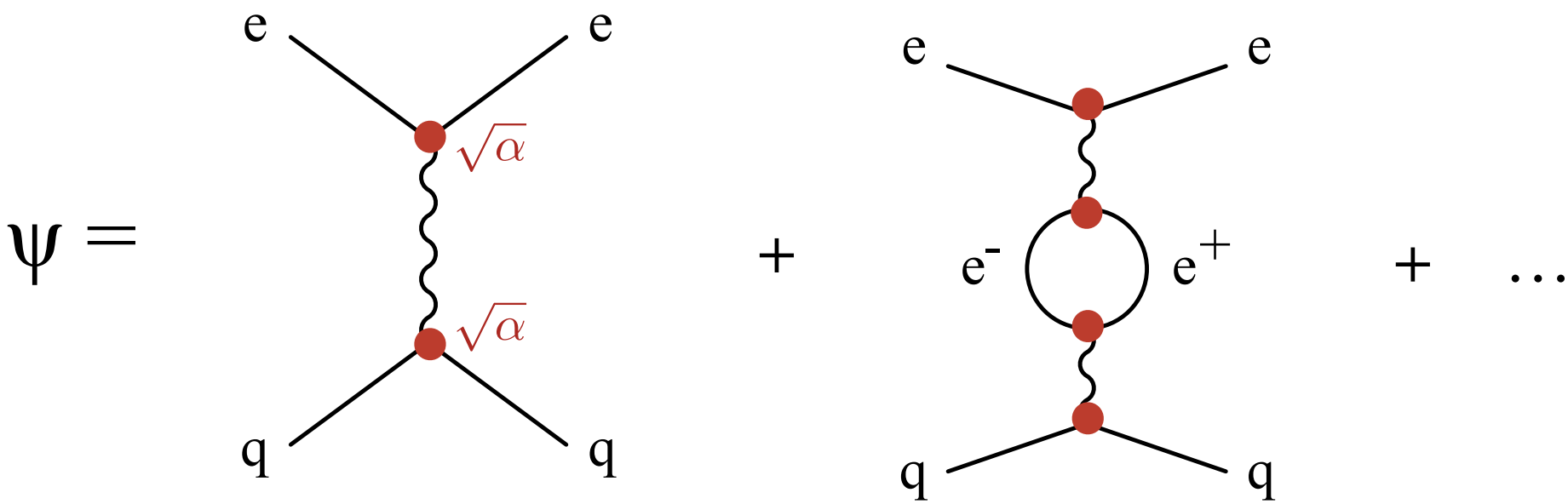

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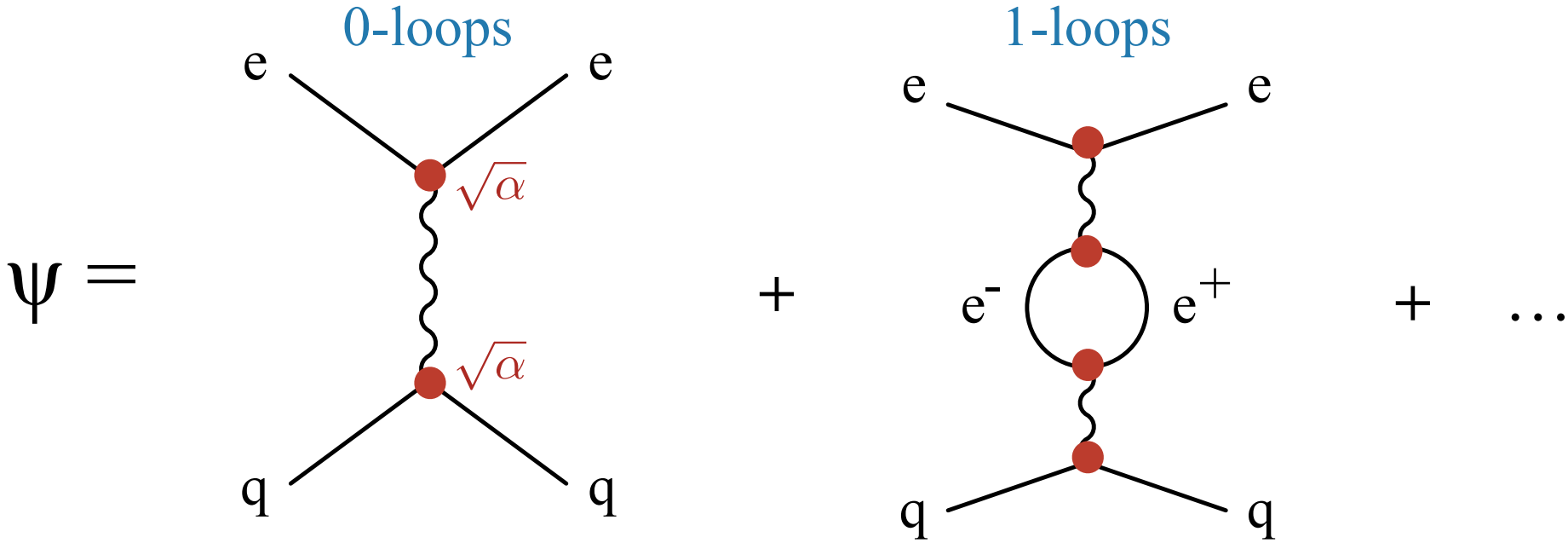

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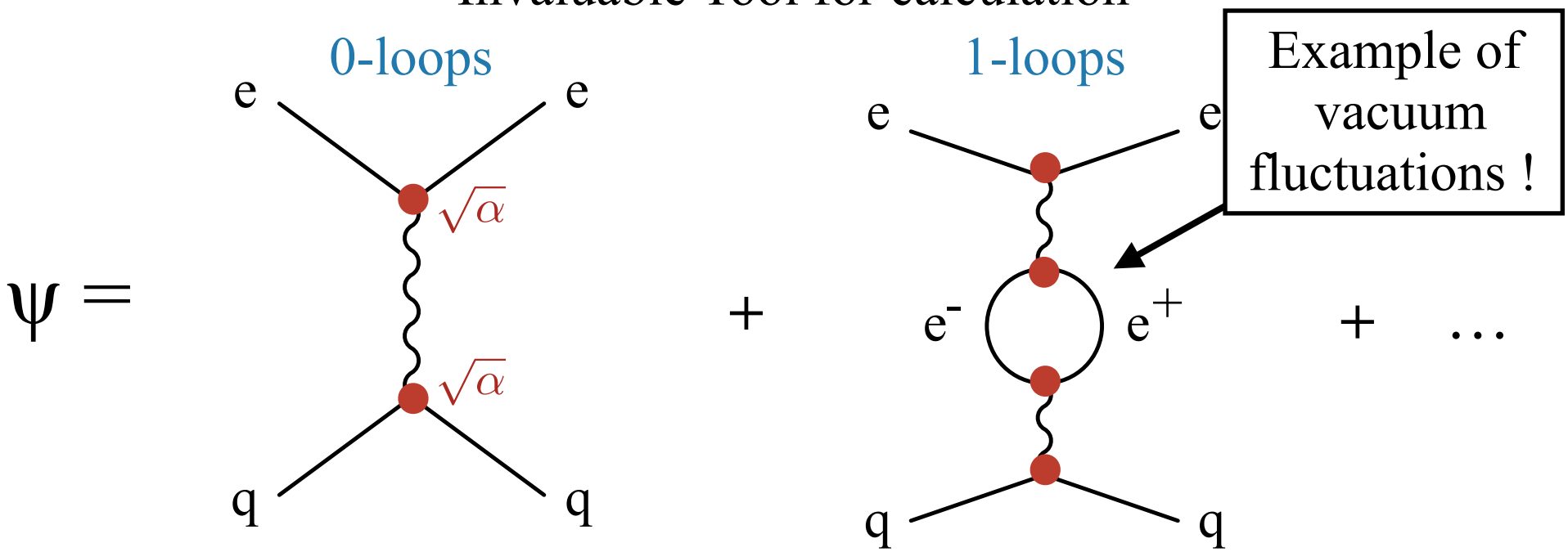

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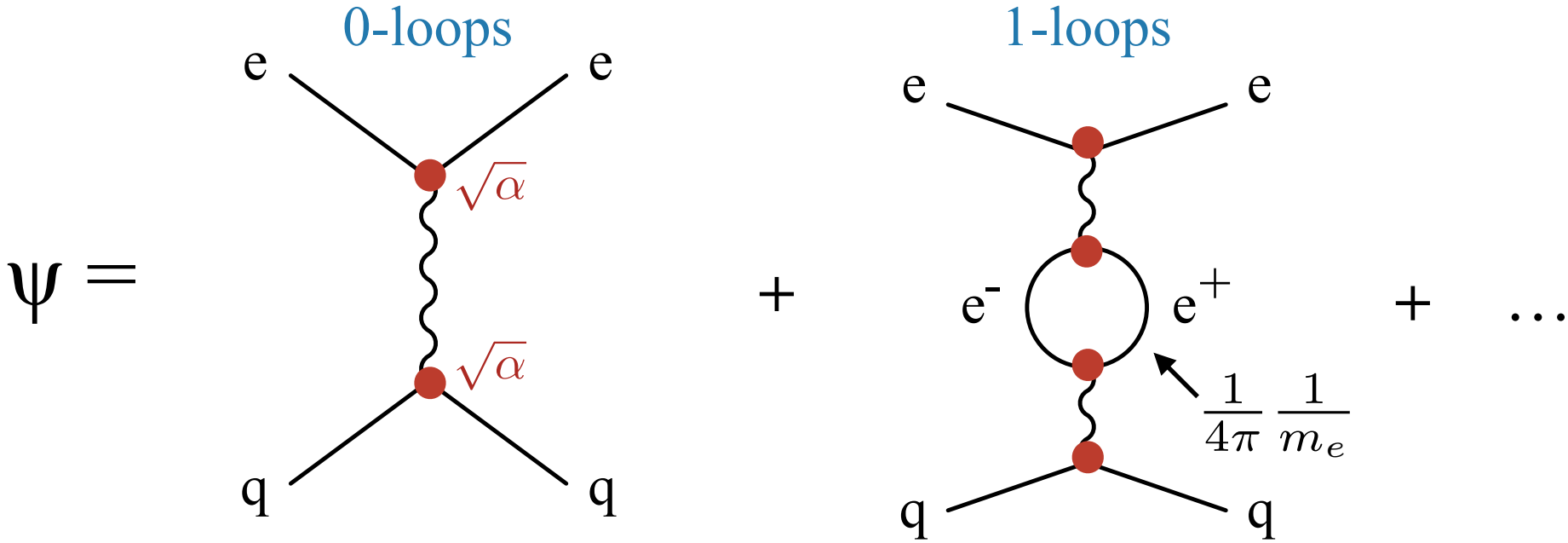

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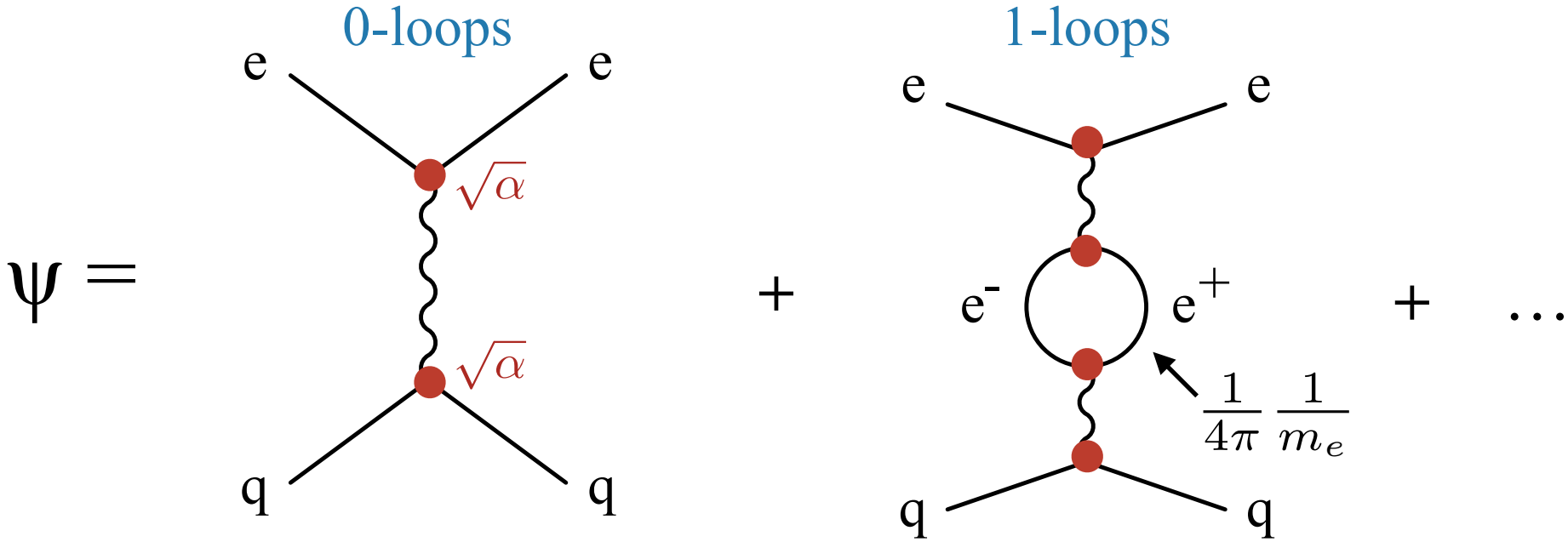

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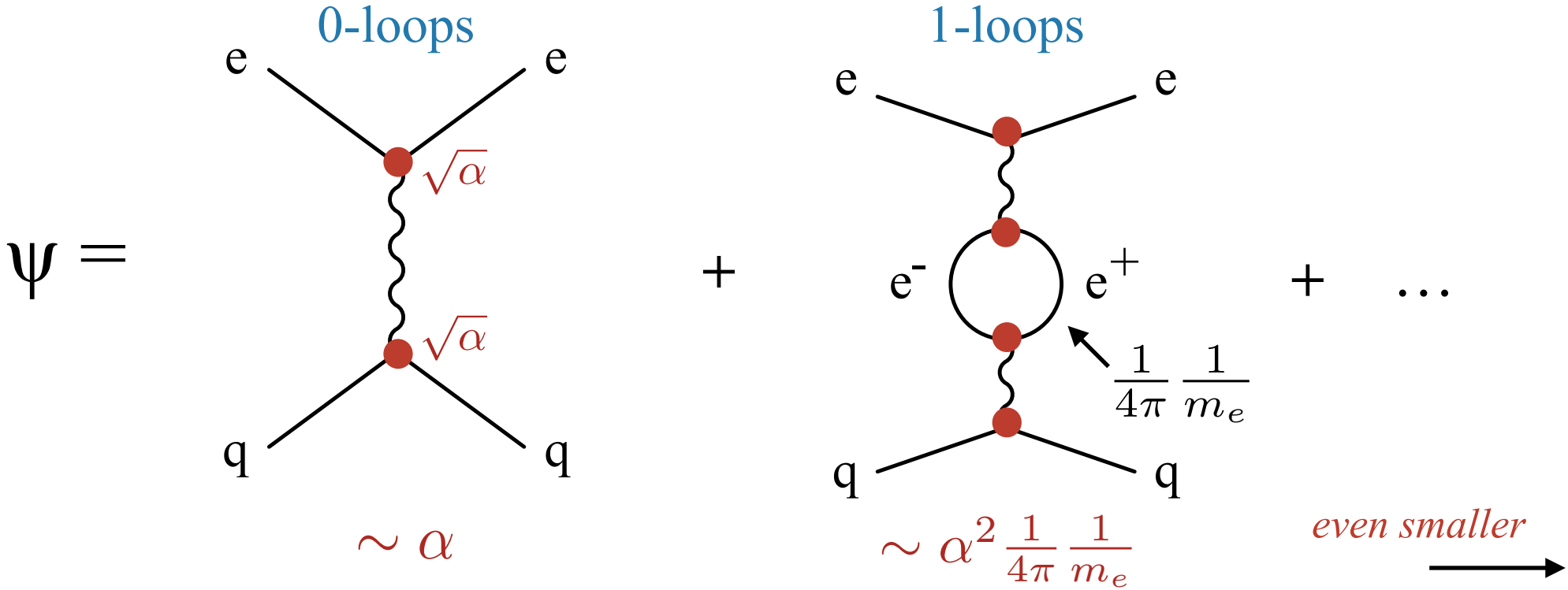

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Can also calculate basic properties of particles

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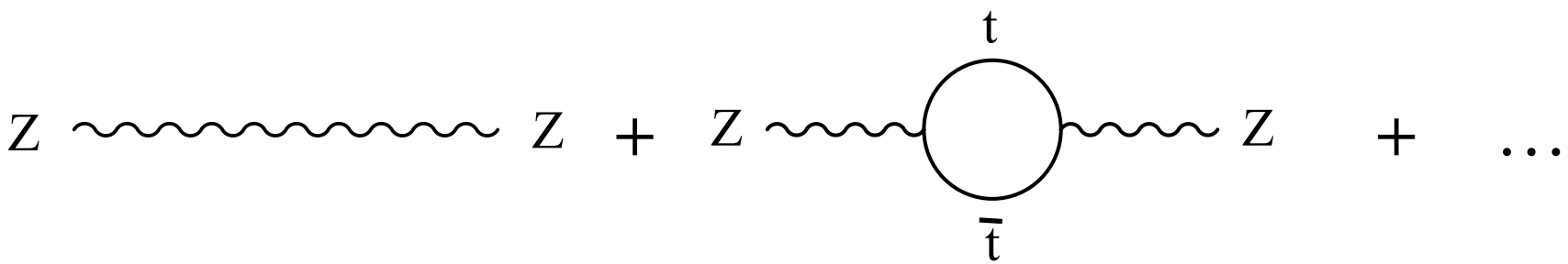

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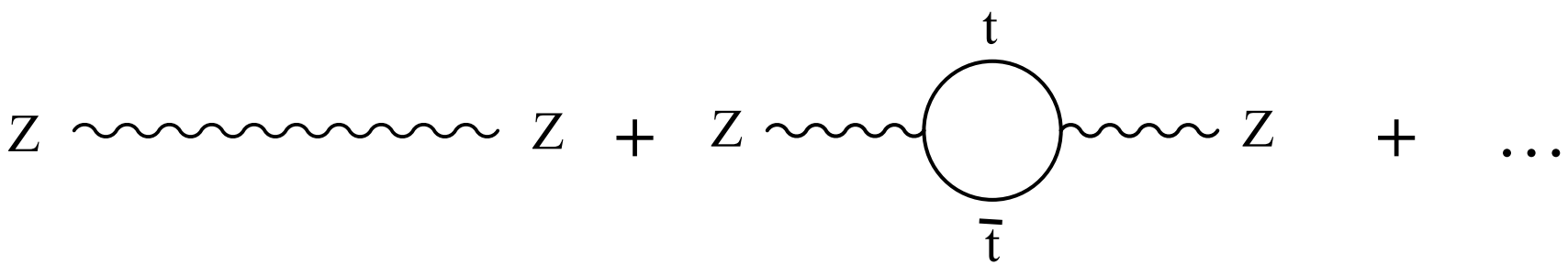
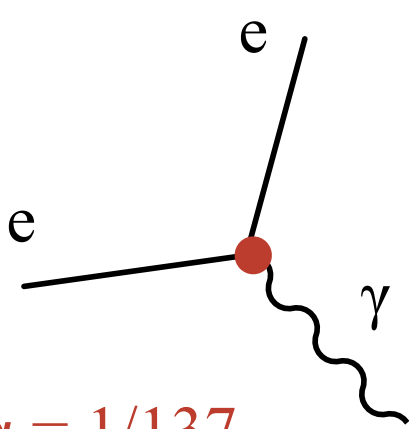


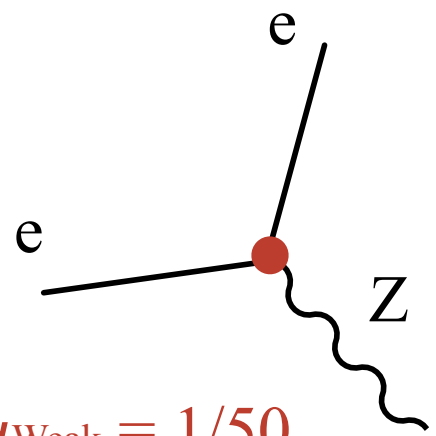
- Seems impossible given mtop > mZ
- Allowed by Quantum theory (Uncertainty principle $\Delta E \Delta t \geq h$)
- "Quantum Corrections" to mass
- Confirmed observable consequences

Forces Common Language

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



$\alpha = 1/137$



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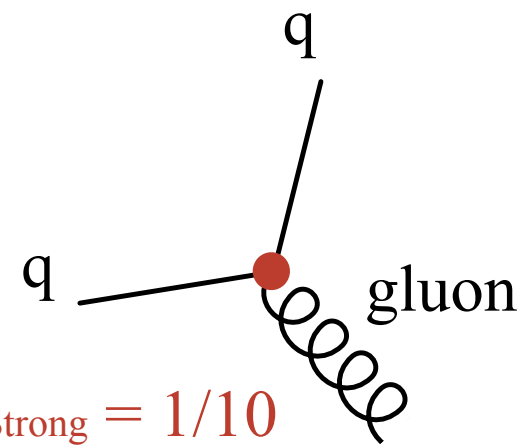
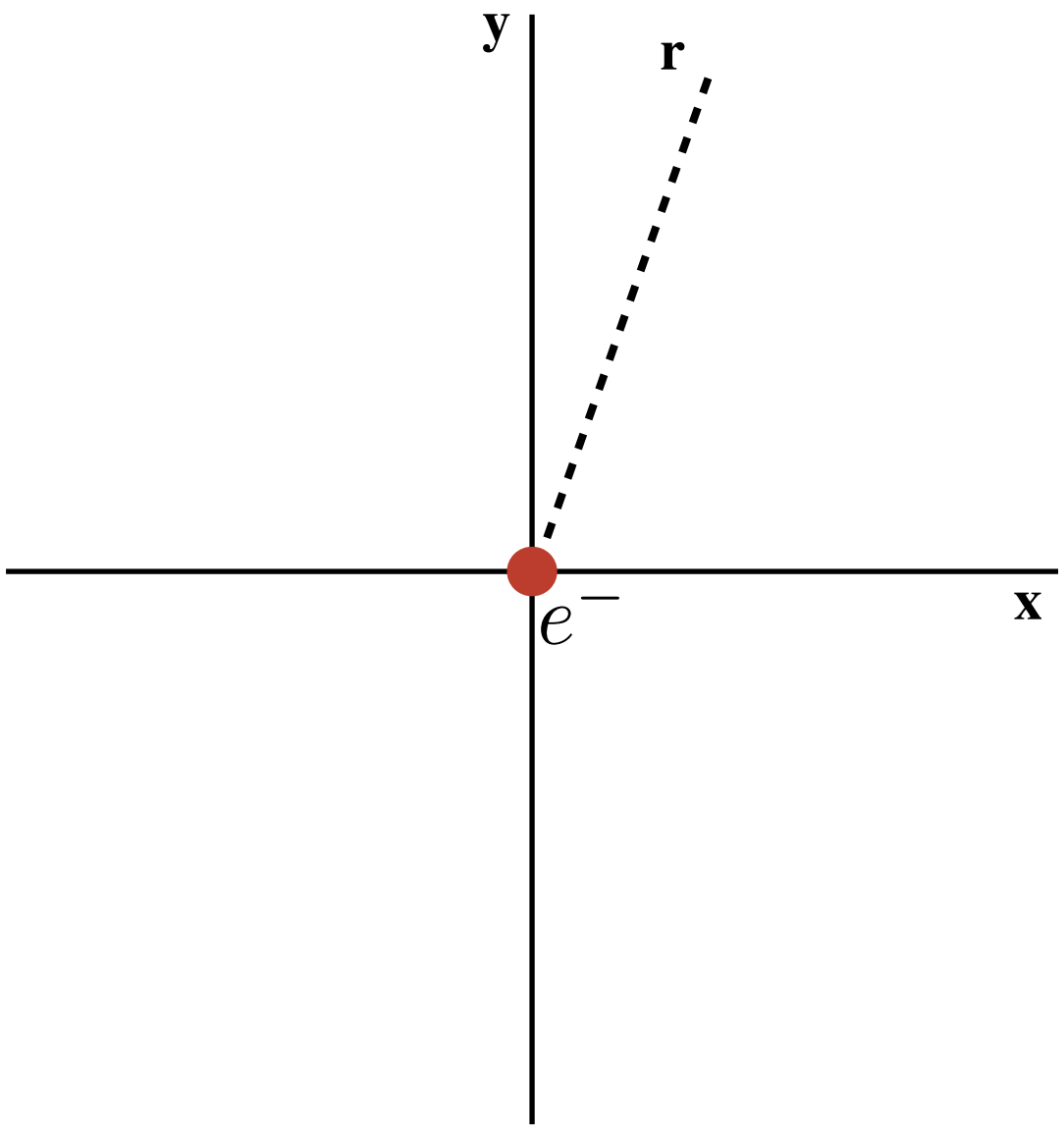
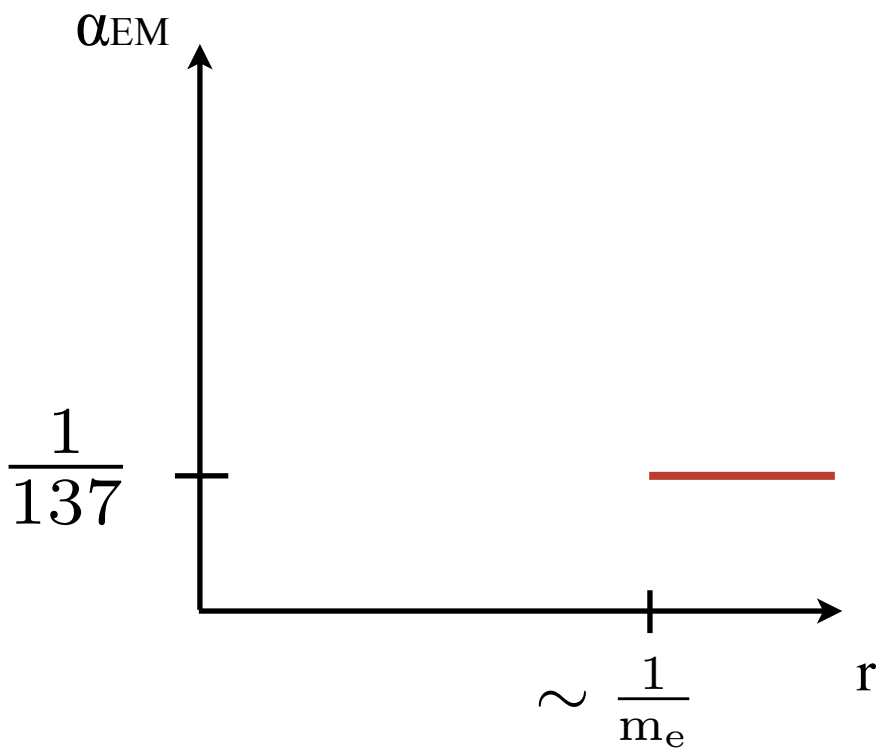


$\alpha_{Strong} = 1/10$

Forces look very different to us…

EM Strength w/Distance





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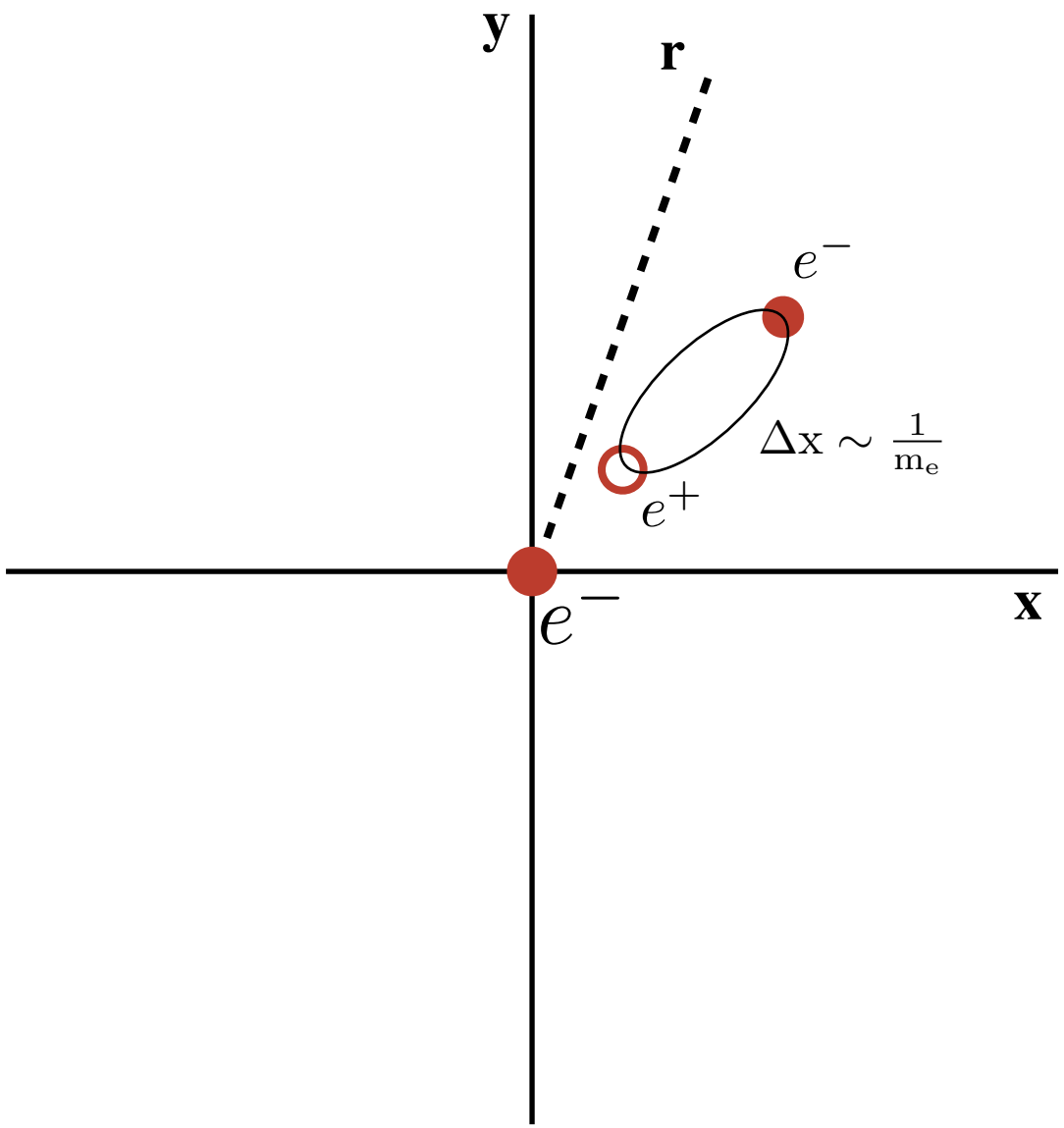

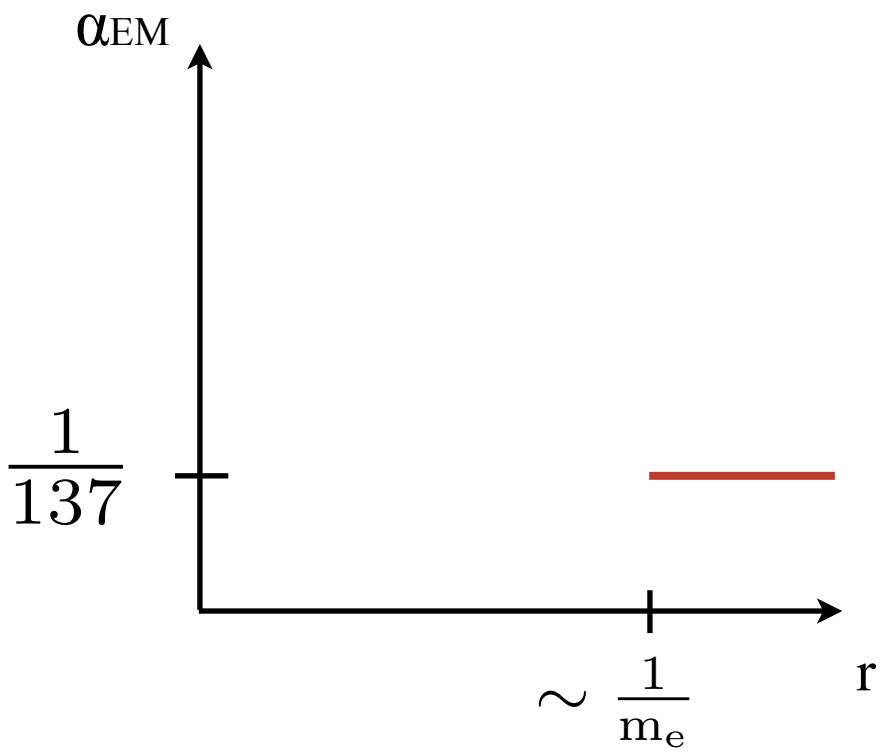

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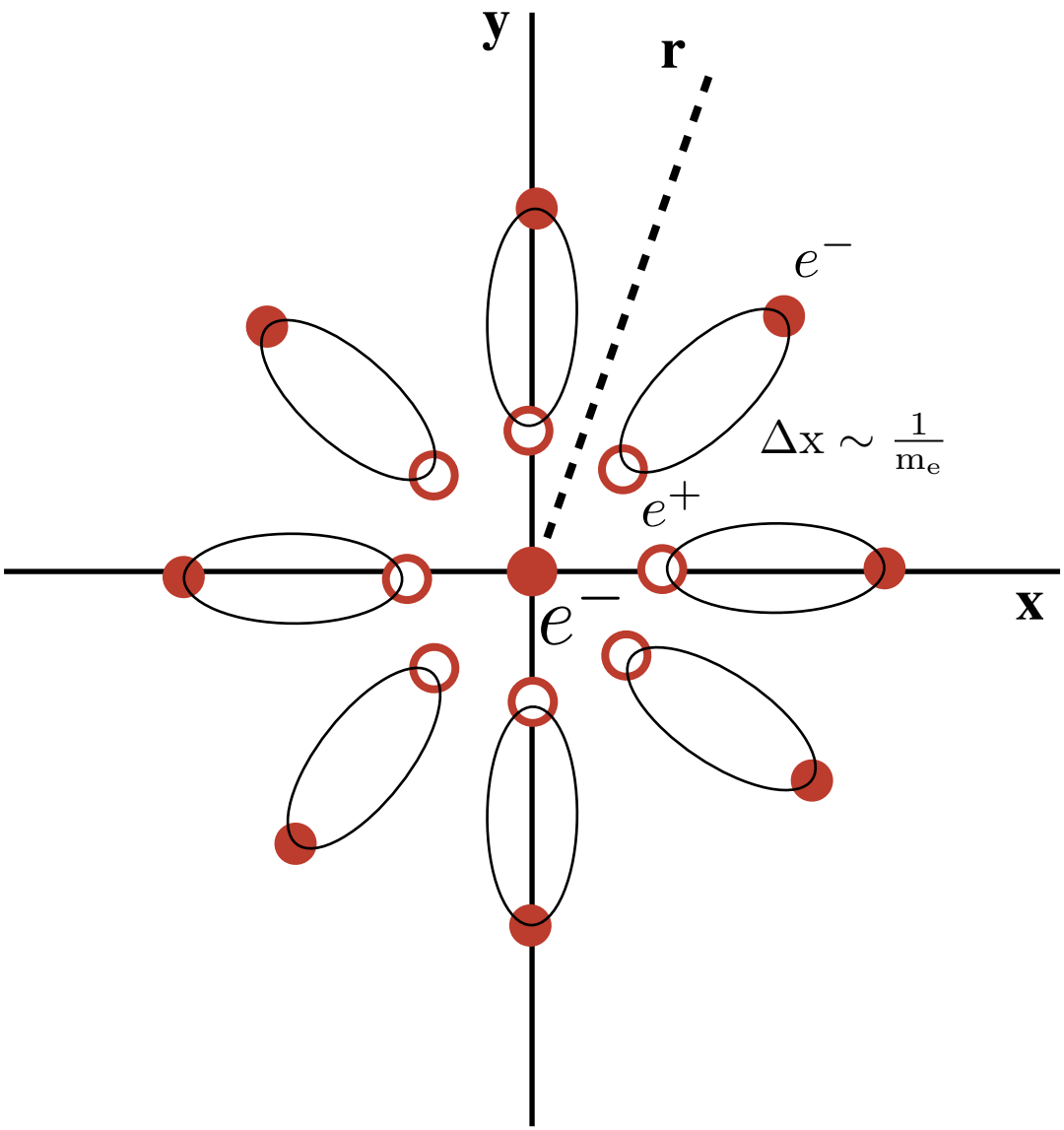

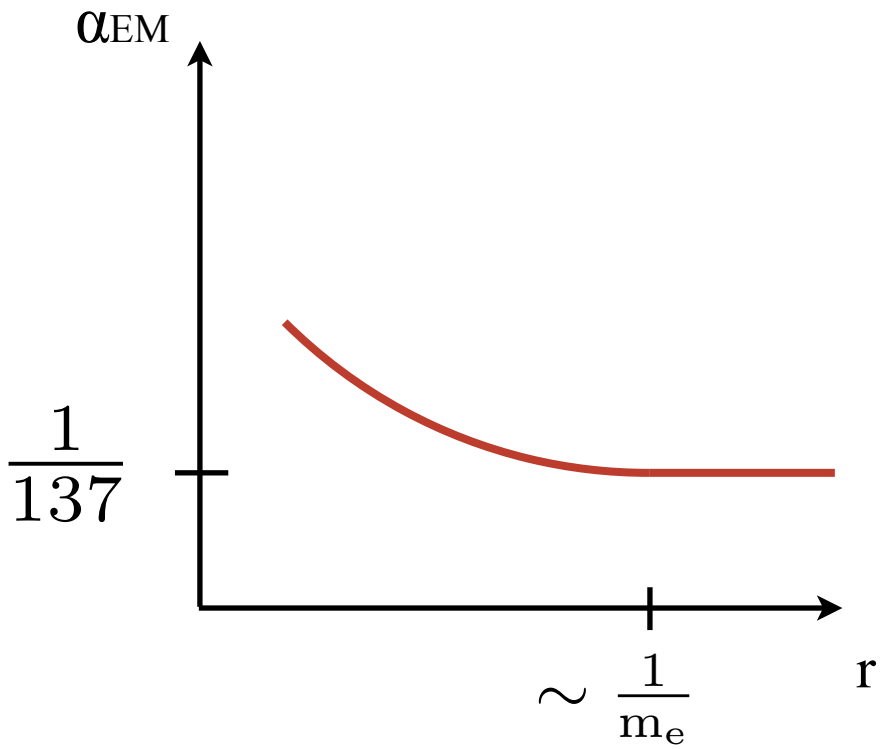

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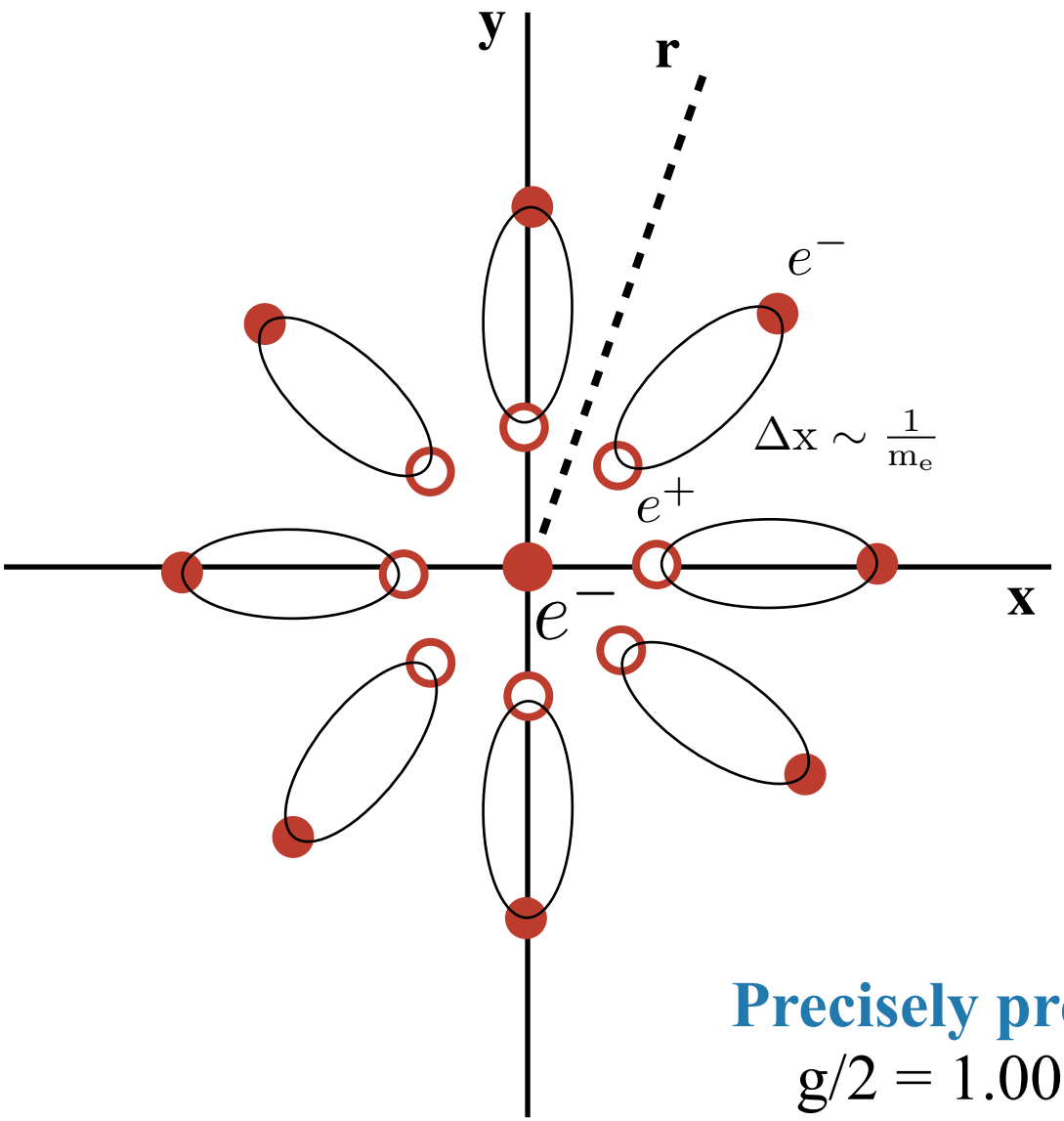
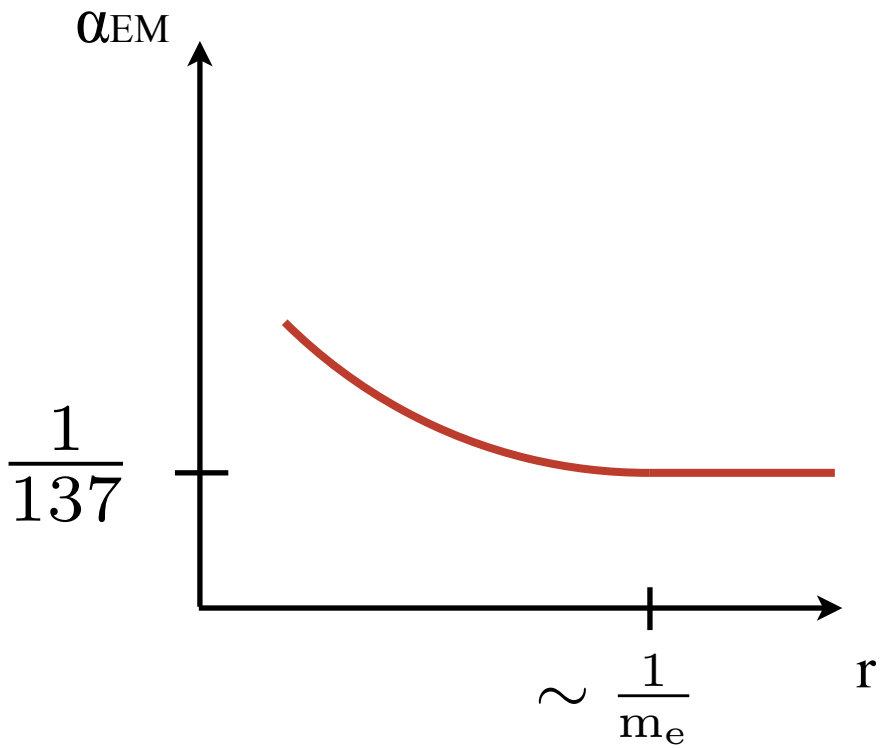


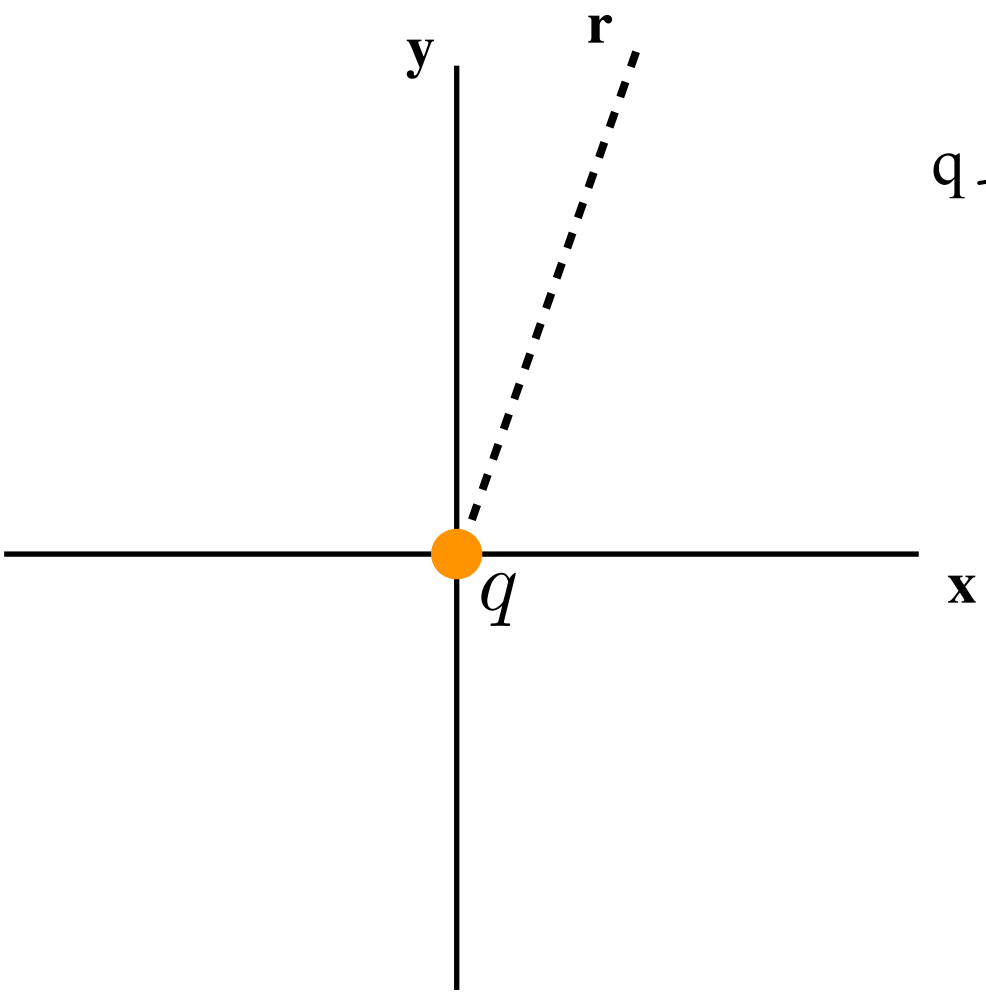


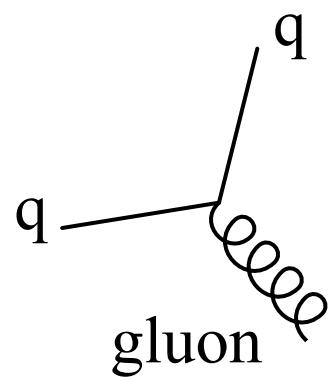
Precisely predict magnetic properties

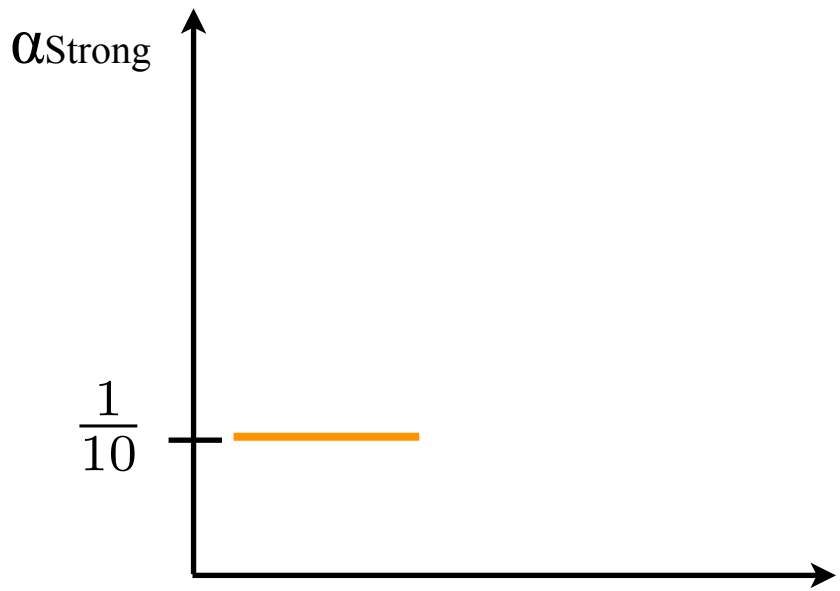
g/2 = 1.00115965218**09**(8),

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

Strong Interaction w/Distance







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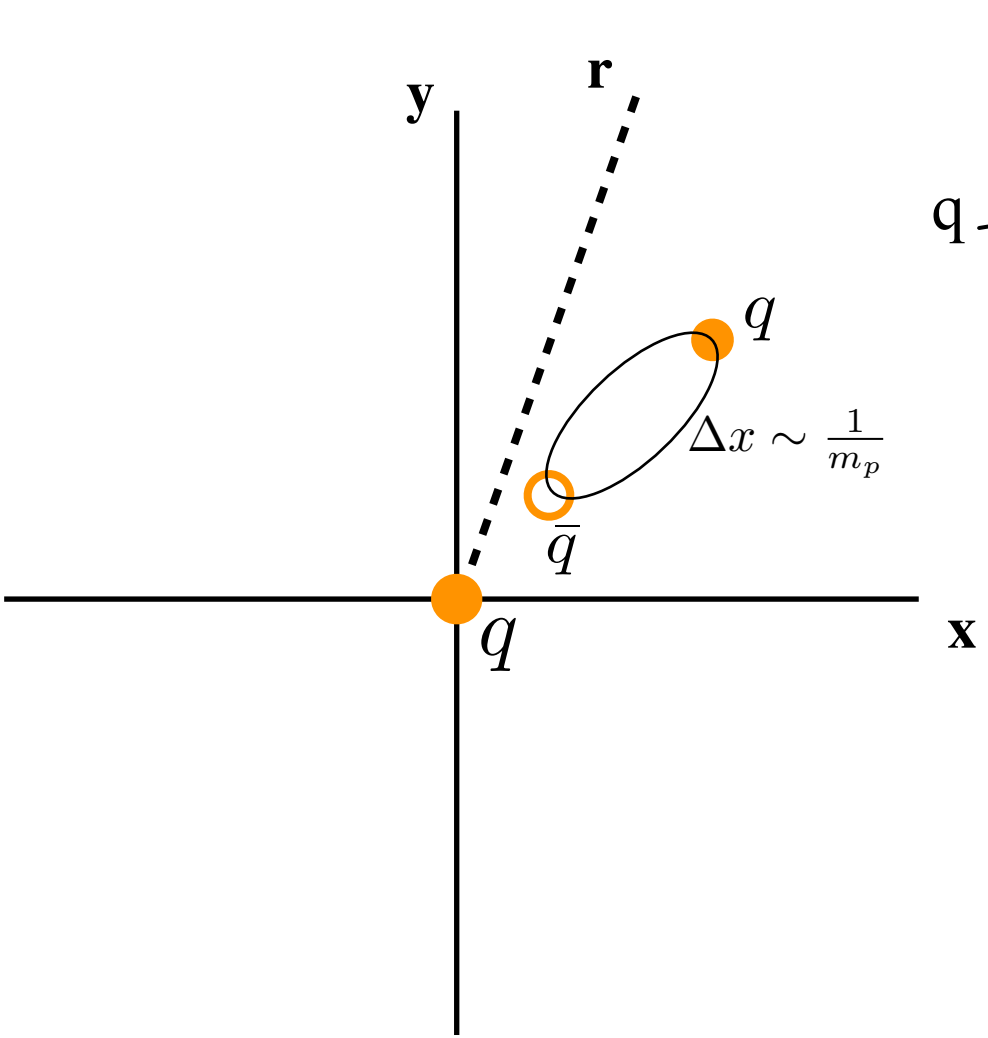
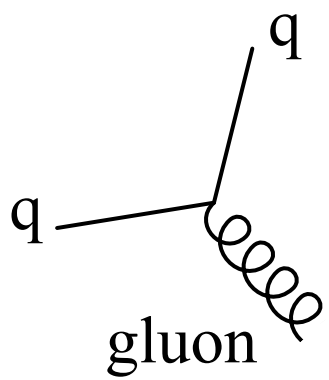
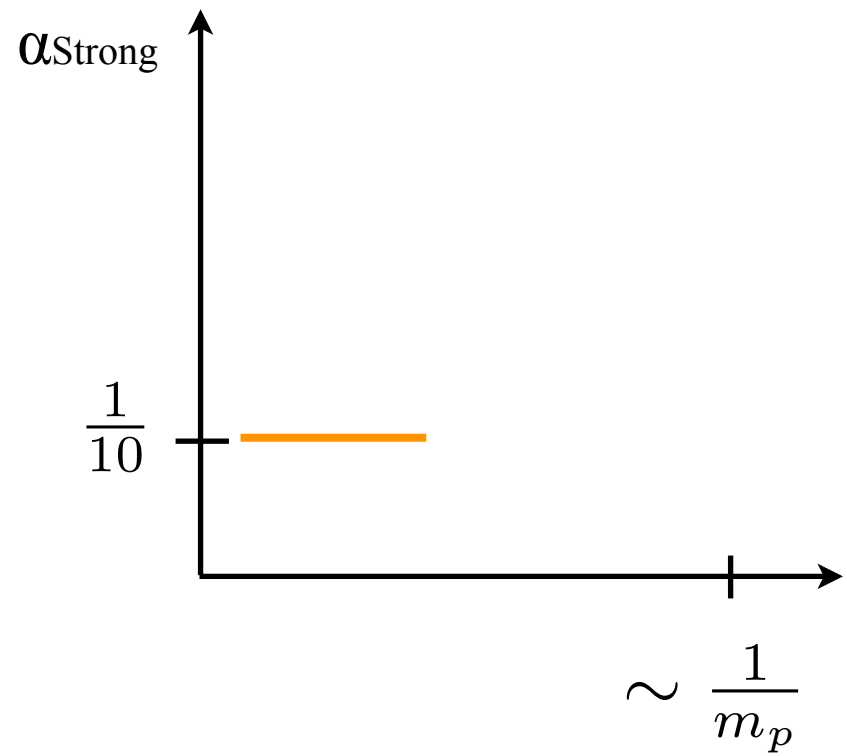
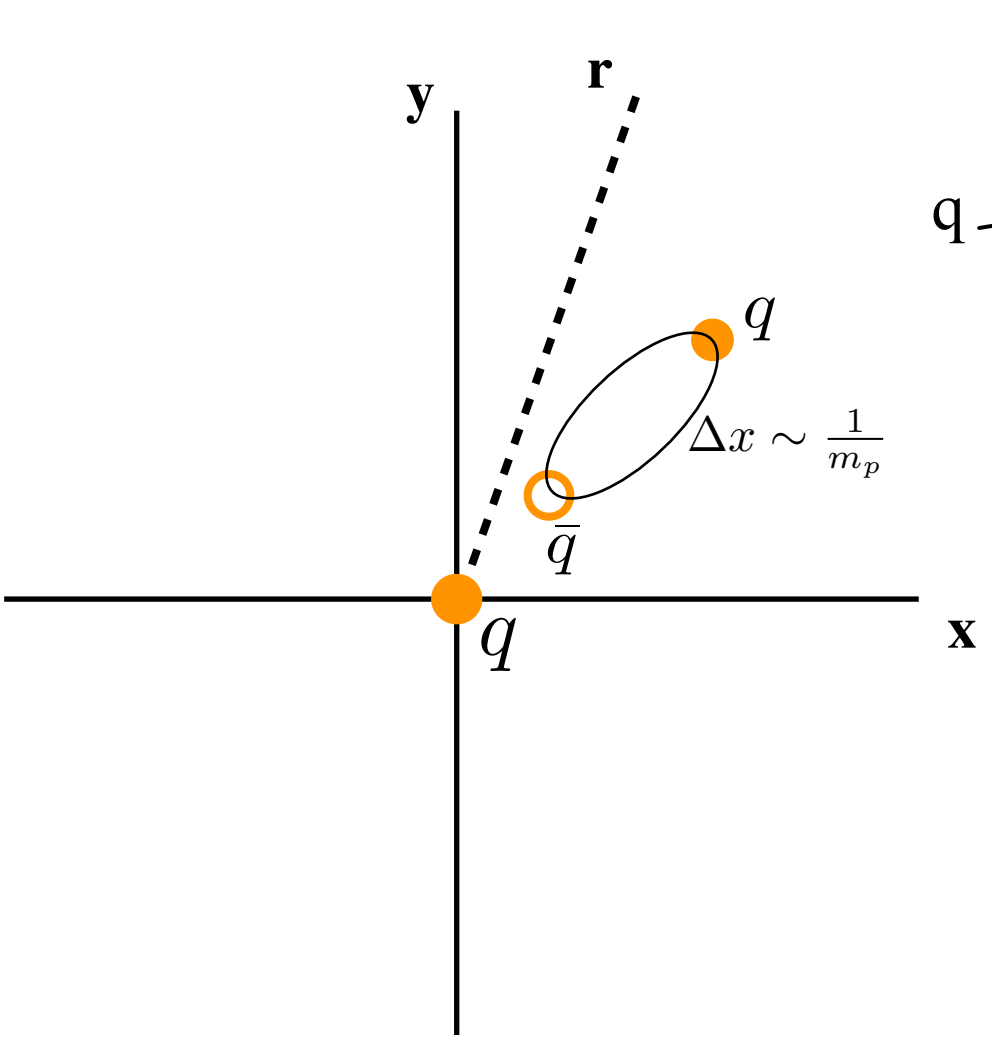


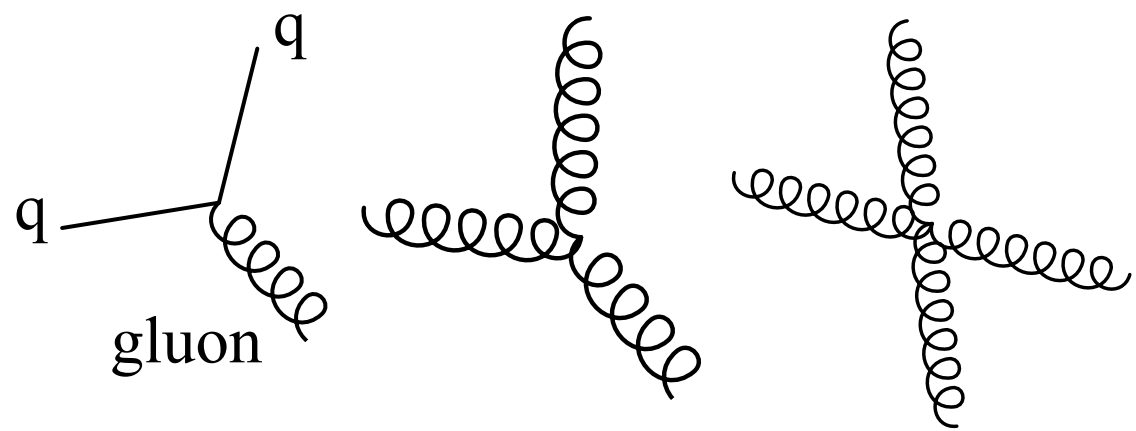


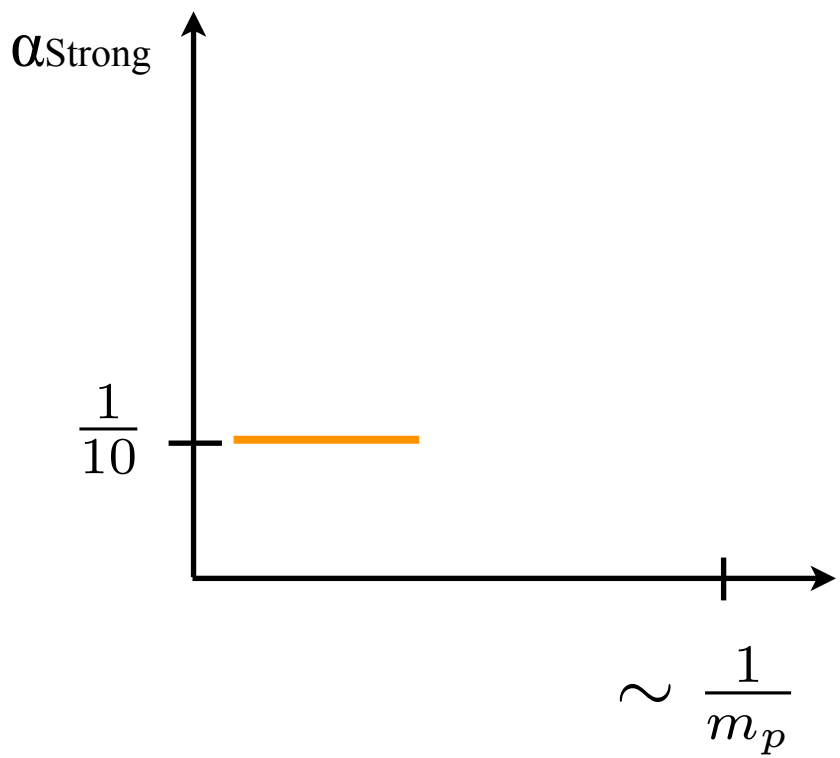


Strong Interaction w/Distance

Unlike photons, gluons can self interact.







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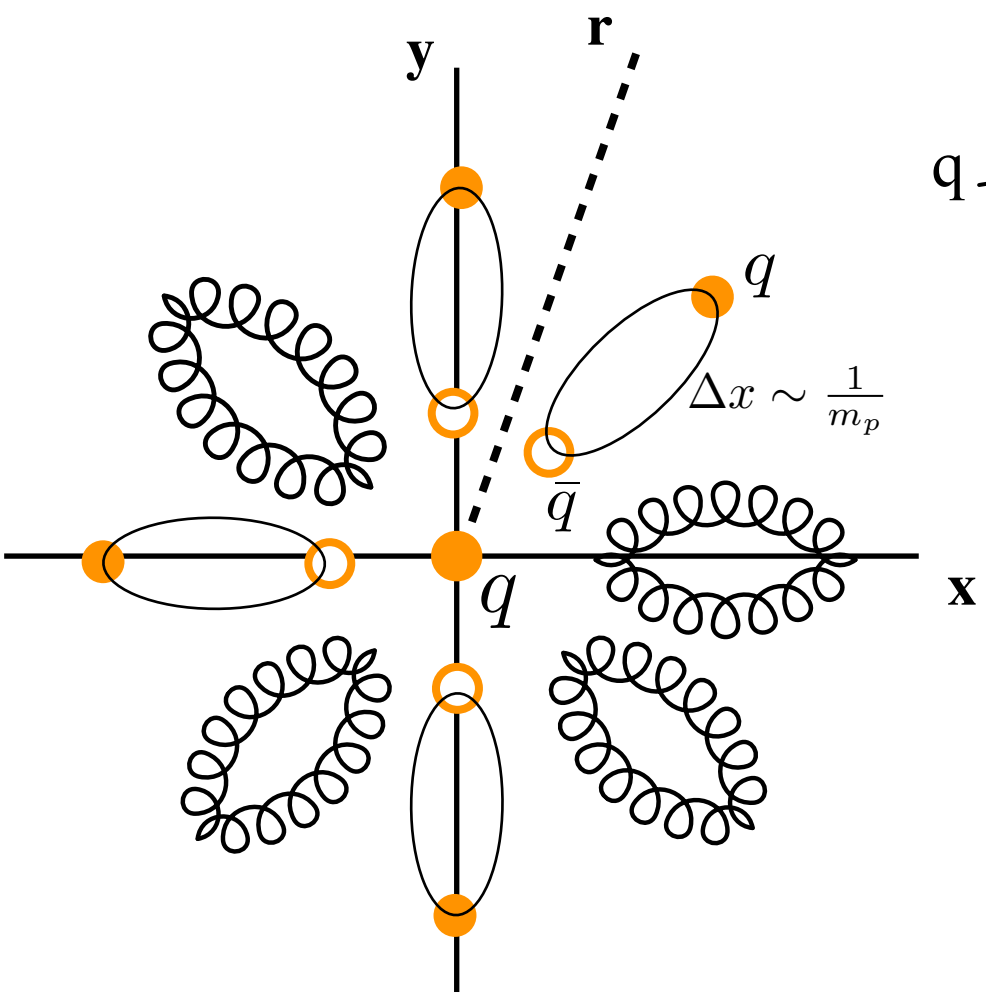

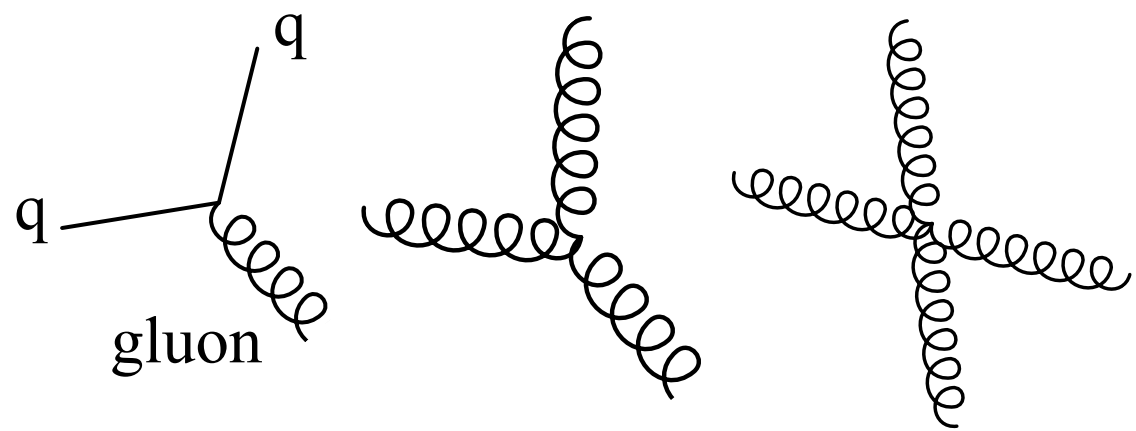

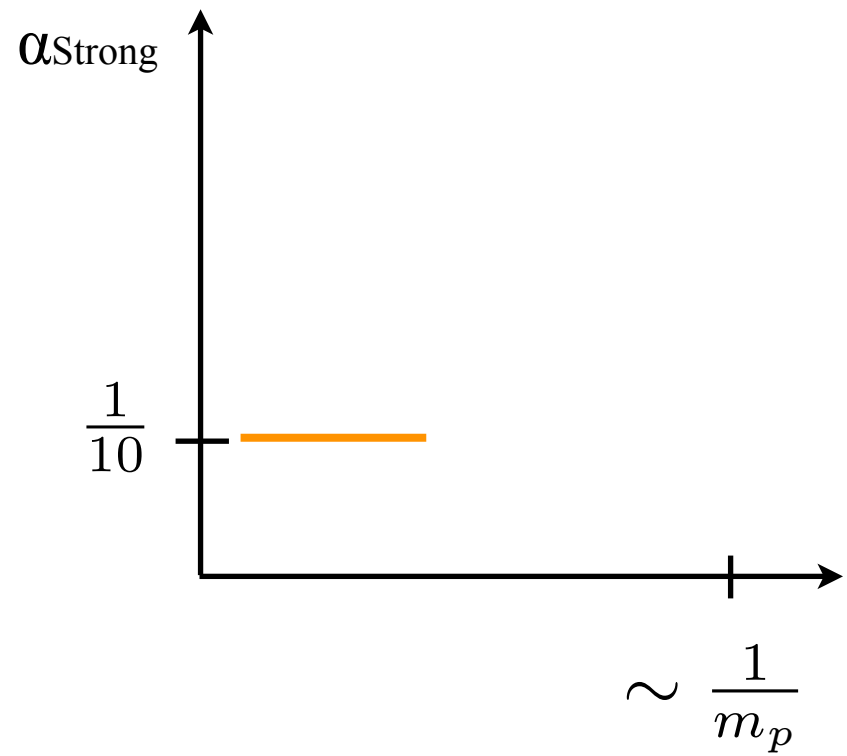

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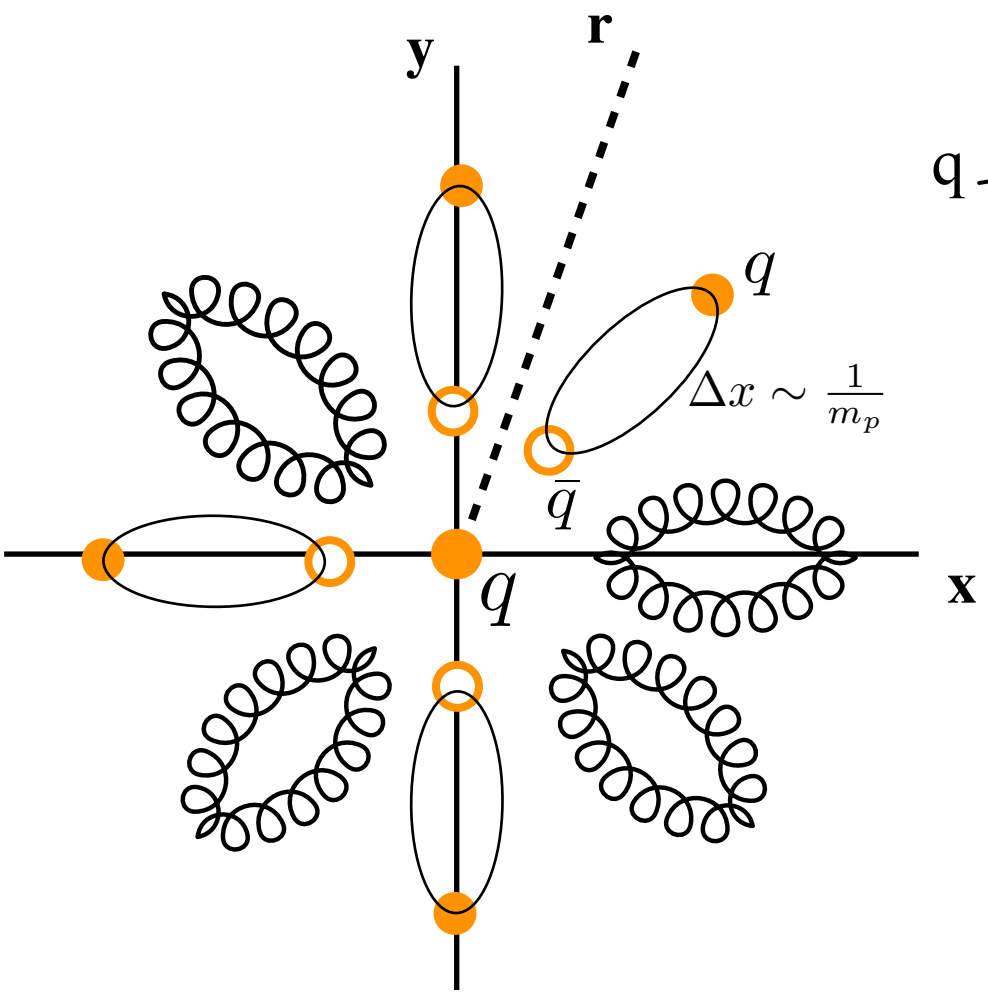

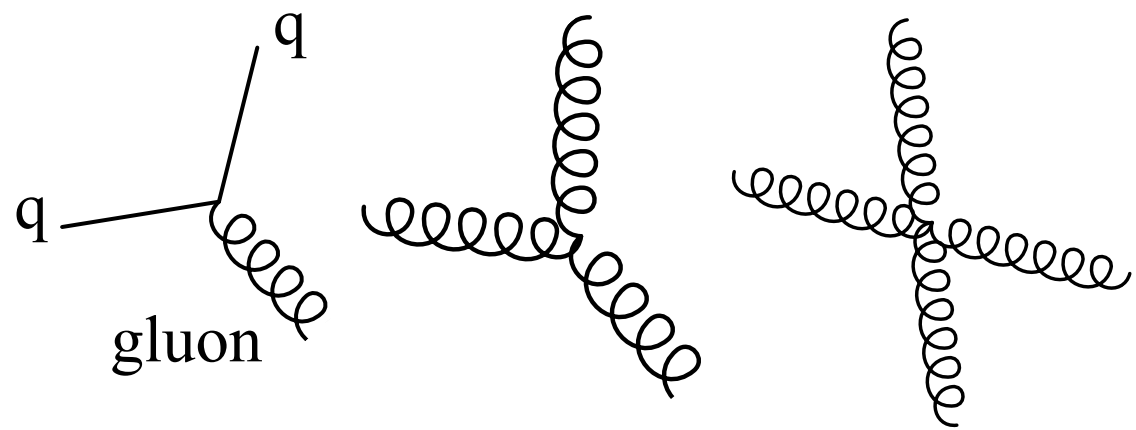

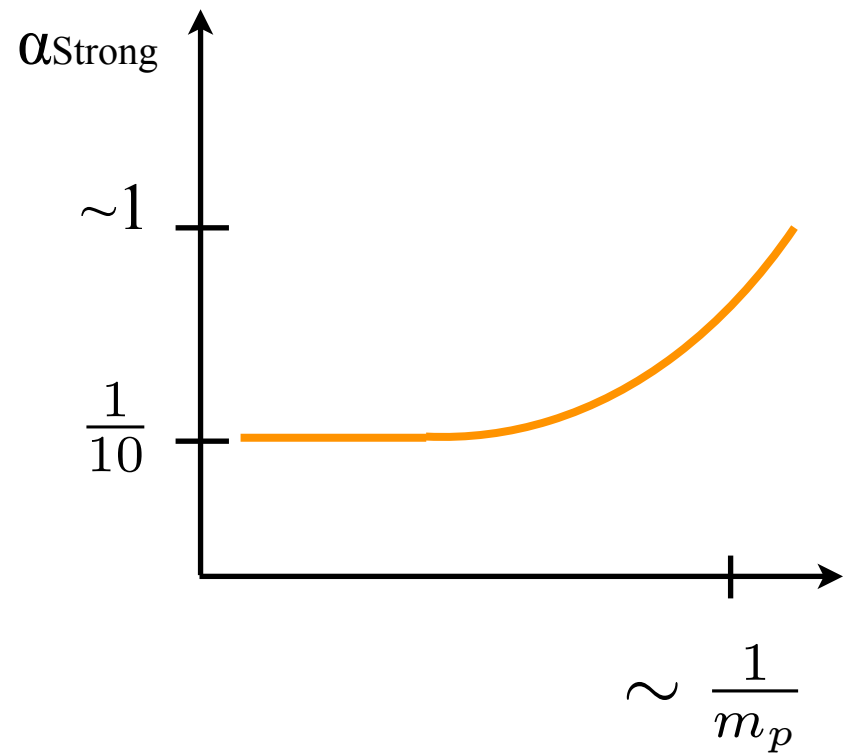

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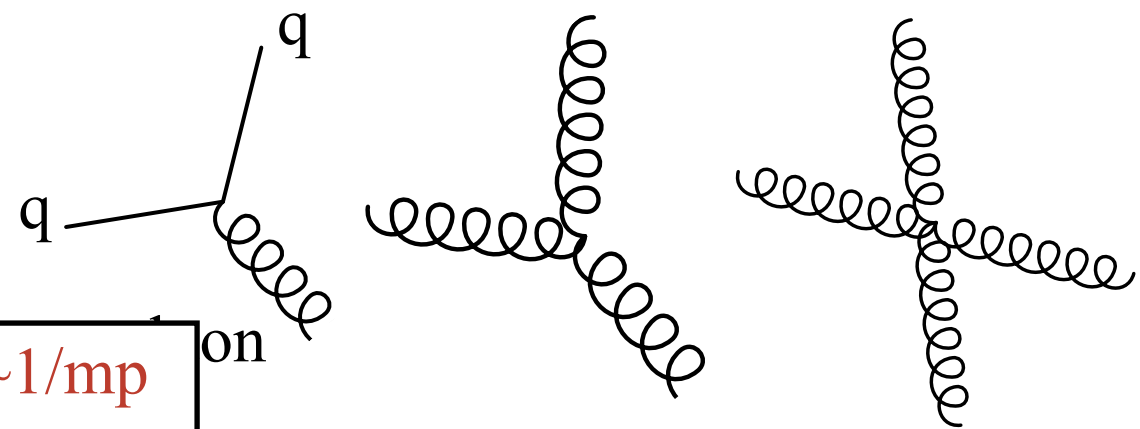
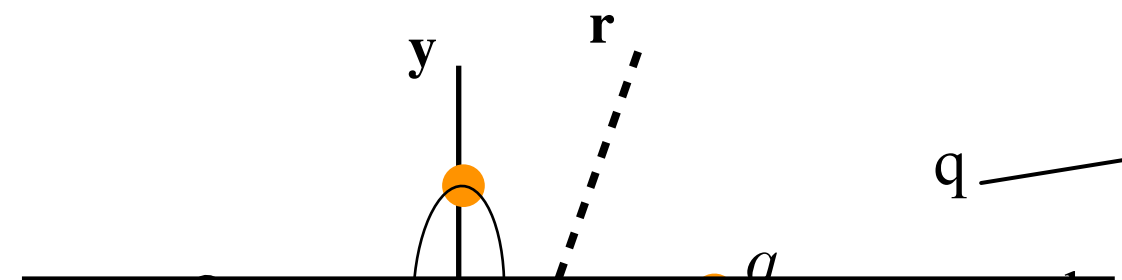
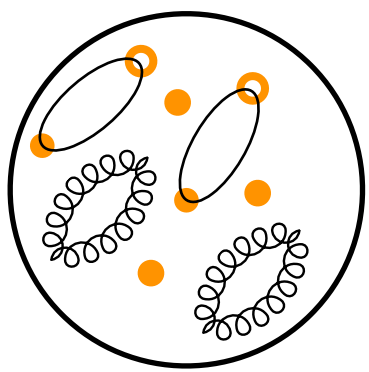




Interaction become very strong ~1/mp

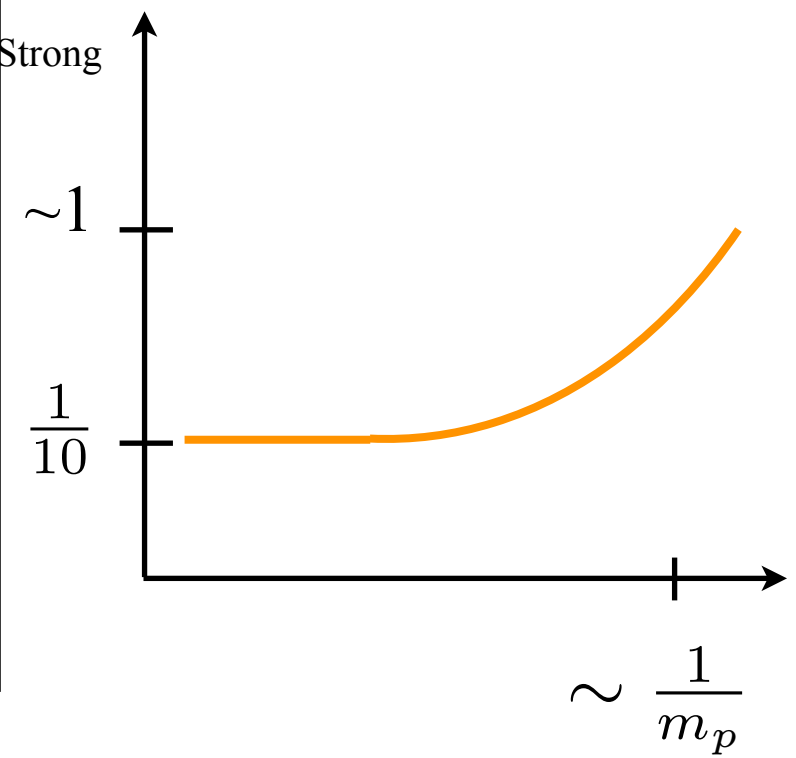
Proton:



B/c force grows with distance:

- Cant pull them out of the proton
- q and gluons “confined “

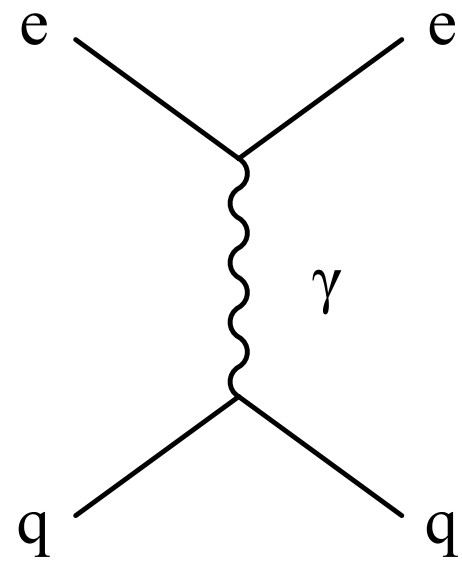
Sets the size of protons (neutrons)



Back to EM Interaction

Electron high probability to emit γ when:

Electro-magnetic Force



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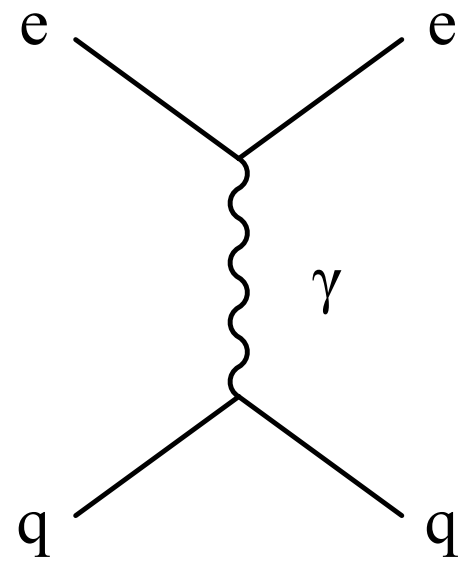
Electron high probability to emit γ when:

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

Electro-magnetic Force



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$r < h/Ec$

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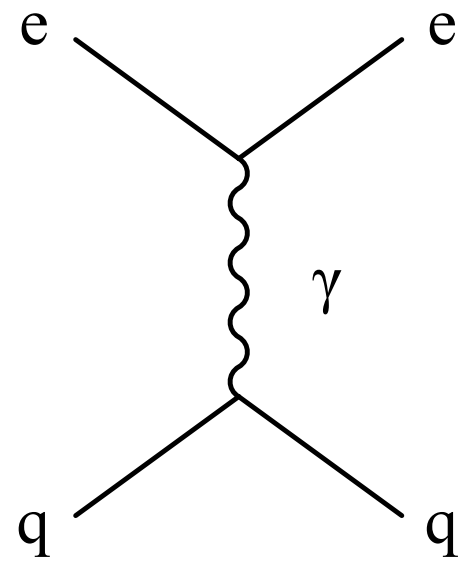

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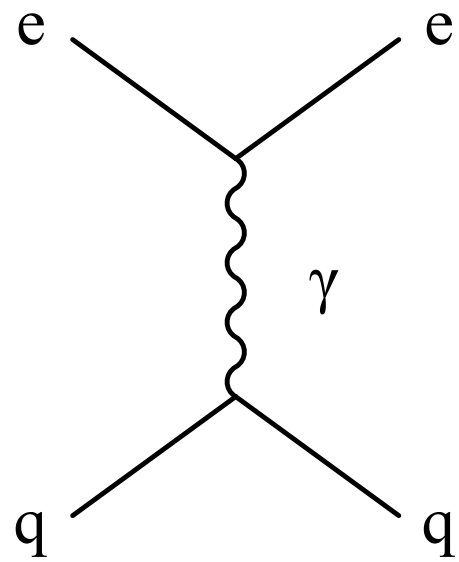
Electro-magnetic Force



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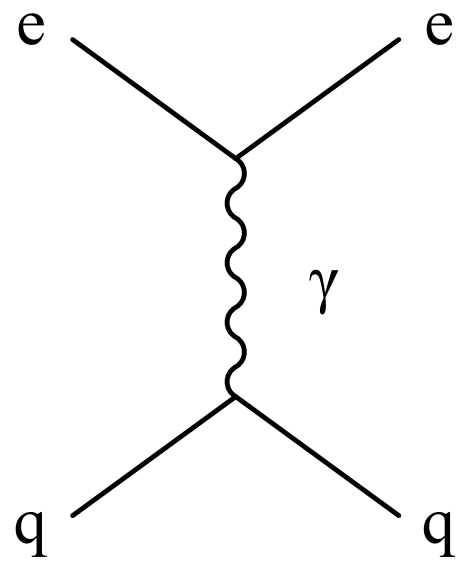

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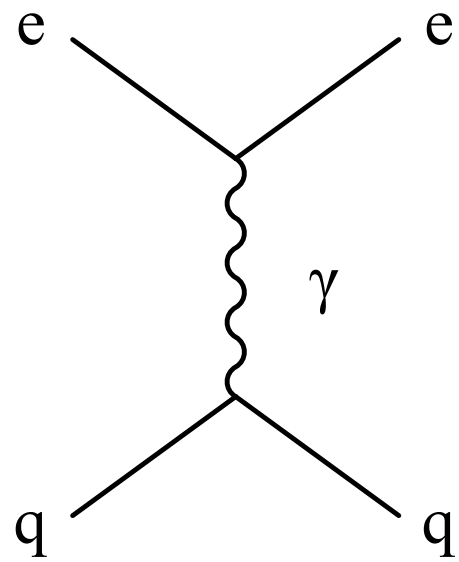

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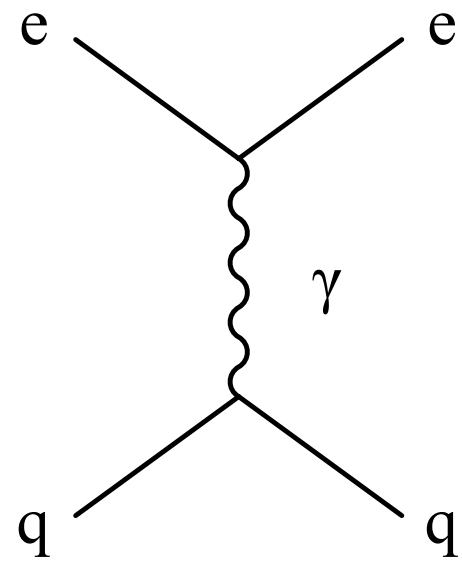

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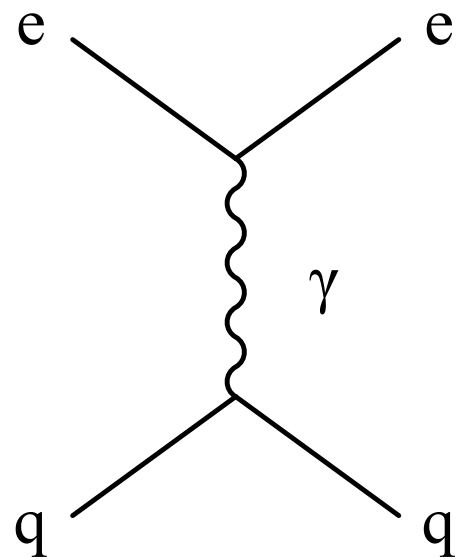

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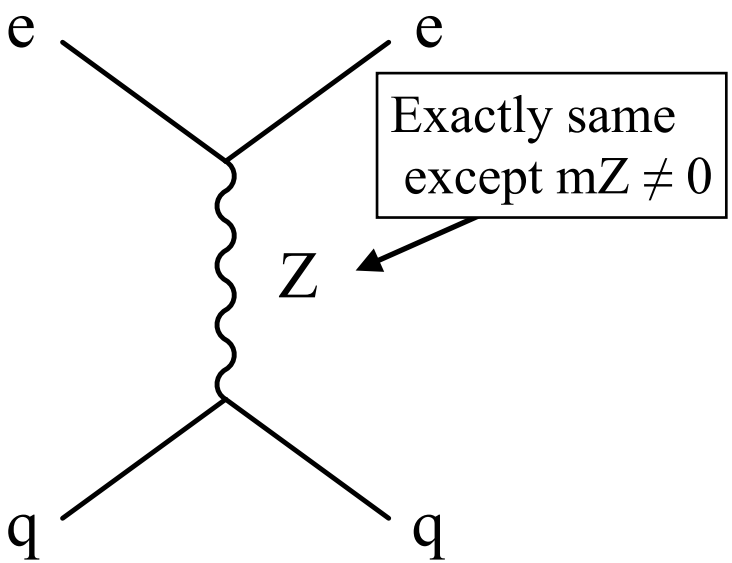

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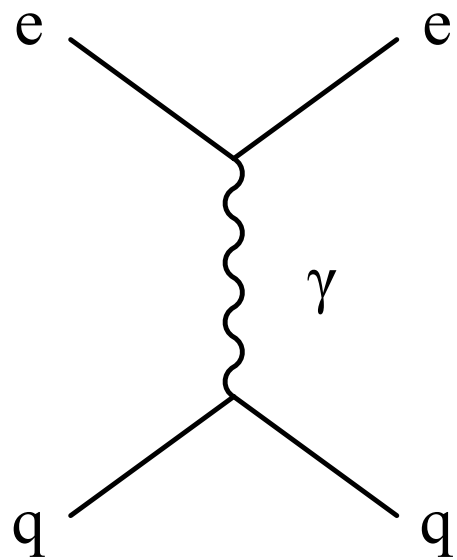

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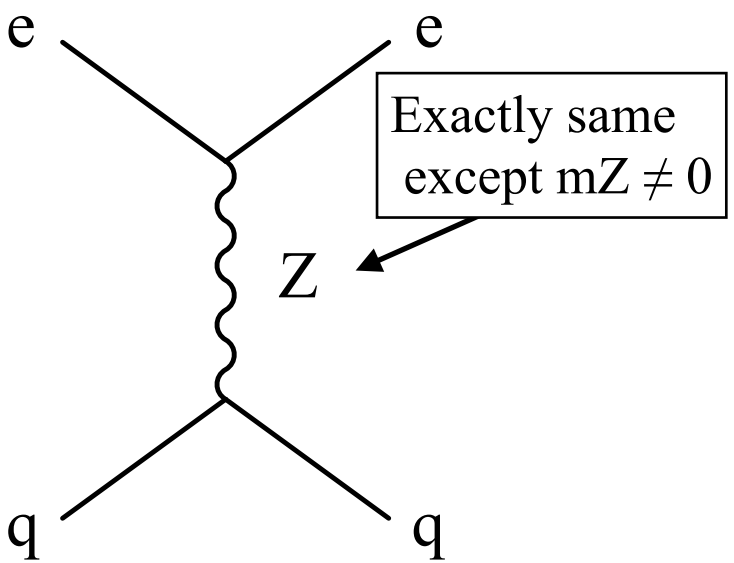

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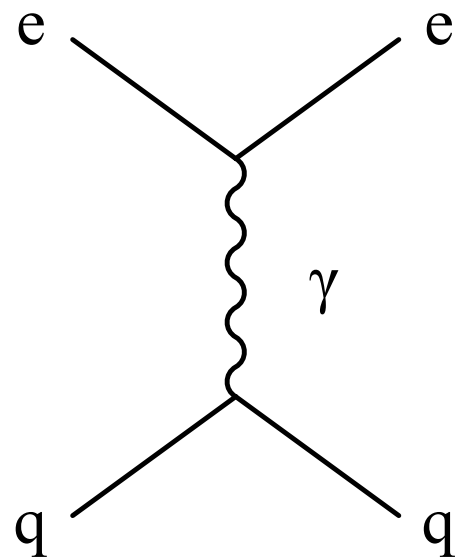

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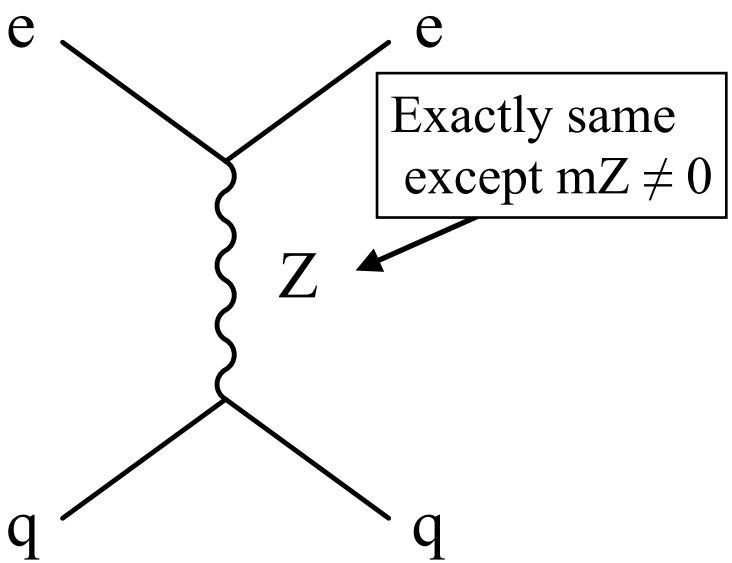

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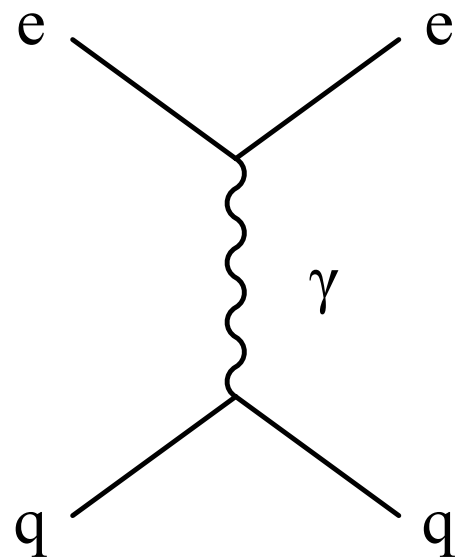

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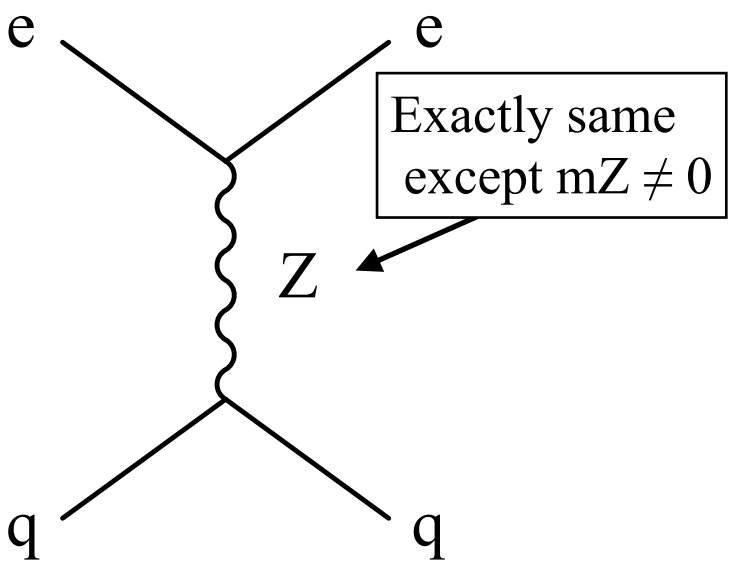

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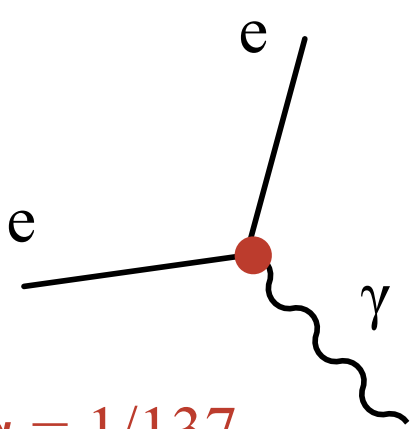
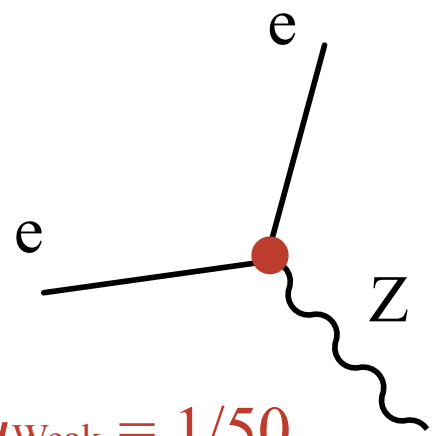
Mass of Z makes weak force short ranged.

Forces Common Language

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



$\alpha = 1/137$



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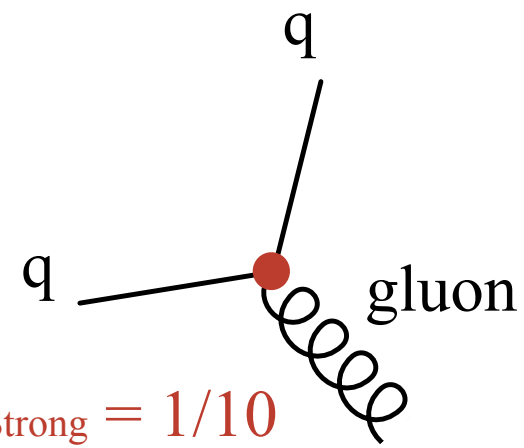

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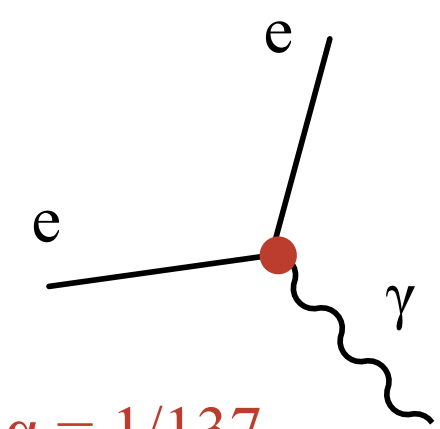

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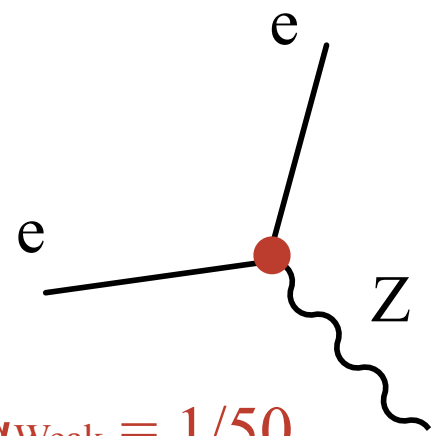

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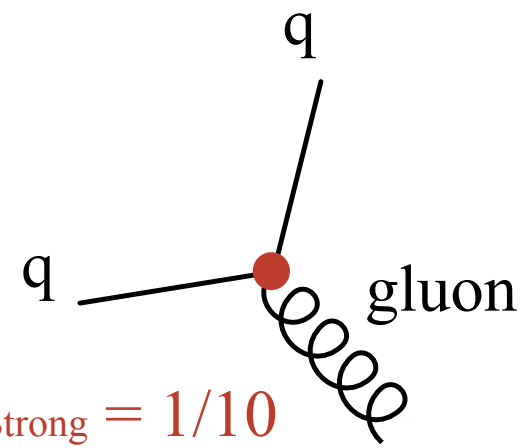

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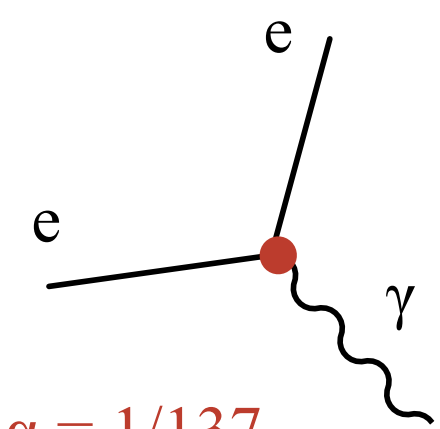

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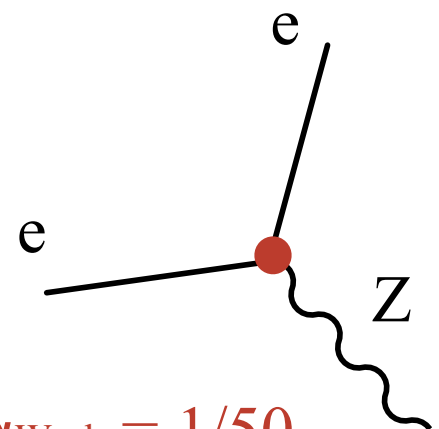

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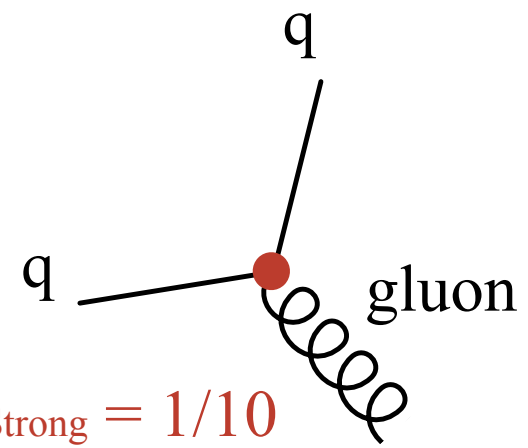

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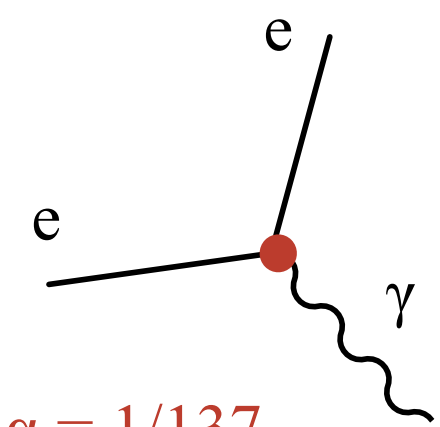

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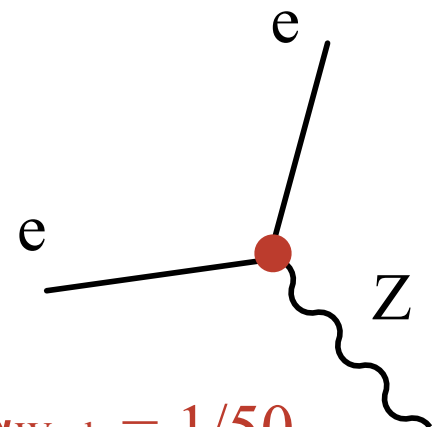

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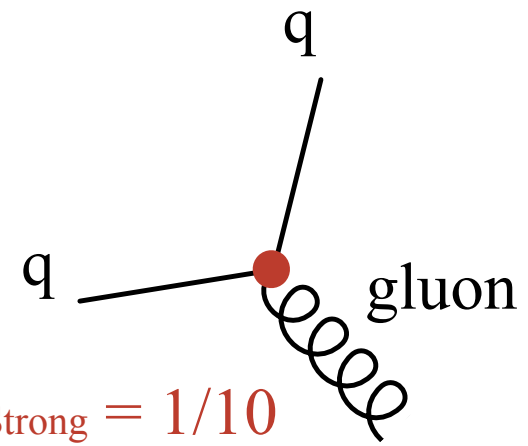

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This is the reason we build colliders! Unity at small scales.

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Makes very precise predictions, shown to be highly accurate.

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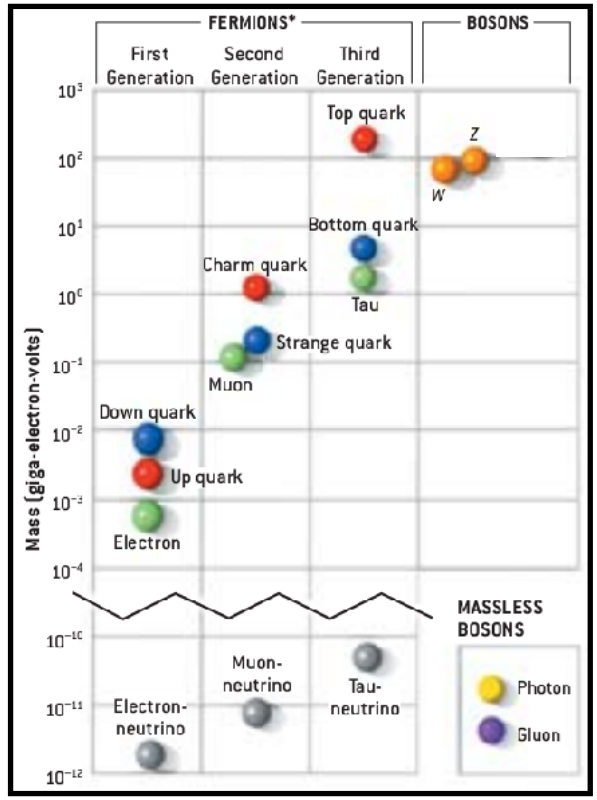

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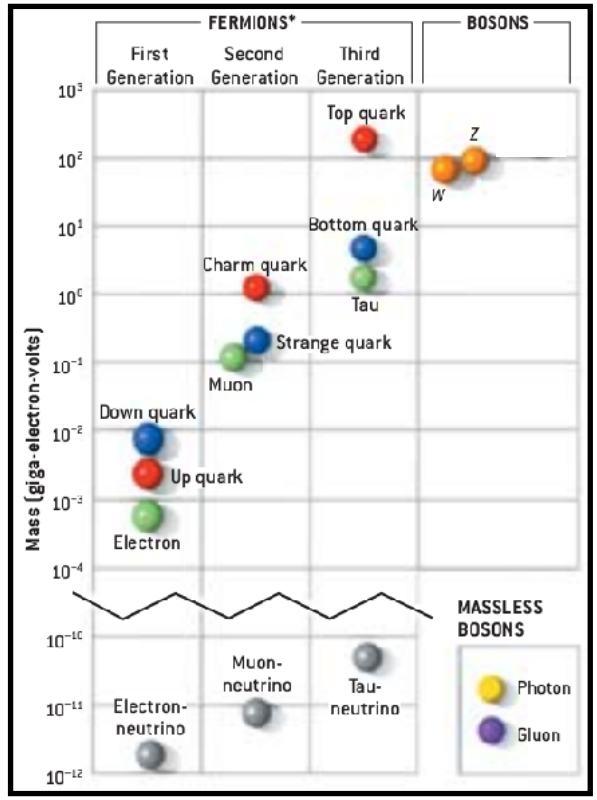
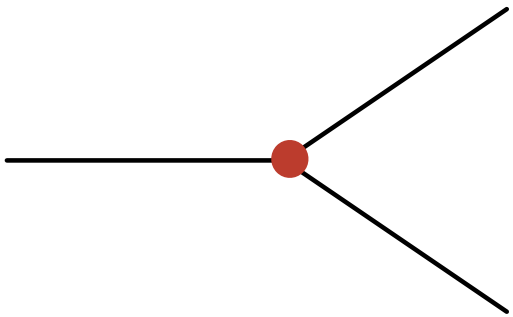


Pick up here next time.

Bonus

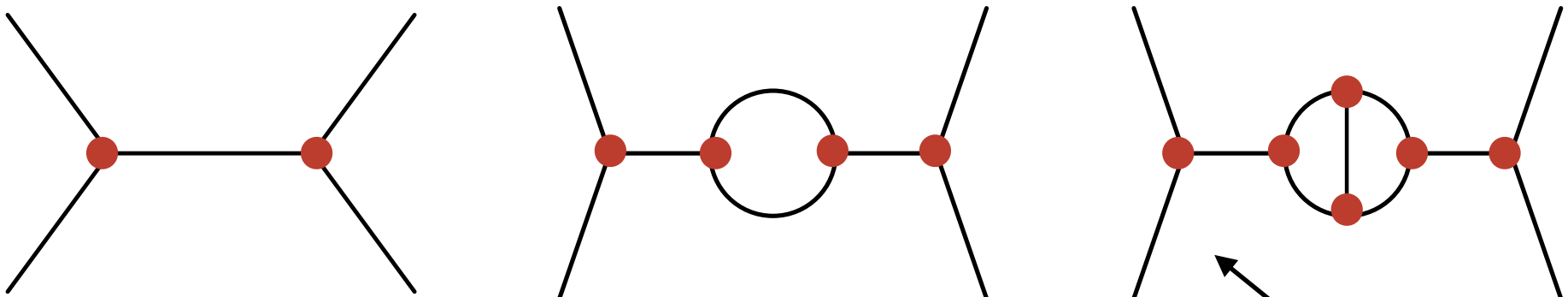
Number of Parameters



Vertex interaction strength input to the theory
- Taken from data

QFT ⇒ Only this "three point" interaction relevant

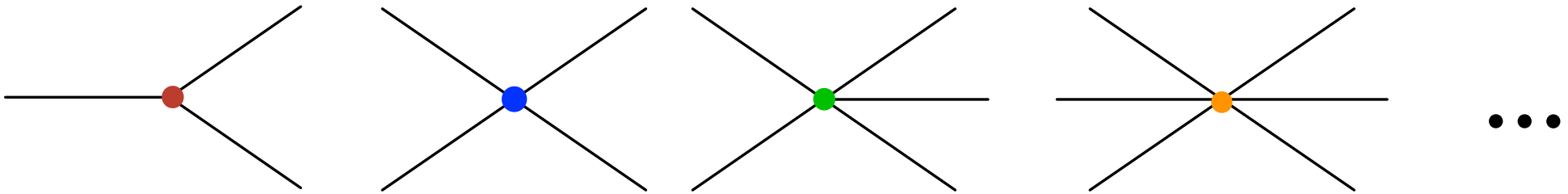
All calculations done by just stitch together this one basic vertex



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