Feynman diagrams and the Weak Force

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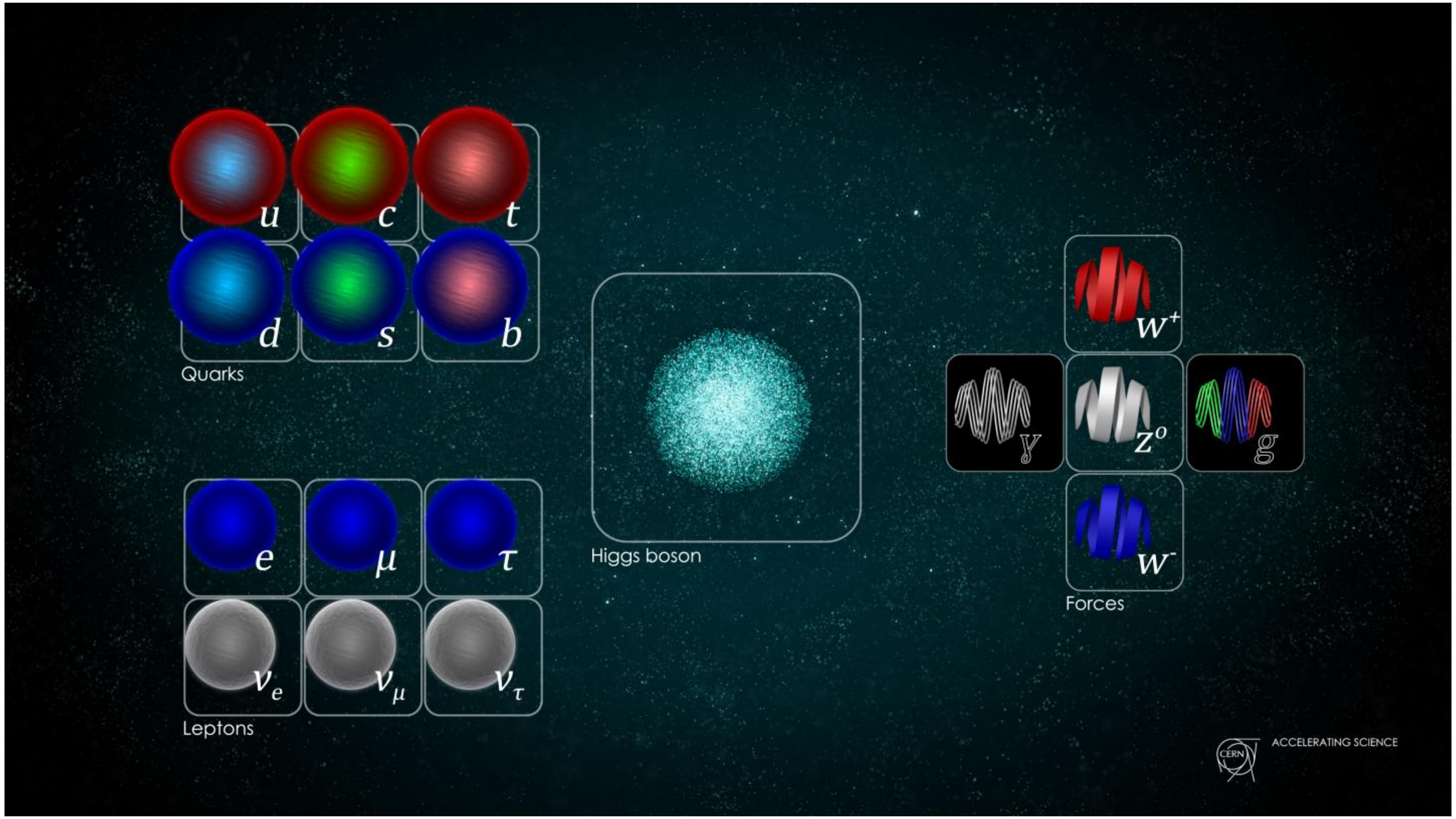
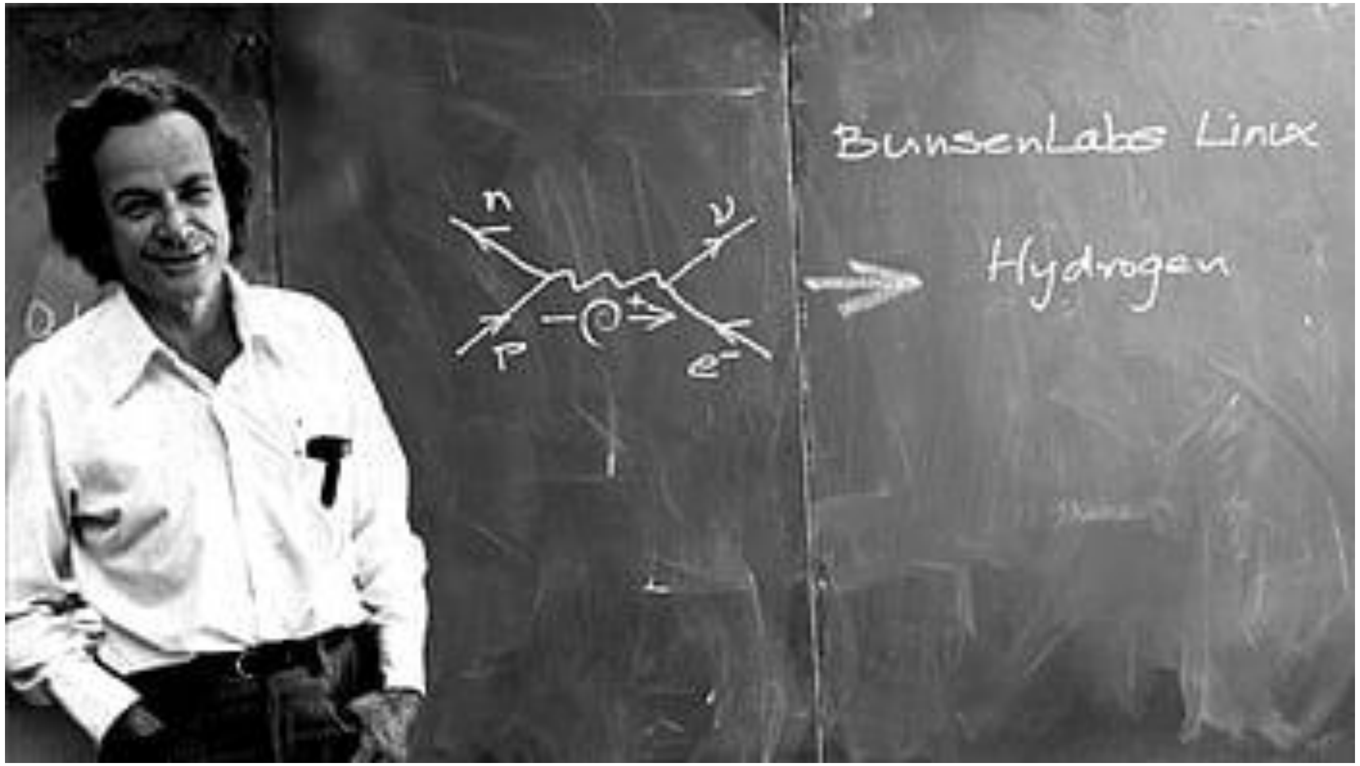
The Standard Model

- ❑ 3 families of quarks & leptons (differ only by their masses)
- ❑ 3 forces (Strong, EM, Weak), each with their own set of force carriers
- ❑ Conservation Laws / Symmetries dictate how these particles interact

That's it, in a nutshell!



Part I
Feynman diagrams and how to understand them



Preliminary

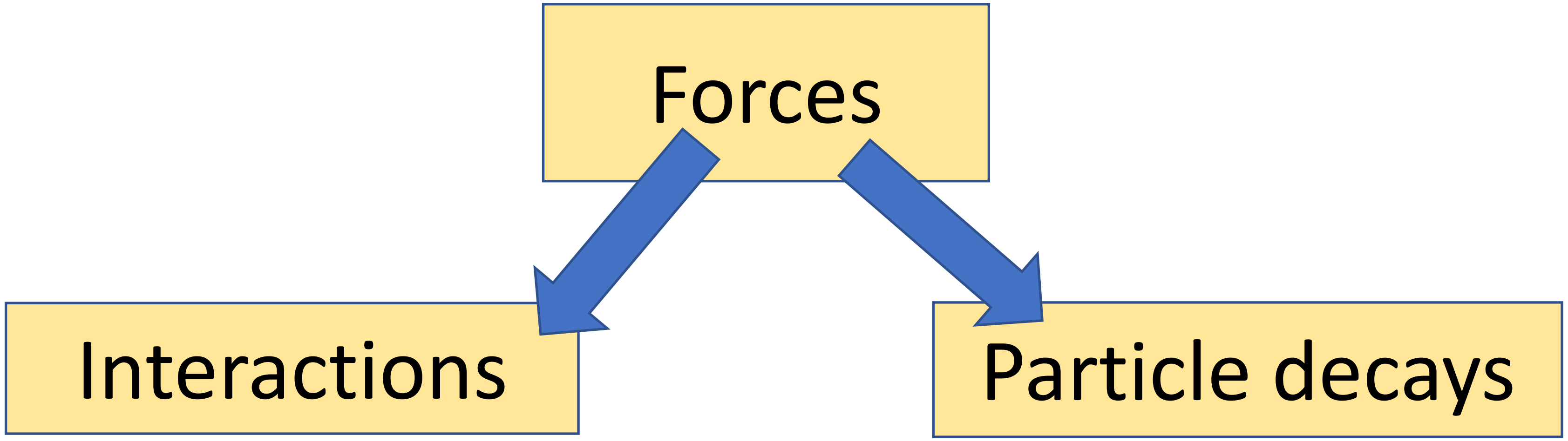
- ❑ In particle physics, we universally use “eV” units, and usually it’s MeV, GeV or even TeV! (1 eV = 1.6 x 10^{-19} J)

- ❑ **Energy units:** **[MeV], [GeV]**

- ❑ Since $E = mc^2 \Rightarrow m = E/c^2$

- ❑ **Mass units: [Energy] / c^2 ➔ [MeV/c^2], [GeV/c^2]**

- ❑ **Momentum units: [MeV/c], [GeV/c]**



Cross-section (area)

$\sigma(a + b \rightarrow c + d)$

Decay rate (1/s)

$N = N_0 e^{-\boldsymbol{\Gamma} t}$ $\boldsymbol{\Gamma(A \rightarrow \text{anything})}$

Forces

Interactions

Cross-section (area)

$\sigma(a + b \rightarrow c + d)$

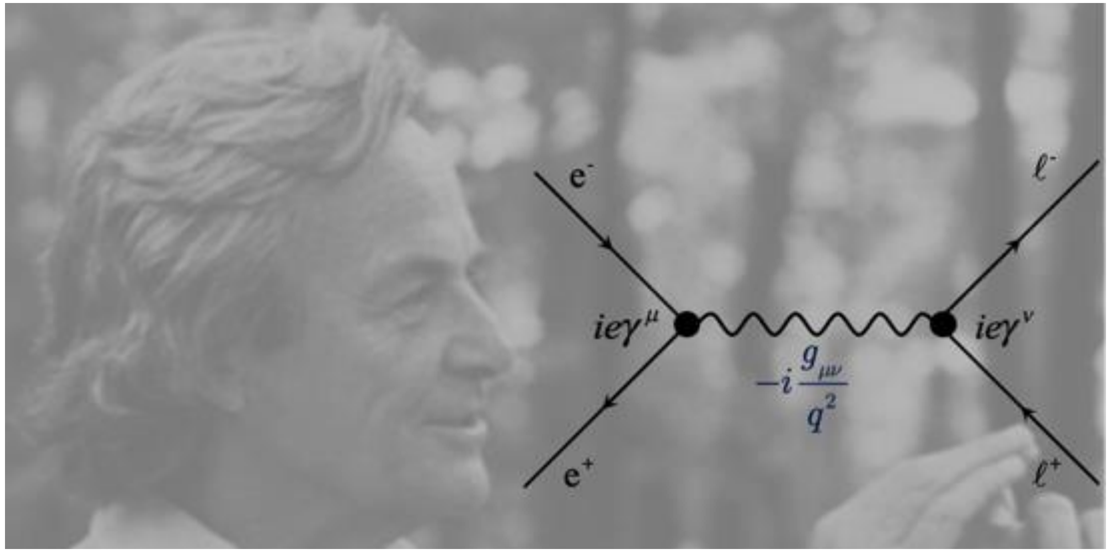
Particle decays

Decay rate (1/s)

$N = N_0 e^{-\boldsymbol{\Gamma} t}$ $\boldsymbol{\Gamma(A \rightarrow \text{anything})}$

Feynman Diagrams

- ❑ Provide a means to represent a given process (interaction or decay)
- ❑ **Feynman rules**: Allow to go from cartoon → Computing σ or $\boldsymbol{\Gamma}$.



Forces

Interactions

Cross-section (area)

$\sigma(a + b \rightarrow c + d)$

Let's begin with interactions

Feynman Diagrams

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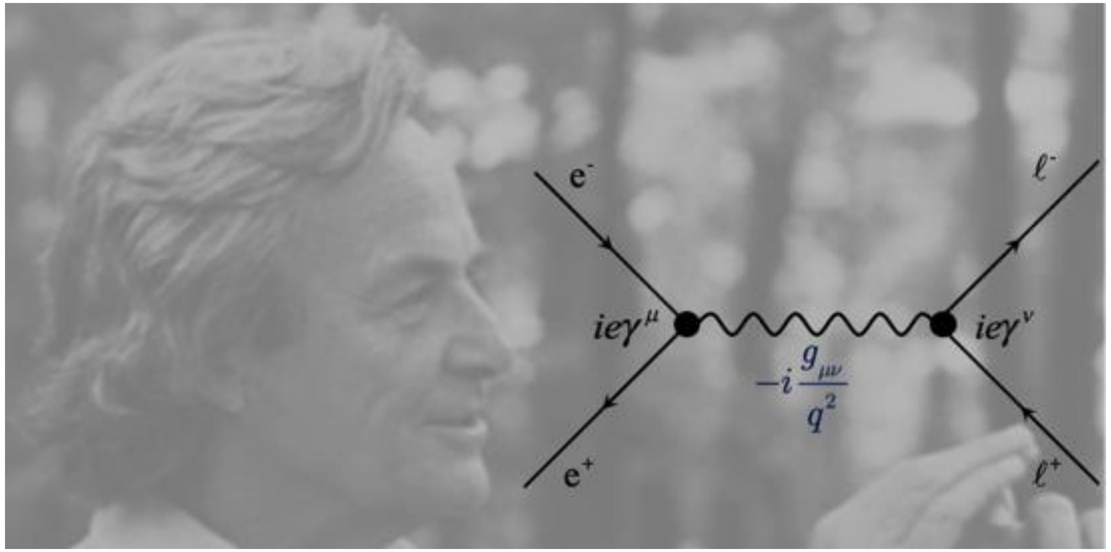

Feynman Diagrams (1)

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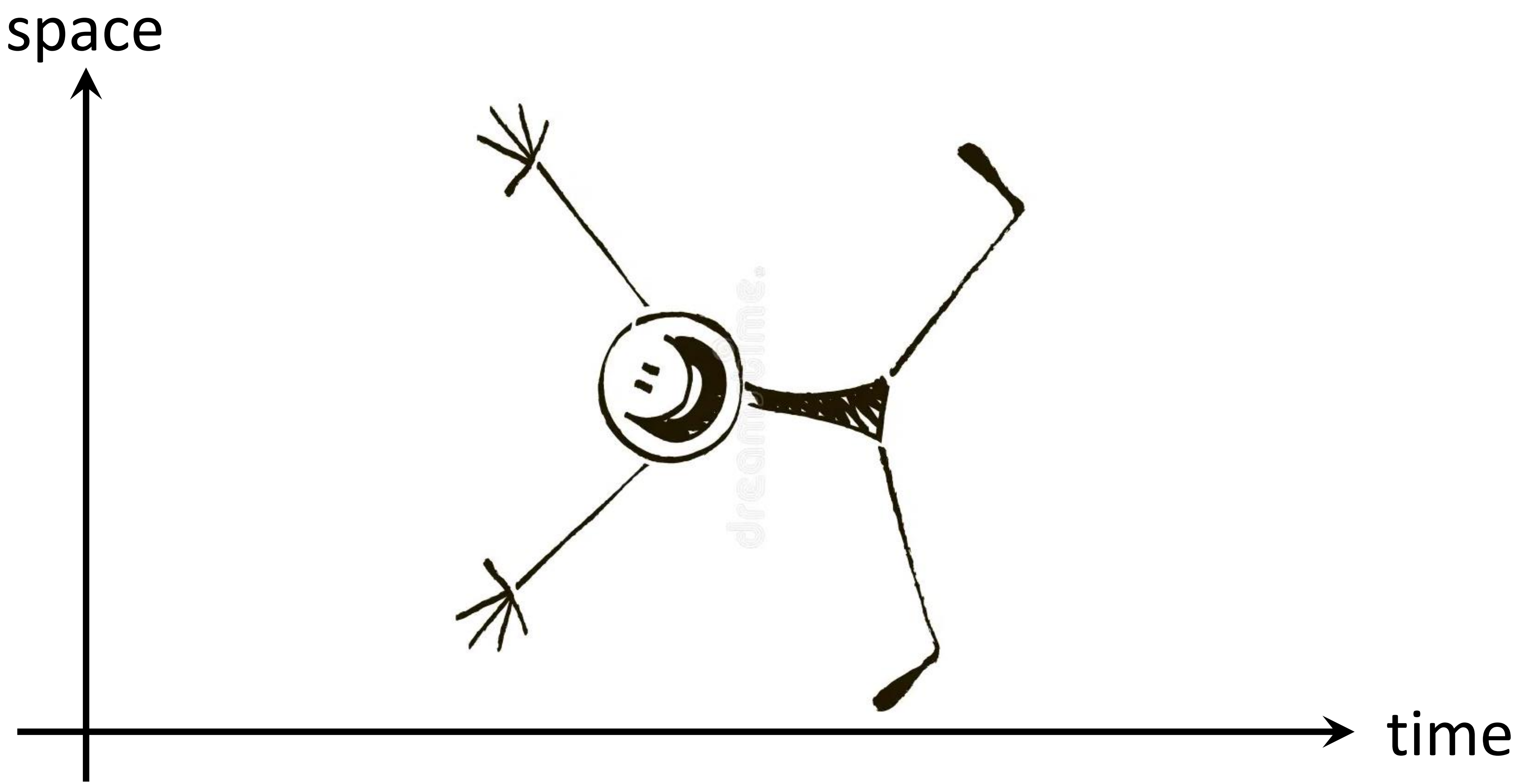

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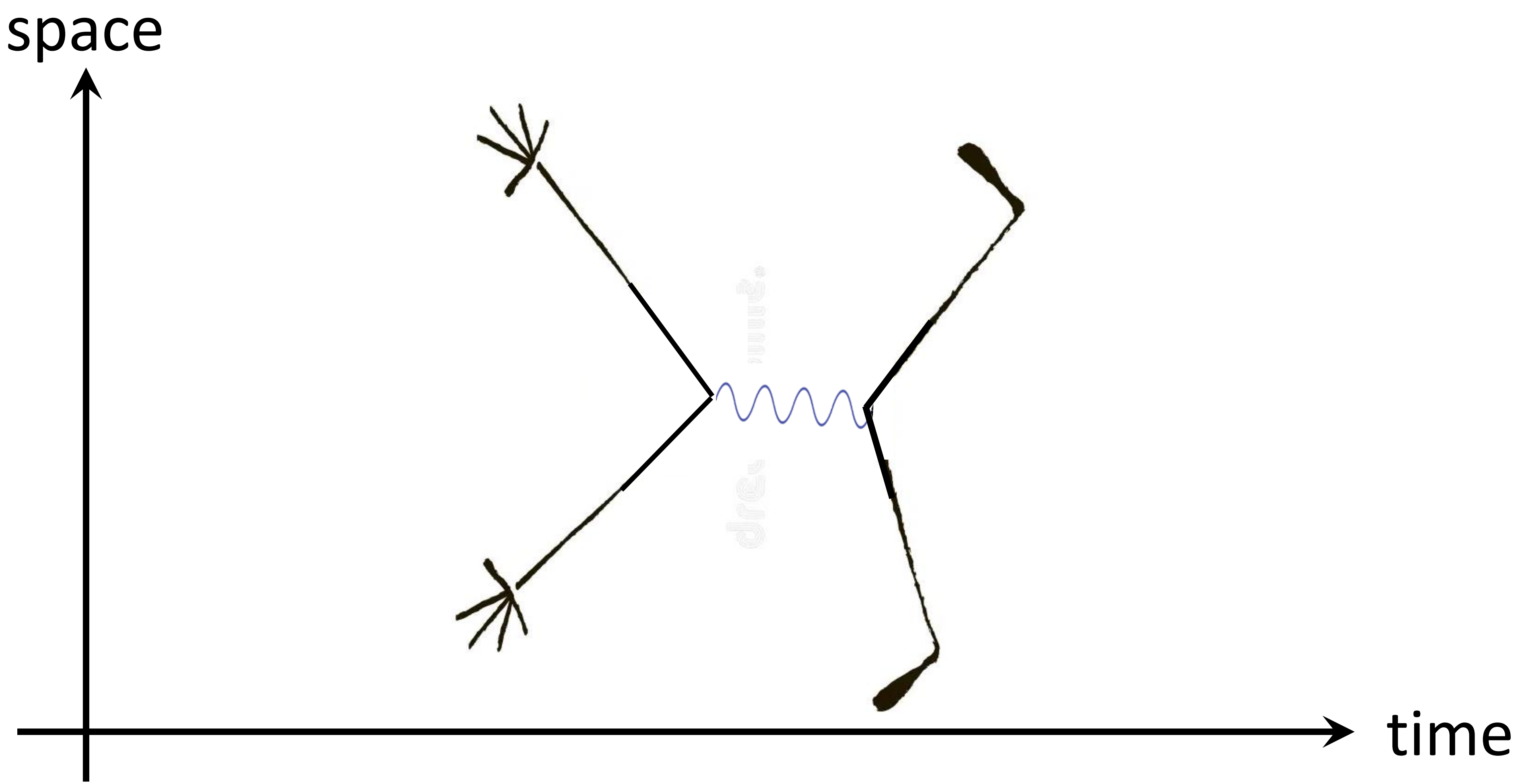
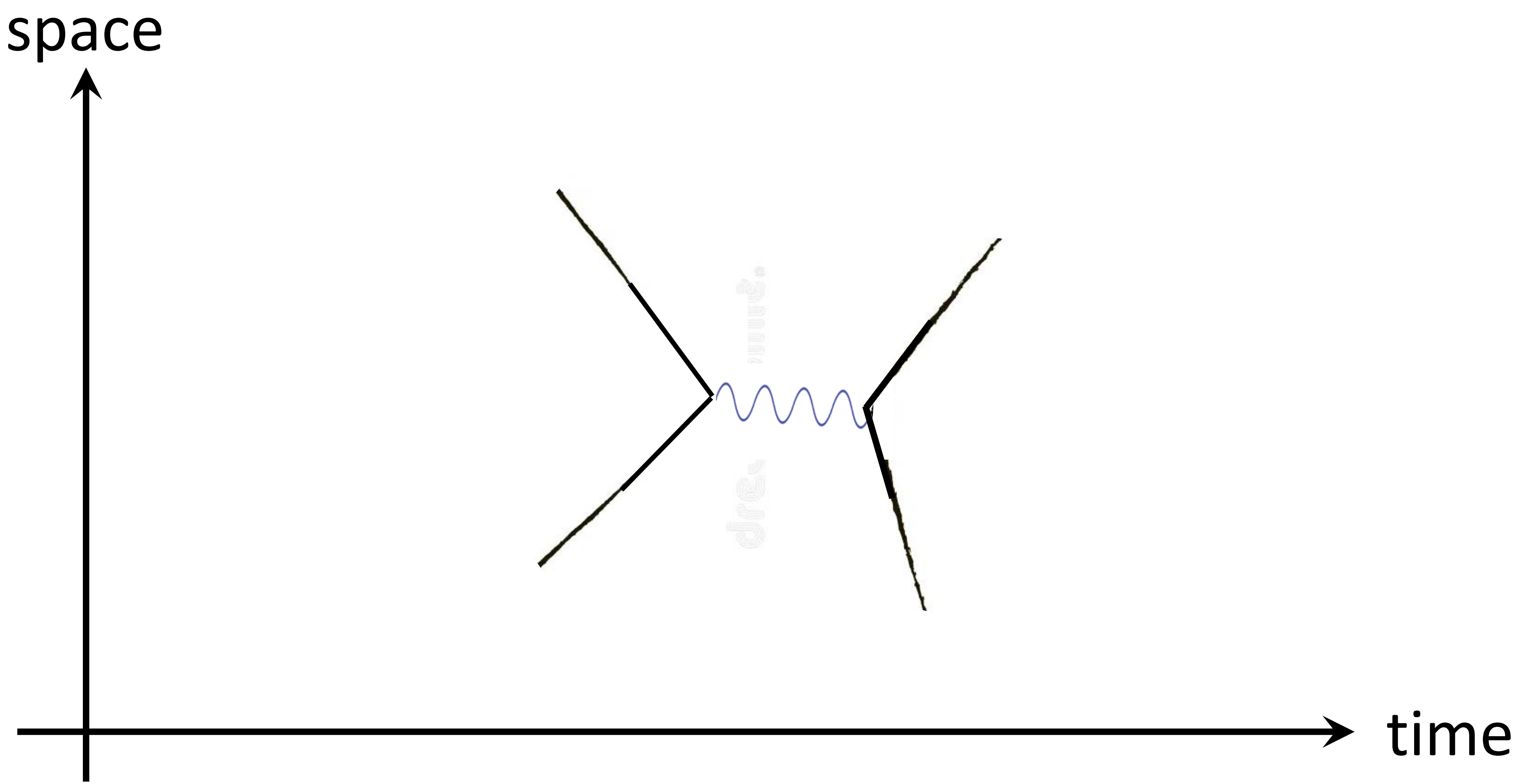
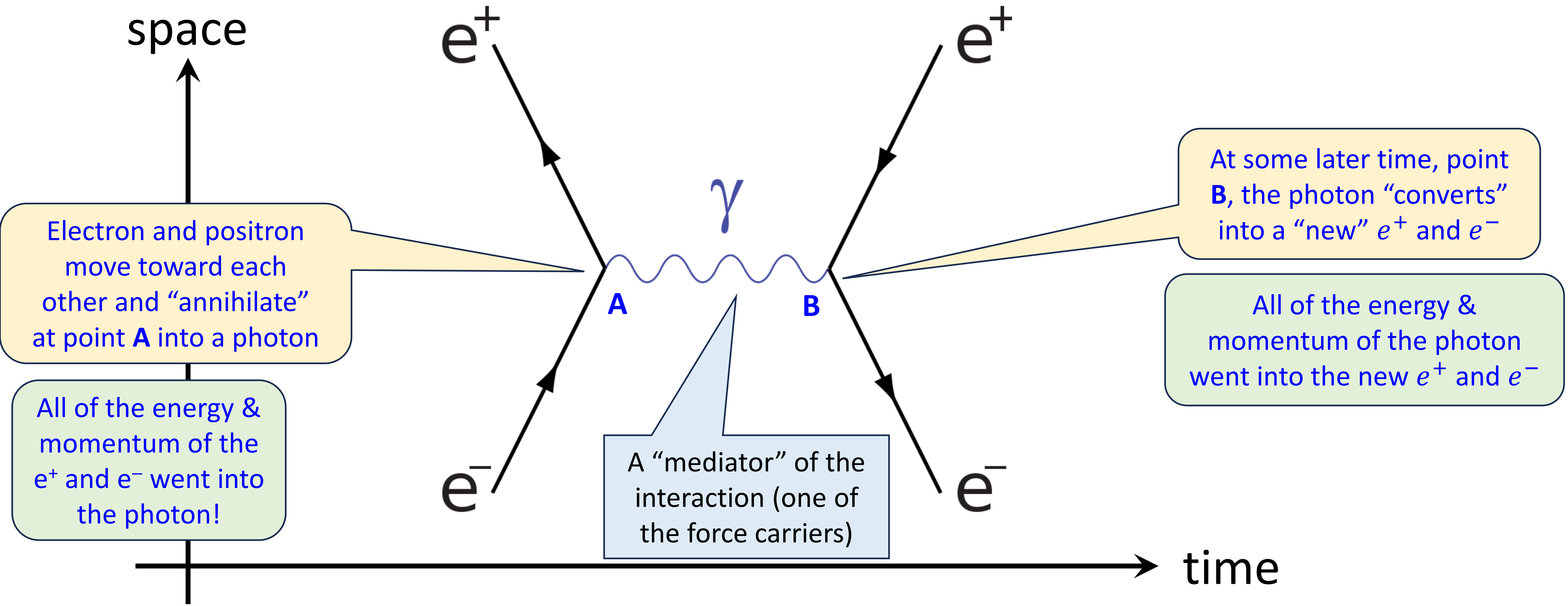


Feynman Diagrams (1)



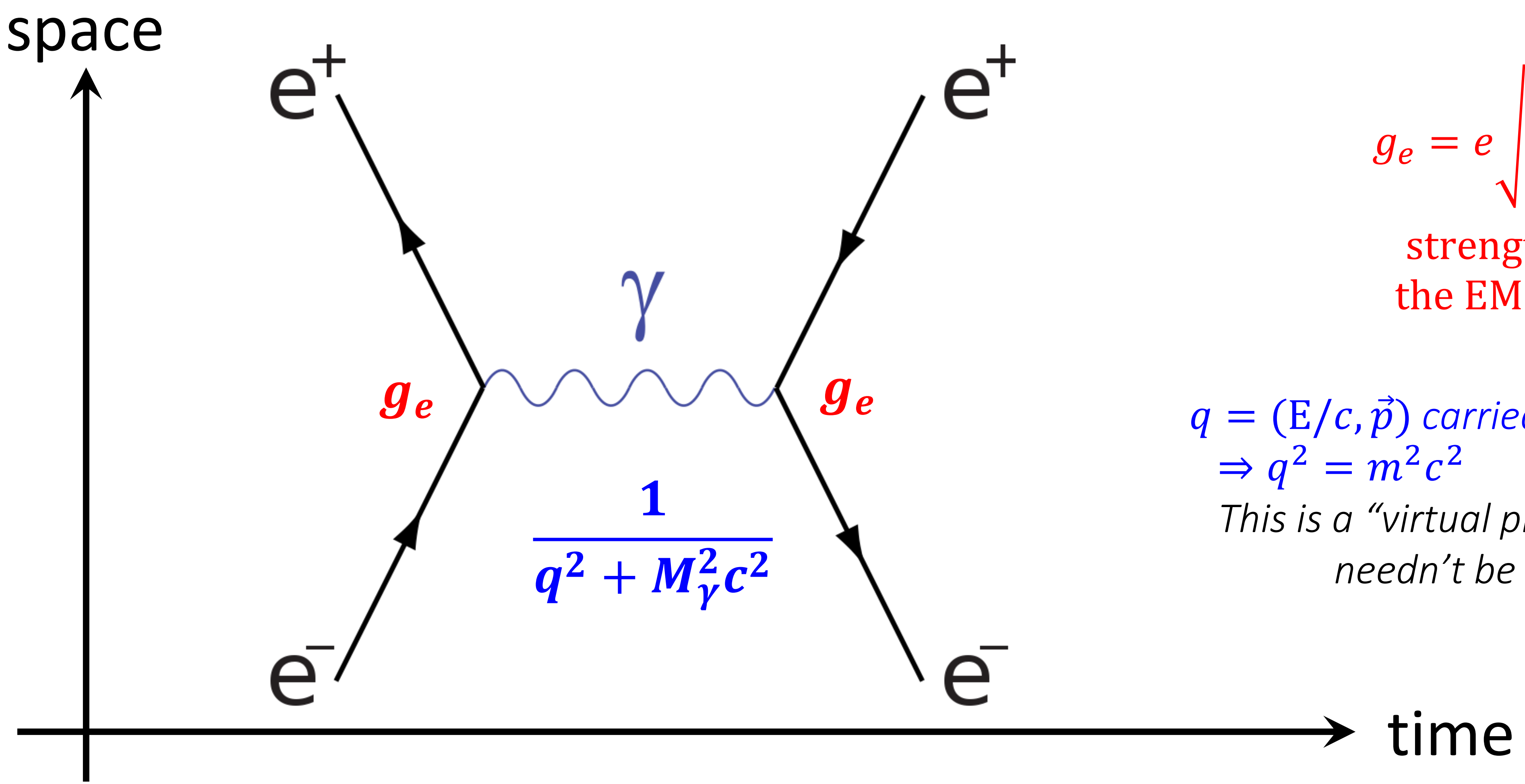
Whallah, a Feynman diagram ☺

Feynman Diagrams (2)



- ❑ What kind of interaction does this represent?
  - ❑ **ELECTROMAGNETIC INTERACTION** (how do we know this?)
- ❑ **A detail**: Antiparticles have their arrows drawn backward in time.

Key parts of the Feynman rules



$g_e = e\sqrt{\frac{4\pi}{\hbar c}}$

strength of the EM force

$q = (\mathrm{E}/c, \vec{\mathrm{p}})$ *carried by the photon*

$\Rightarrow q^2 = m^2c^2$

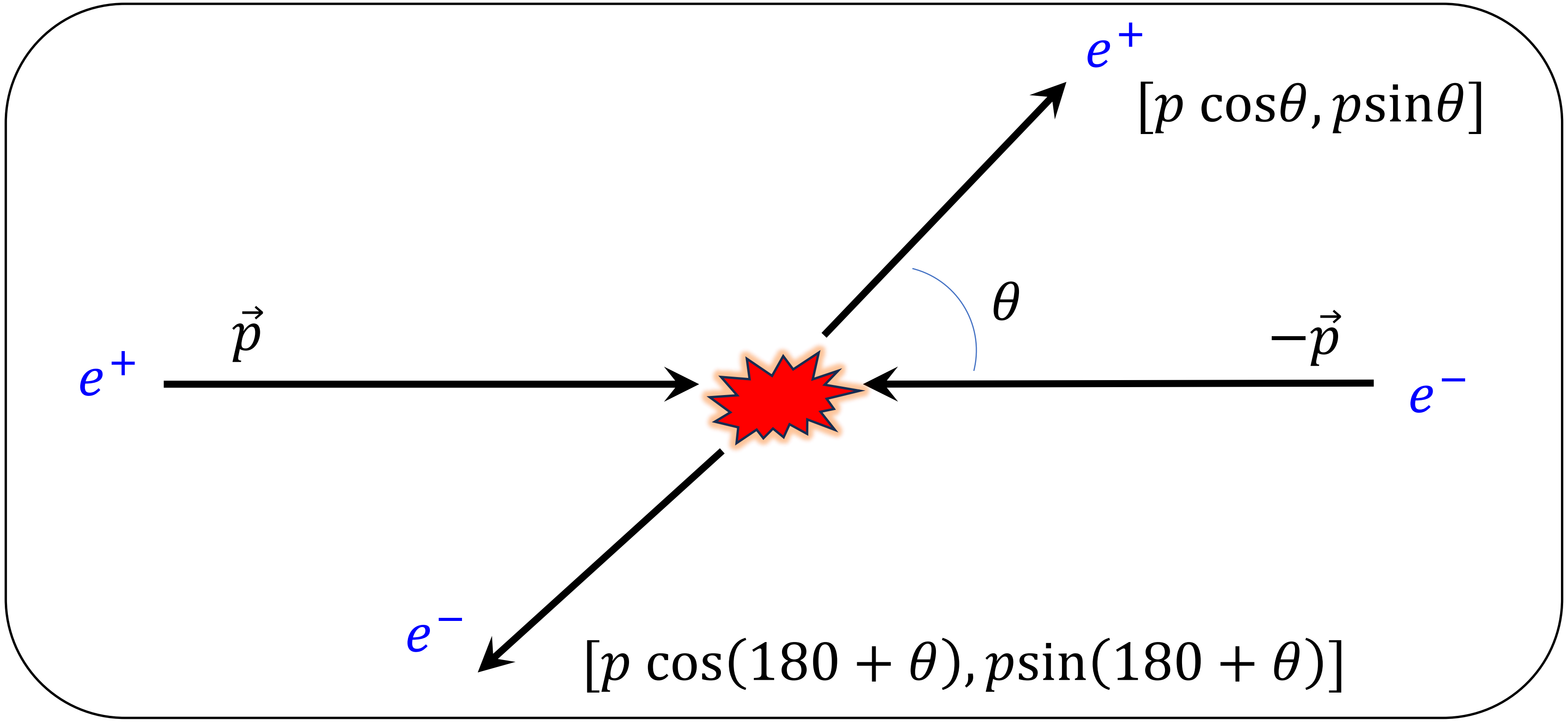
This is a "virtual photon", so m *needn't be zero!*

$$d\sigma \propto \left(\frac{g_e^2}{q^2 + M_\gamma^2 c^2}\right)^2$$

$$M_\gamma \;\; = ?$$

$$d\sigma(e^+e^- \to e^+e^-) \propto \frac{g_e^4}{q^4}$$

Collision in the "center of mass"

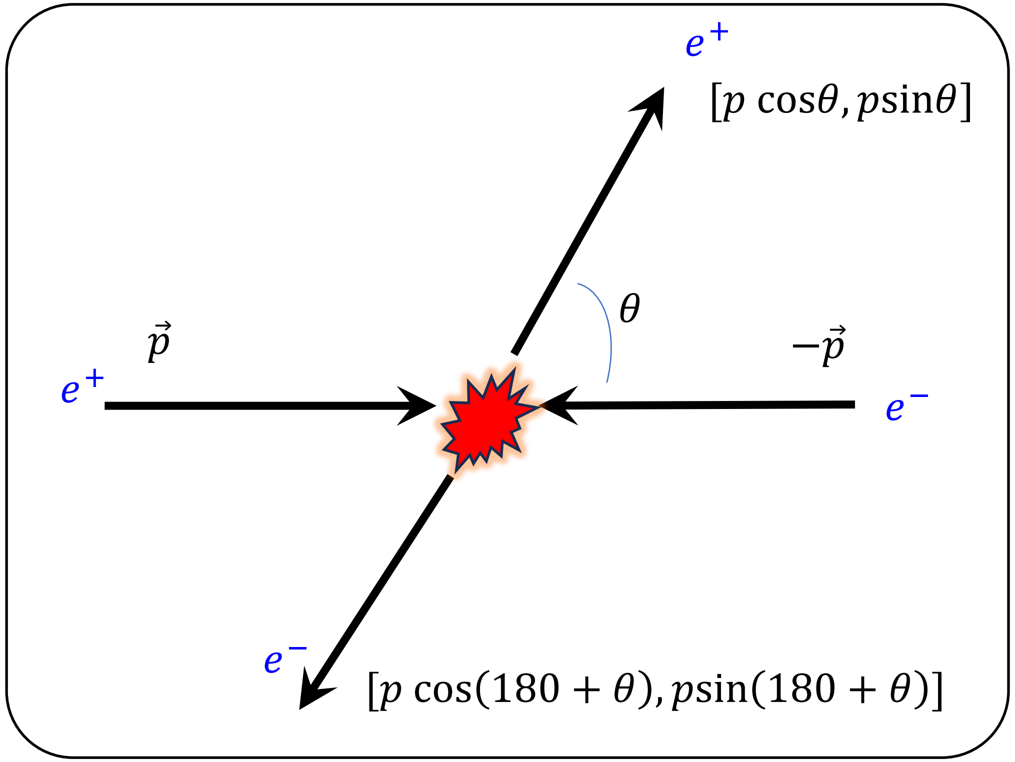


Can show that for moderately high energy

$$q^2 \approx 2p^2 \sin^2(\theta/2)$$

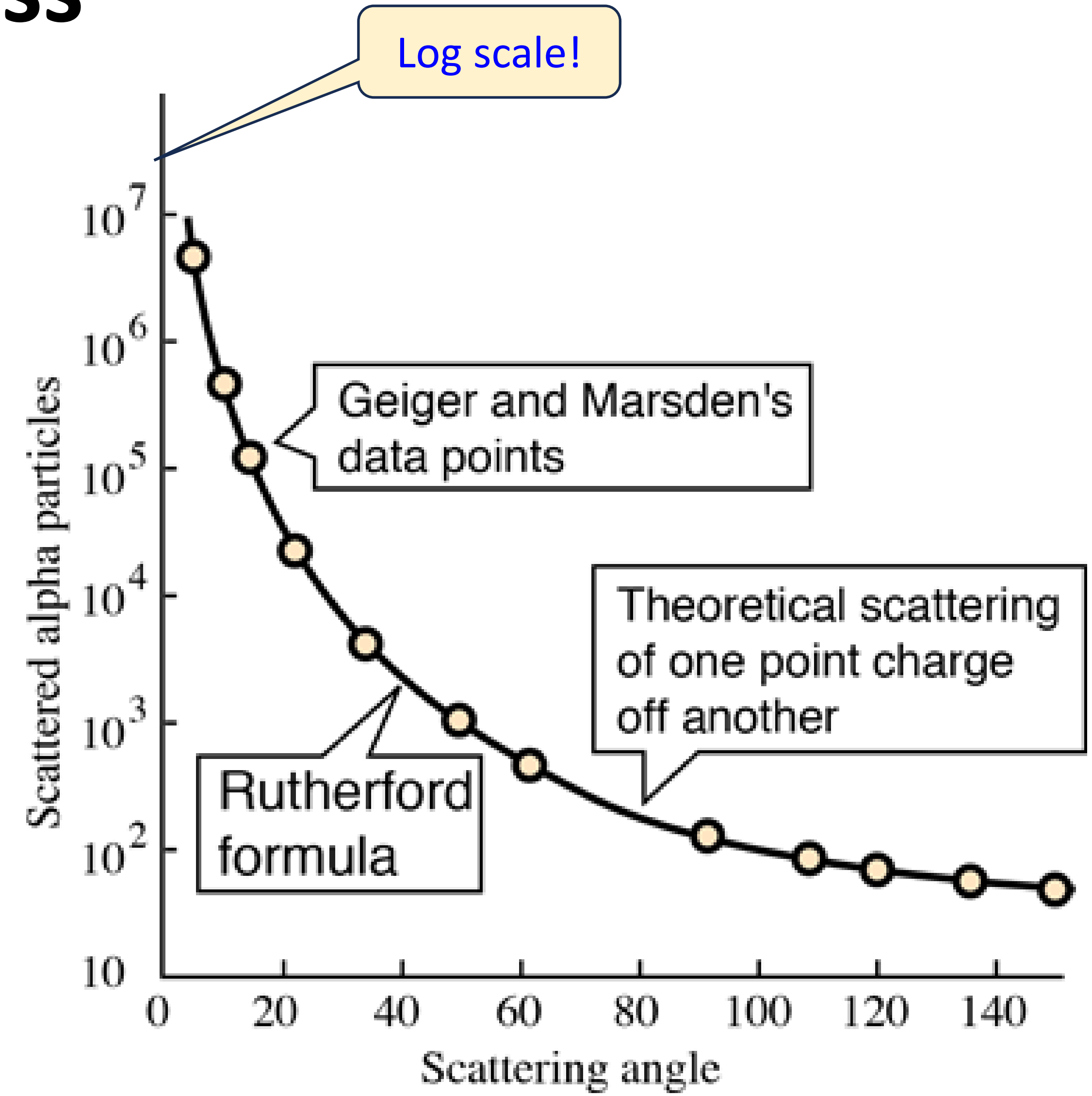
$$\frac{d\sigma}{d\theta}(e^+e^- \to e^+e^-) \propto \frac{g_e^4}{p^4 \sin^4(\theta/2)}$$

Collision in the "center of mass"



$$\frac{d\sigma}{d\theta}(e^+e^- \to e^+e^-) \propto \frac{g_e^4}{p^4\sin^4(\theta/2)}$$

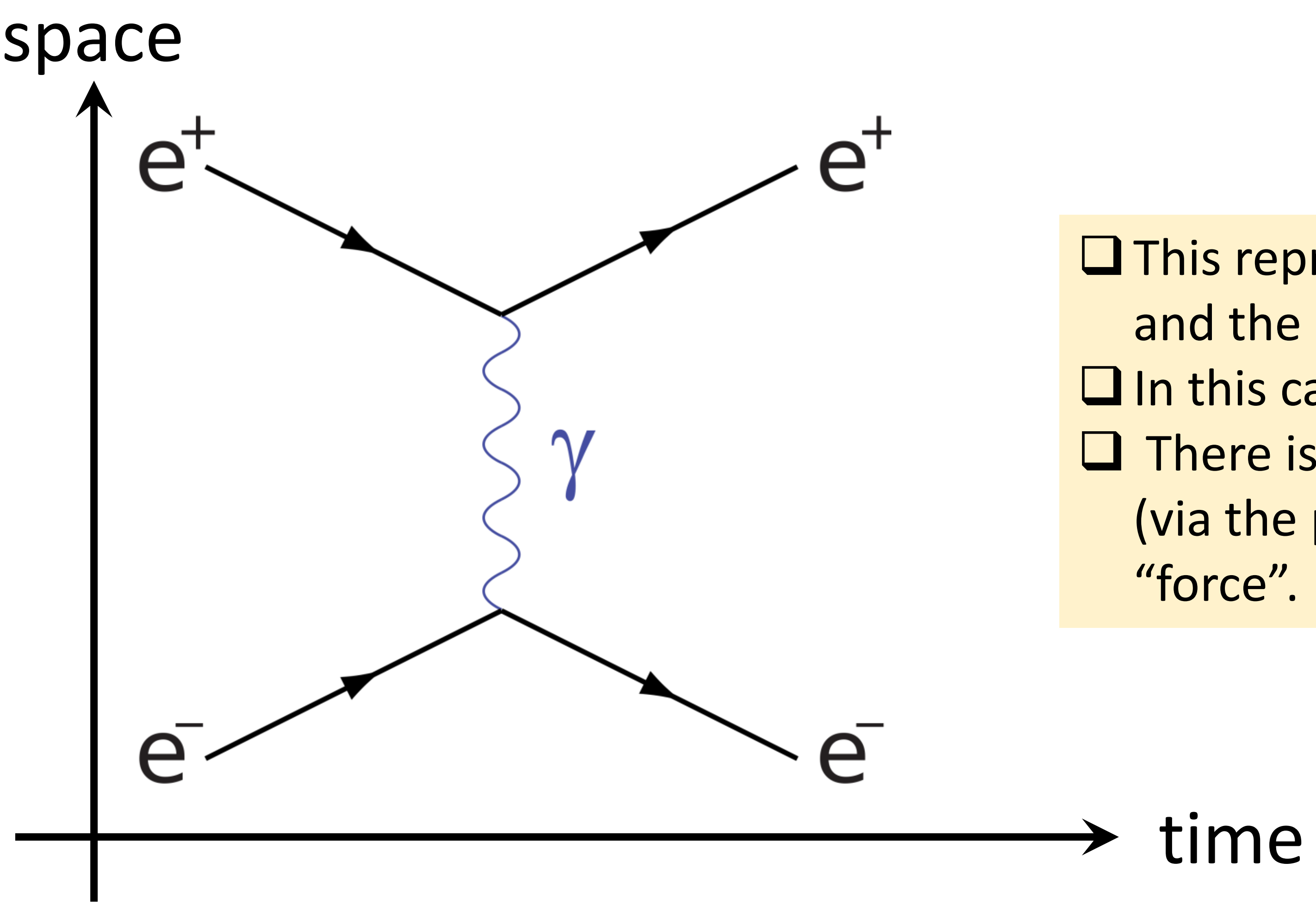
Predicts that scattering angle strongly peaked at small angles!



Precisely what Rutherford & his students found!

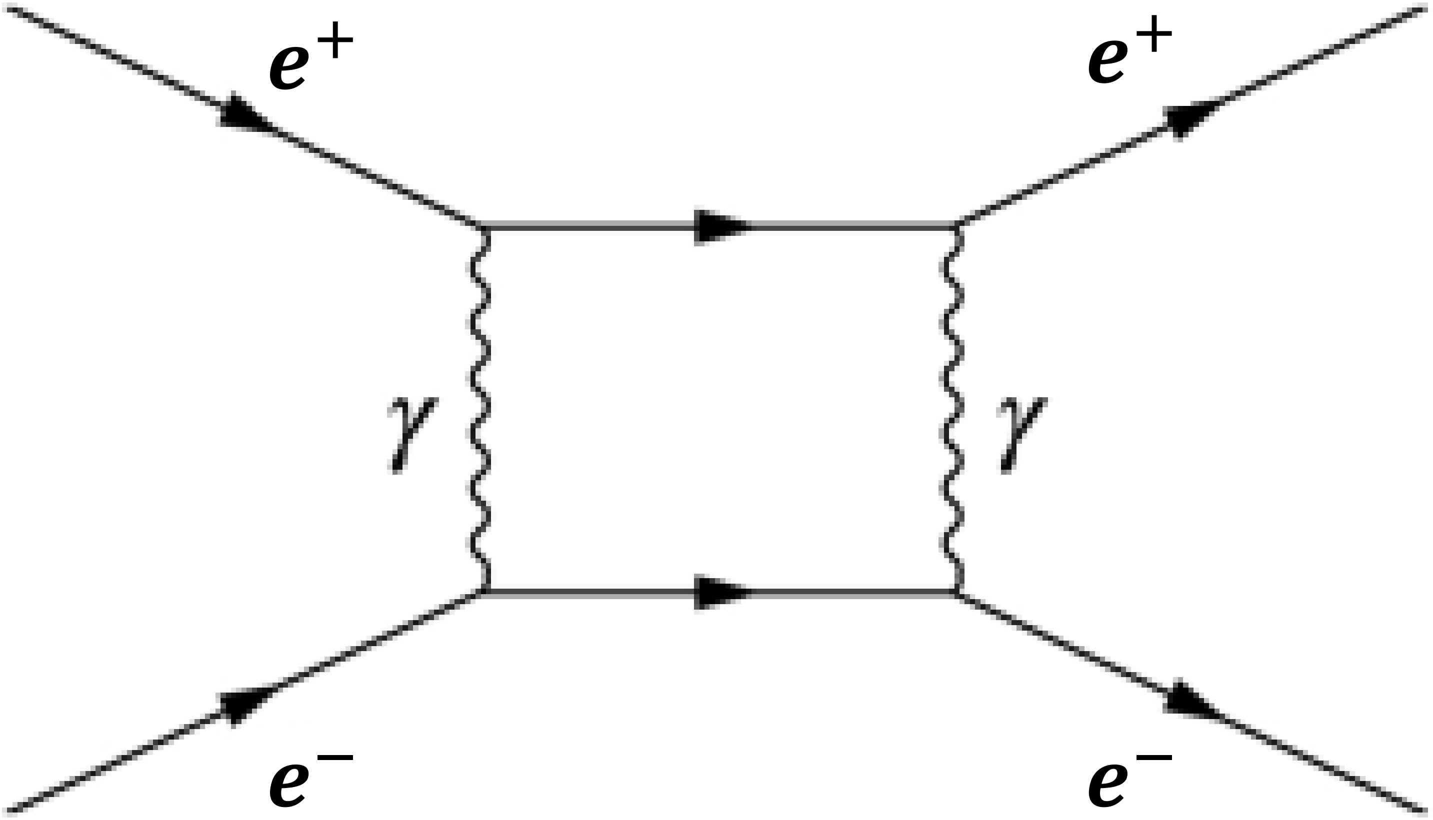
An important detail I skipped

- ❑ Must include **ALL possible diagrams**, so this one also needs to be computed and included in the calculation.



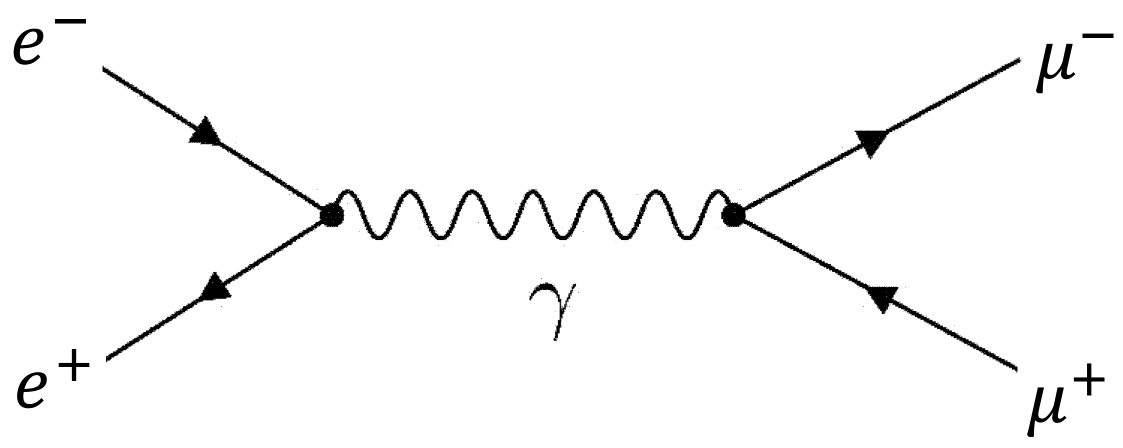
- ❑ This represents the e^- "emitting" a photon, and the e^+ "absorbing" it (or vice versa).
- ❑ In this case, there is no "annihilation".
- ❑ There is "exchange" of energy & momentum, (via the photon) which is synonymous with "force".

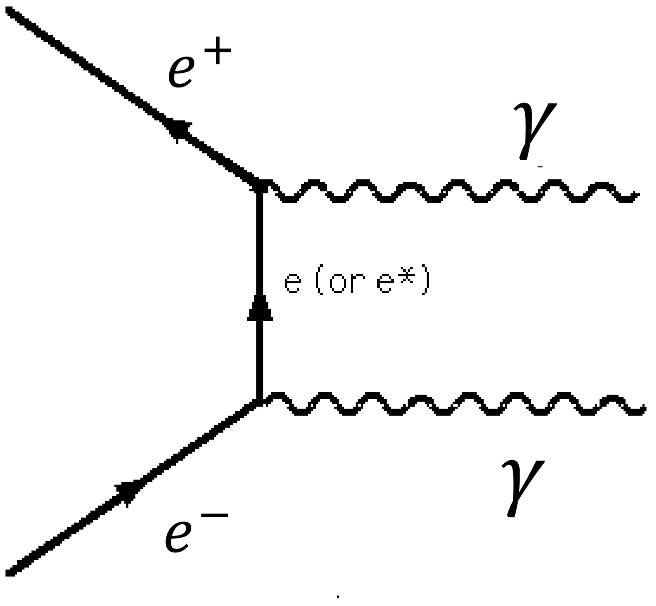
Oh, and what about this?

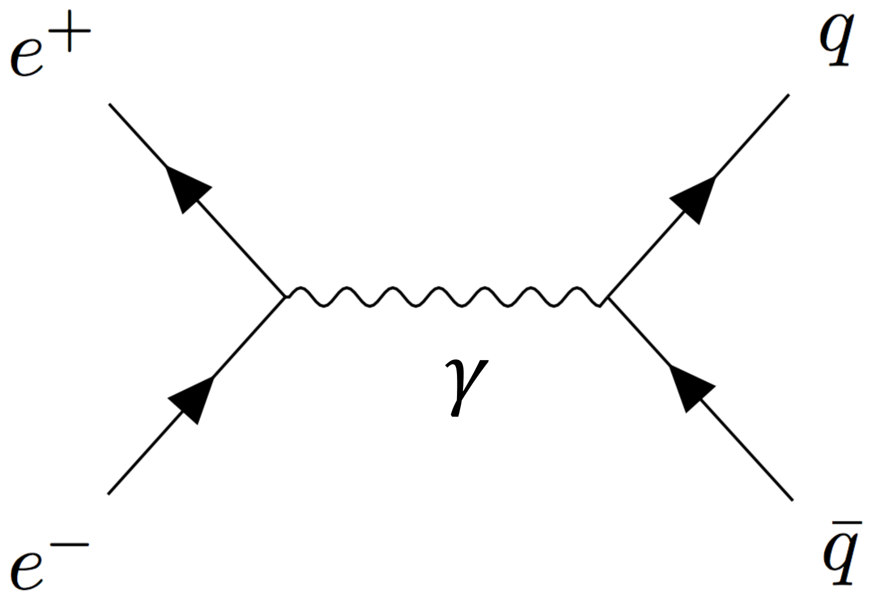


Luckily: Every extra photon being exchanged is suppressed by ~100X!

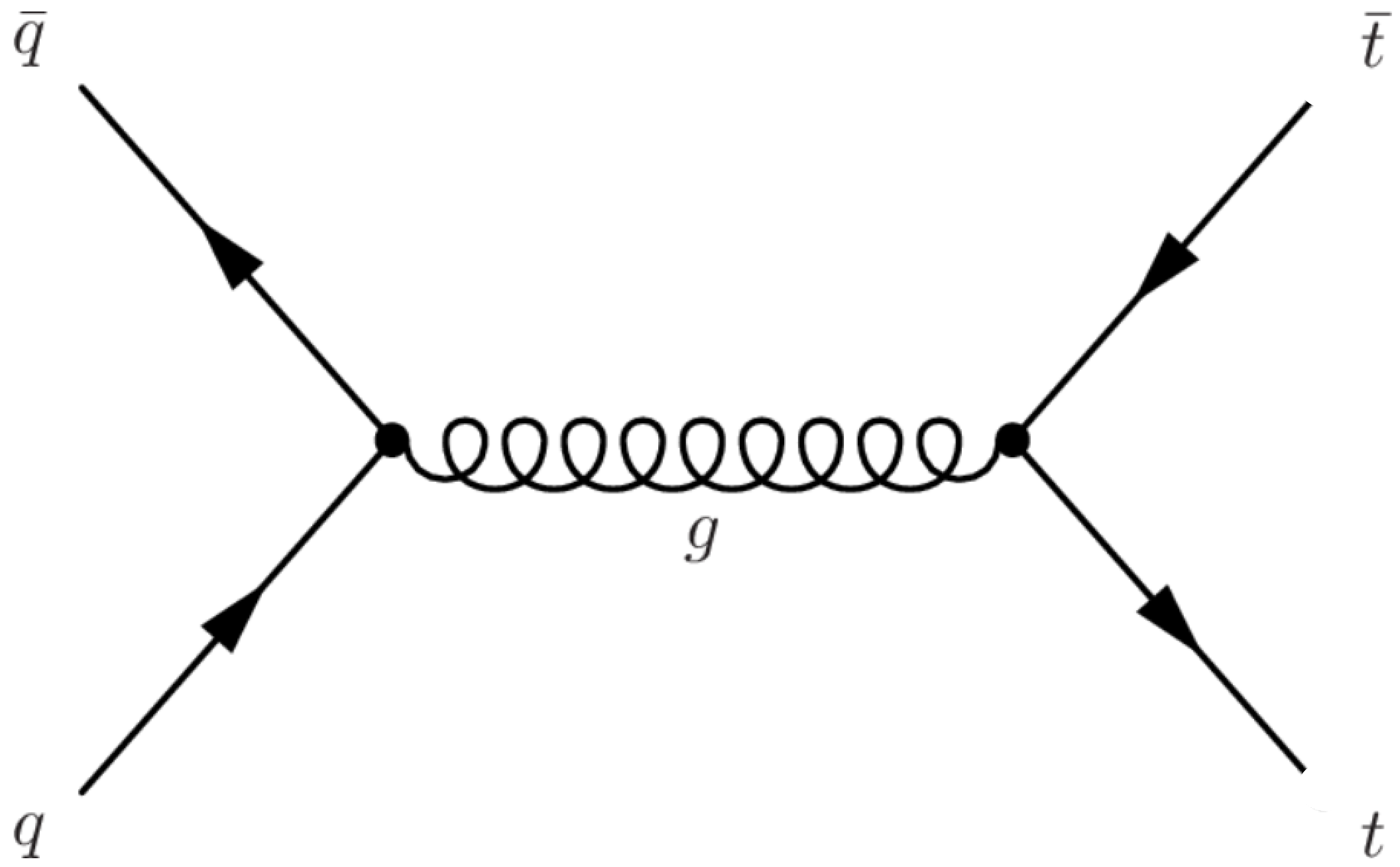
Other Feynman diagrams, EM Interactions





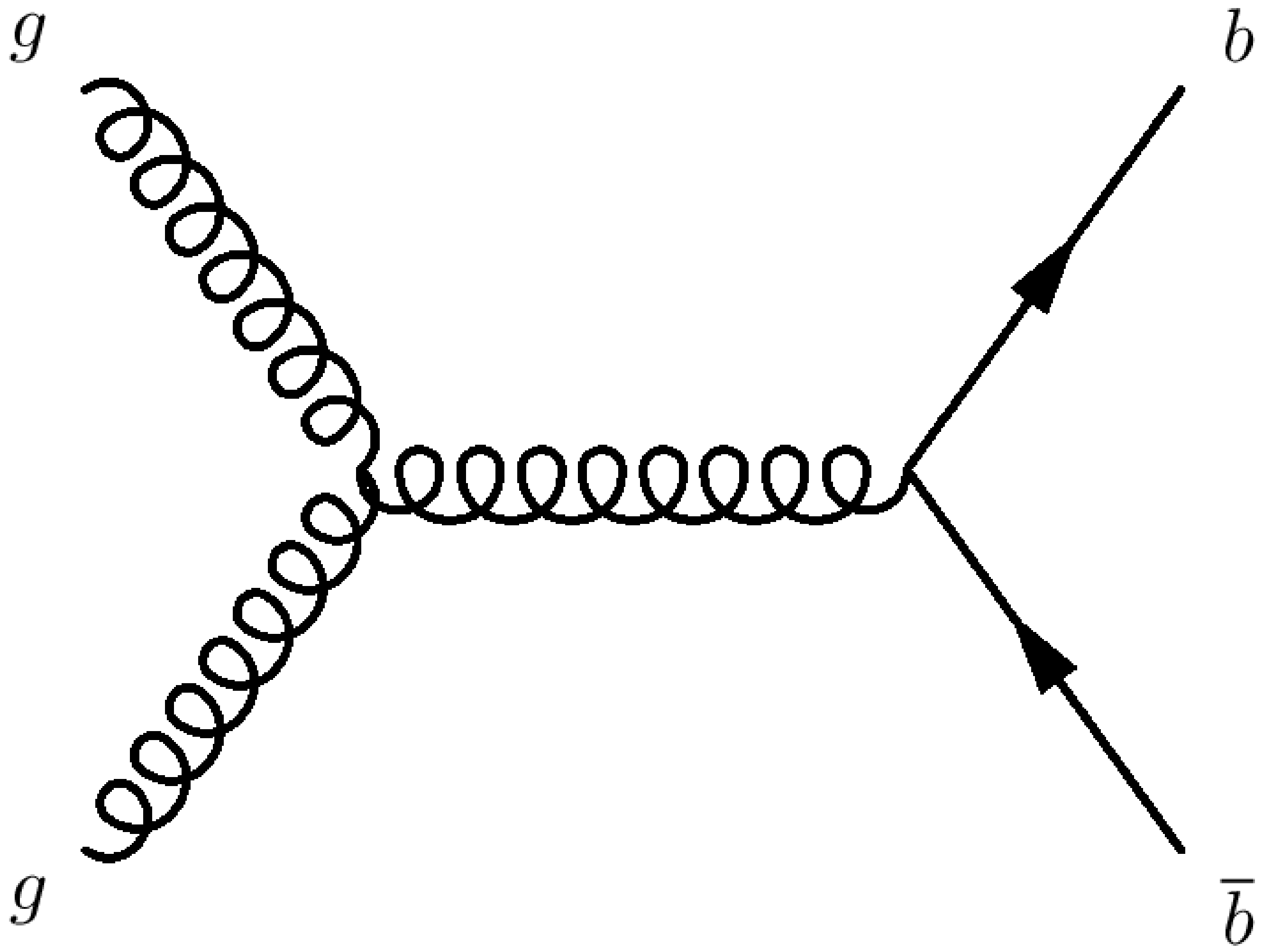


Example of Feynman diagram (1)



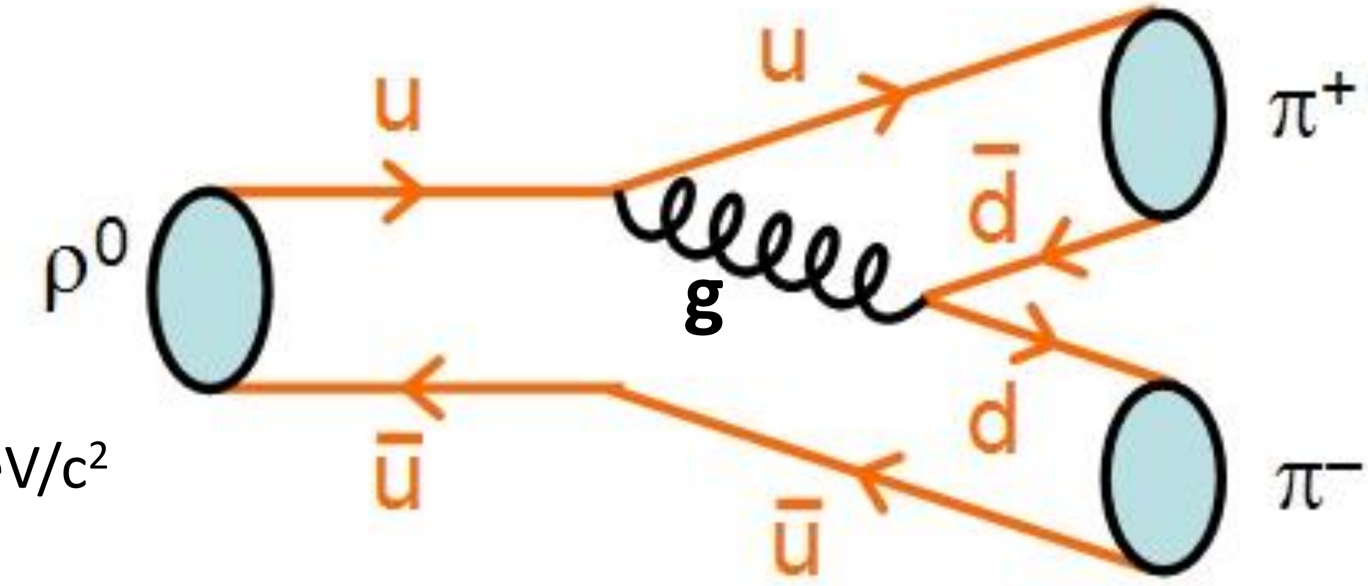
What force is responsible for this interaction?

Example of Feynman diagram (2)



What force is responsible for this interaction?
How does one “collide gluons” ?

Example of a strong decay



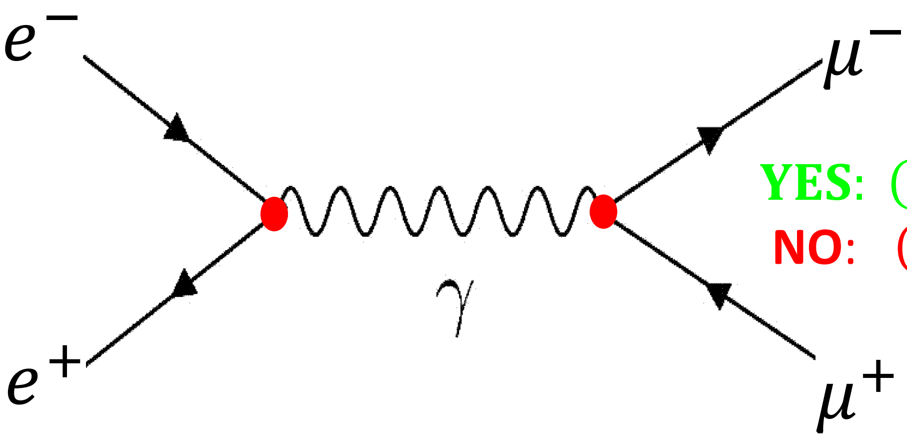
Mass = 139.6 MeV/c^2

Mass = 770 MeV/c^2

Mass = 139.6 MeV/c^2

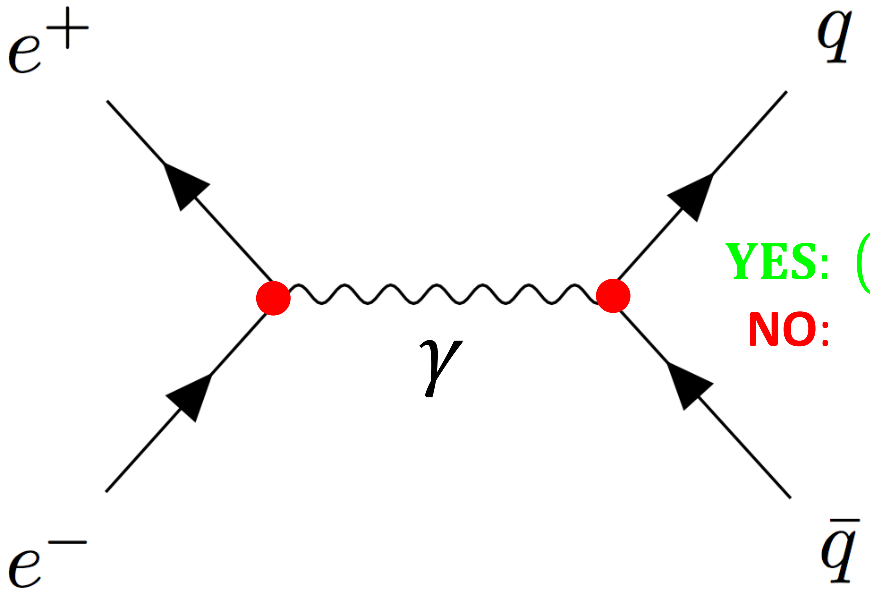
What signals to you that this is a decay mediated by the strong interaction?

Conservation Laws



YES: $(e^+e^-, \mu^+\mu^-, \tau^+\tau^-)$

NO: $(\mu^+e^-, \tau^+e^- \ldots)$



YES: $(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t})$

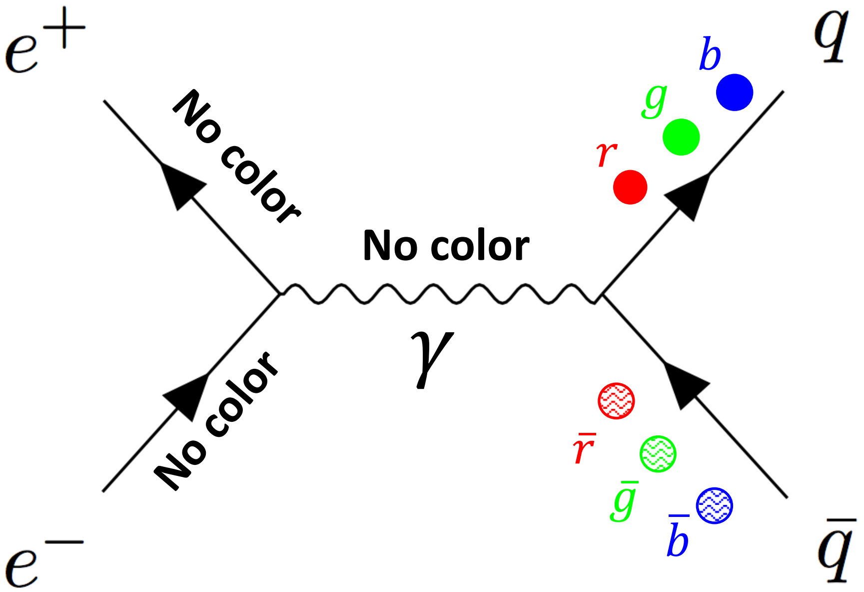
NO: $(u\bar{c}, d\bar{s}, c\bar{t}, \ldots)$

- ❑ Various quantities must be conserved at **each** of the **vertices.**
- ❑ A partial list of conserved quantities for **BOTH EM and Strong Forces**

Conserved quantity
Energy
Linear Momentum
Angular momentum
Electric charge
Color charge (Strong force only, next slide)
Quark or lepton “**flavor**”

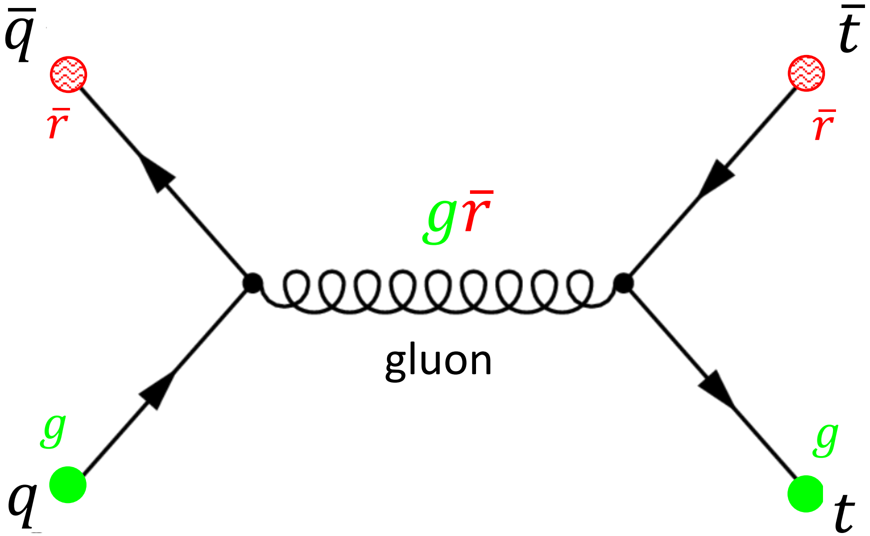
If ANY of these are violated, the process cannot occur.

Conservation of “strong” charge



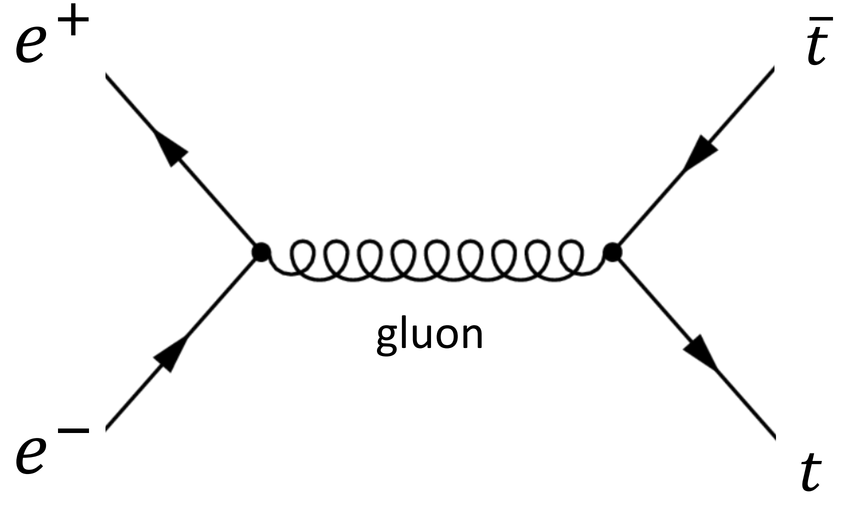
- What does **conservation of color charge** mean?
  - Quarks carry “strong charge”: **3 values**
  - Colorful idea: red(r), green(g), blue(b)

- **Net color charge** needs to be preserved at each vertex.

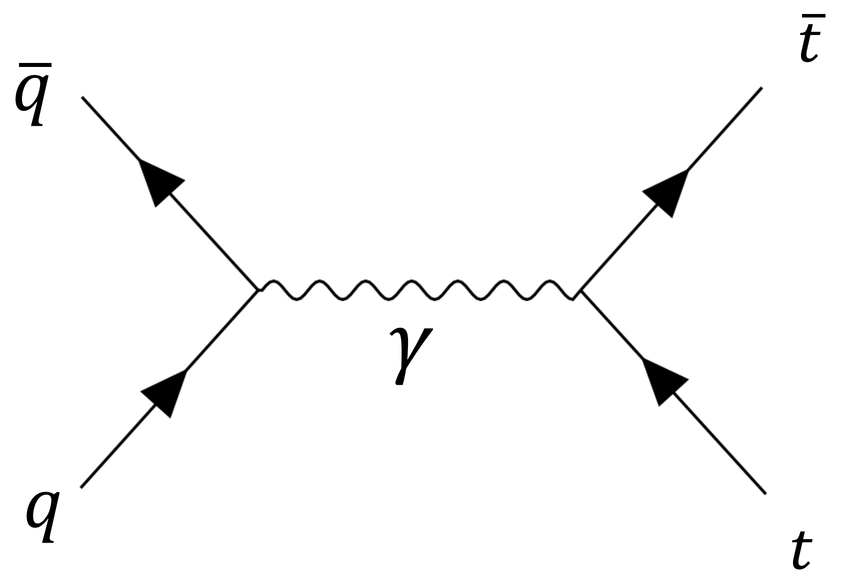


- Gluons carry “color-anticolor”
- Of the fundamental particles:
  - Only quarks and gluons carry color charge.
  - Leptons, photons, $W^{\pm}, Z^0, H^0$ have no color.
    - ➔ Cannot directly interact with a gluon!

Questions



- ❑ Is this a valid Feynman diagram?
  Why or why not?



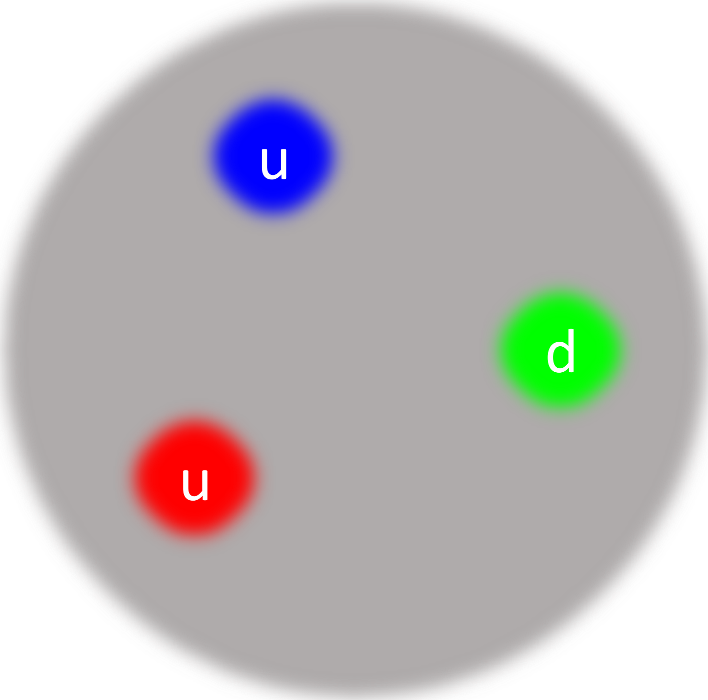
- ❑ Is this a valid Feynman diagram?
  Why or why not?

- ❑ If YES, what can you say about the colors allowed for q and $\bar{q}$?   And for t and $\bar{t}$?

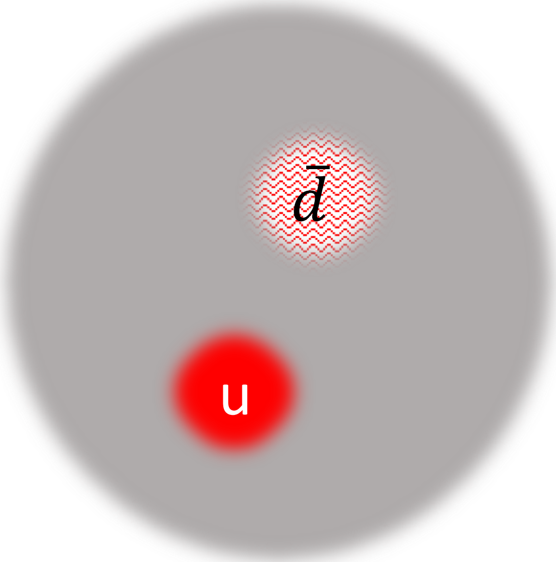
Hadrons, baryons and mesons

- **Hadrons**: Particles containing quarks.
  - All known hadrons have **<u>zero net color</u>**

Conventional baryon (proton)



Conventional meson (pion)

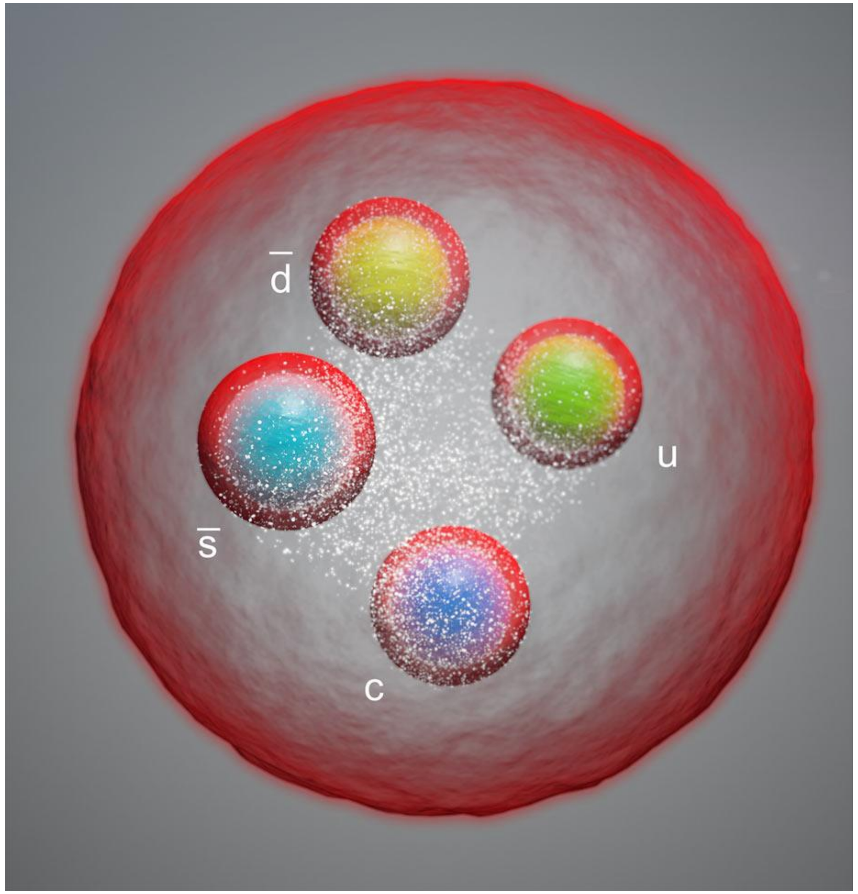


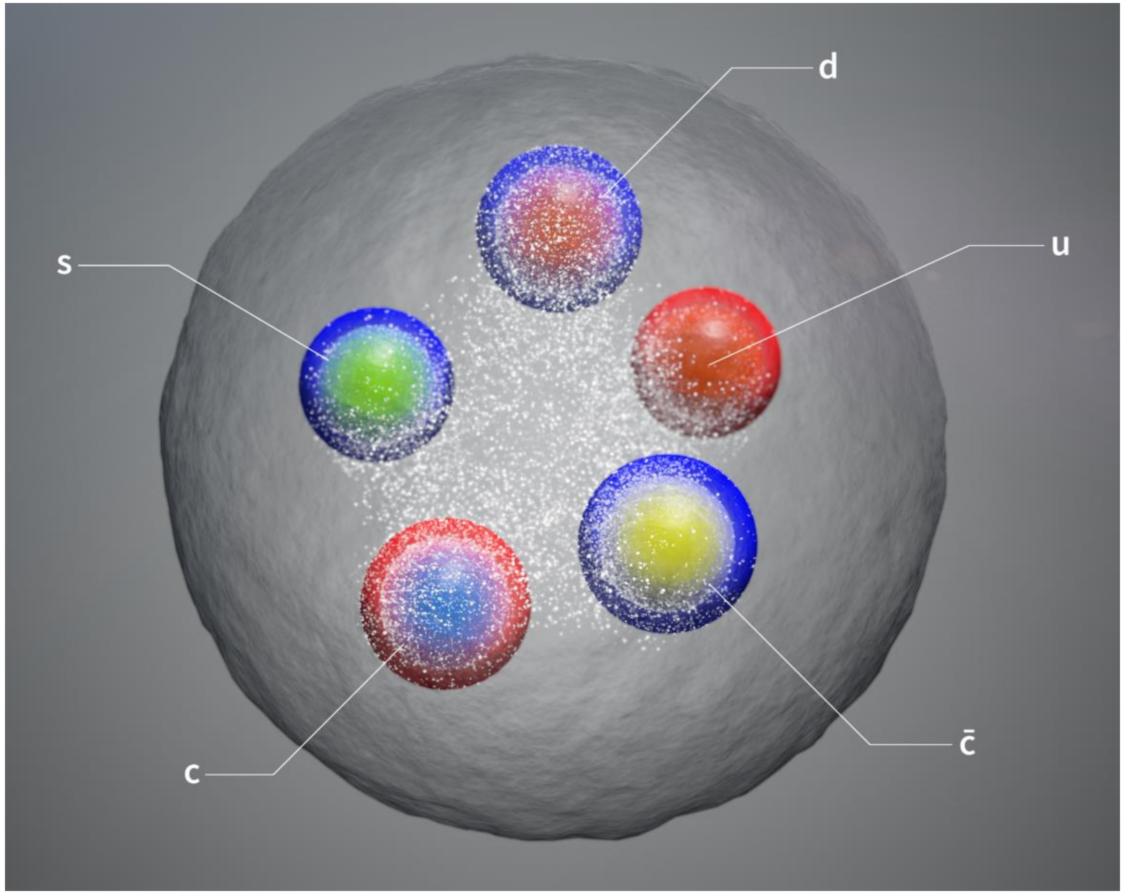
Any 3 quarks (except top) w/ different color can form a baryon that should exist in nature

Any quark + antiquark (with color-anticolor) can form a meson that should exist in nature

Non-conventional hadrons

- In recent years, strong evidence of tetraquarks and pentaquarks, much of it spear-headed by LHCb





The nature of these states still under active investigation: tightly bound or molecular?