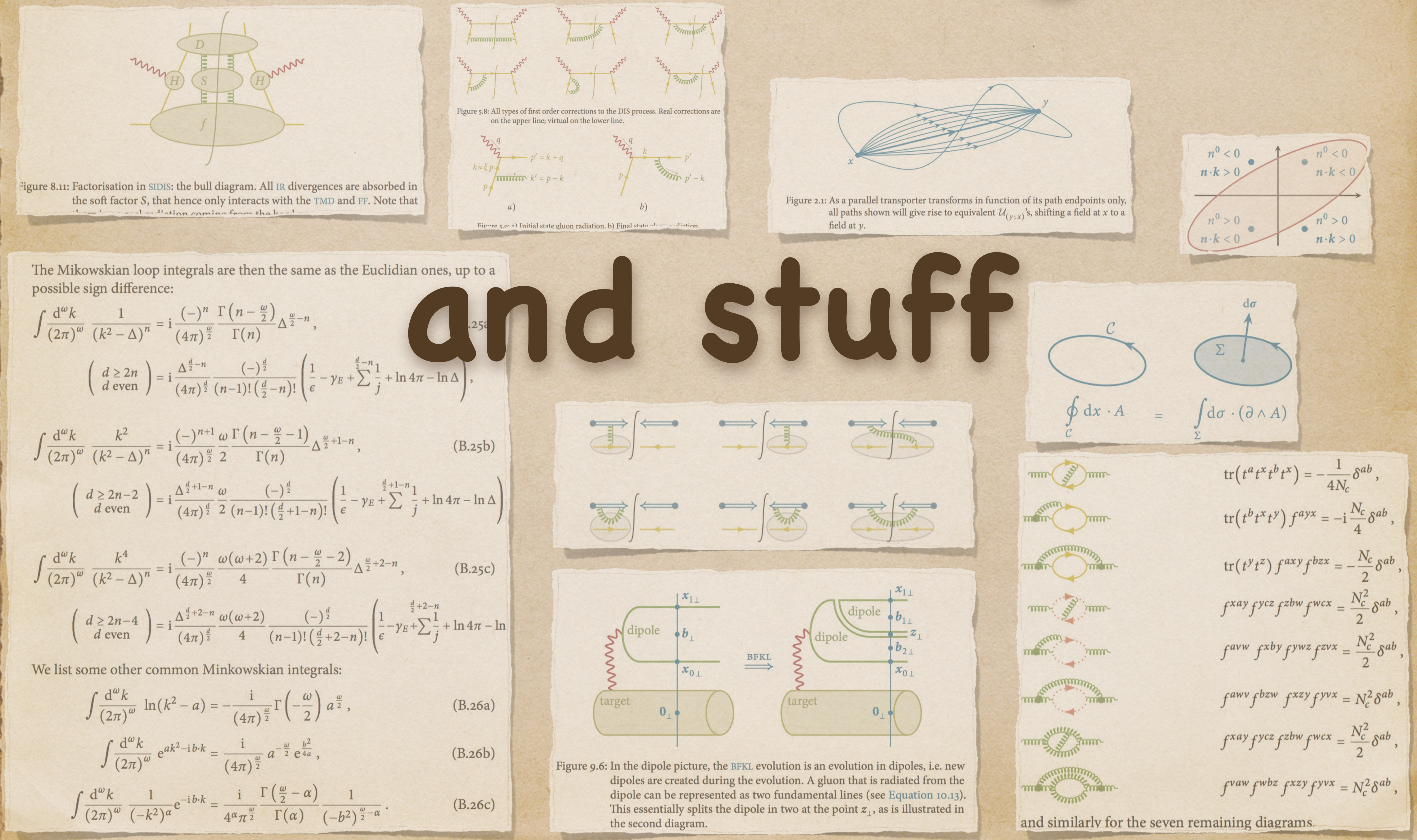
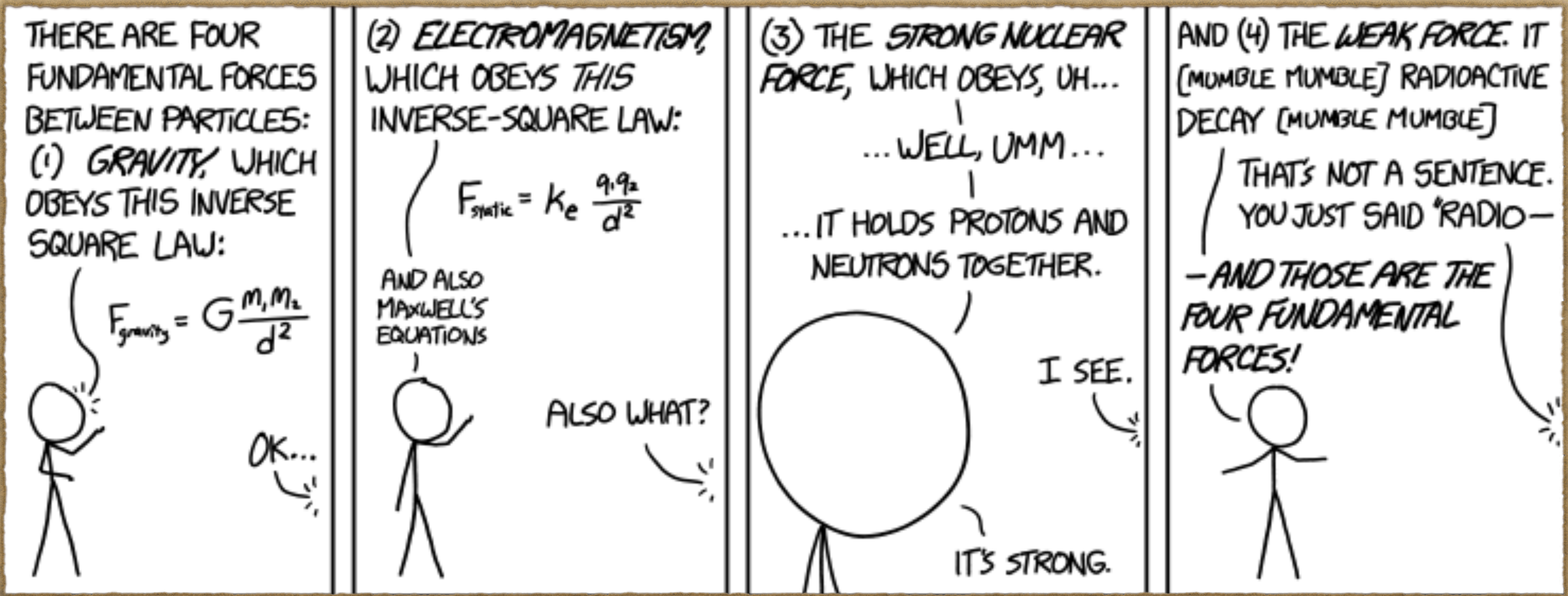
CERN

# Feynman Diagrams and stuff



# Quick recap

# Fundamental Forces



# Elementary Particles

- Three types:
  - Fermions: matter particles
  - Bosons: force carriers ("exchange particles")
  - Higgs: special guy

- Difference lies in spin

# Elementary Particles

- Two types of matter particles:
  - Leptons: electrons, muons, taus, and neutrinos
  - Quarks: don't exist alone, but combine to form hadrons (composite particles)

- Four fundamental forces:
  - Electromagnetic: exchanged by photon
  - Weak: exchanged by $W^+$, $W^-$, $Z^0$
  - Strong: exchanged by gluons
  - Gravity: exchanged by graviton

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# Elementary Particles

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- Two types of matter particles:
  - Leptons: electrons, muons, taus, and neutrinos
  - Quarks: don't exist alone, but combine to form hadrons (composite particles)

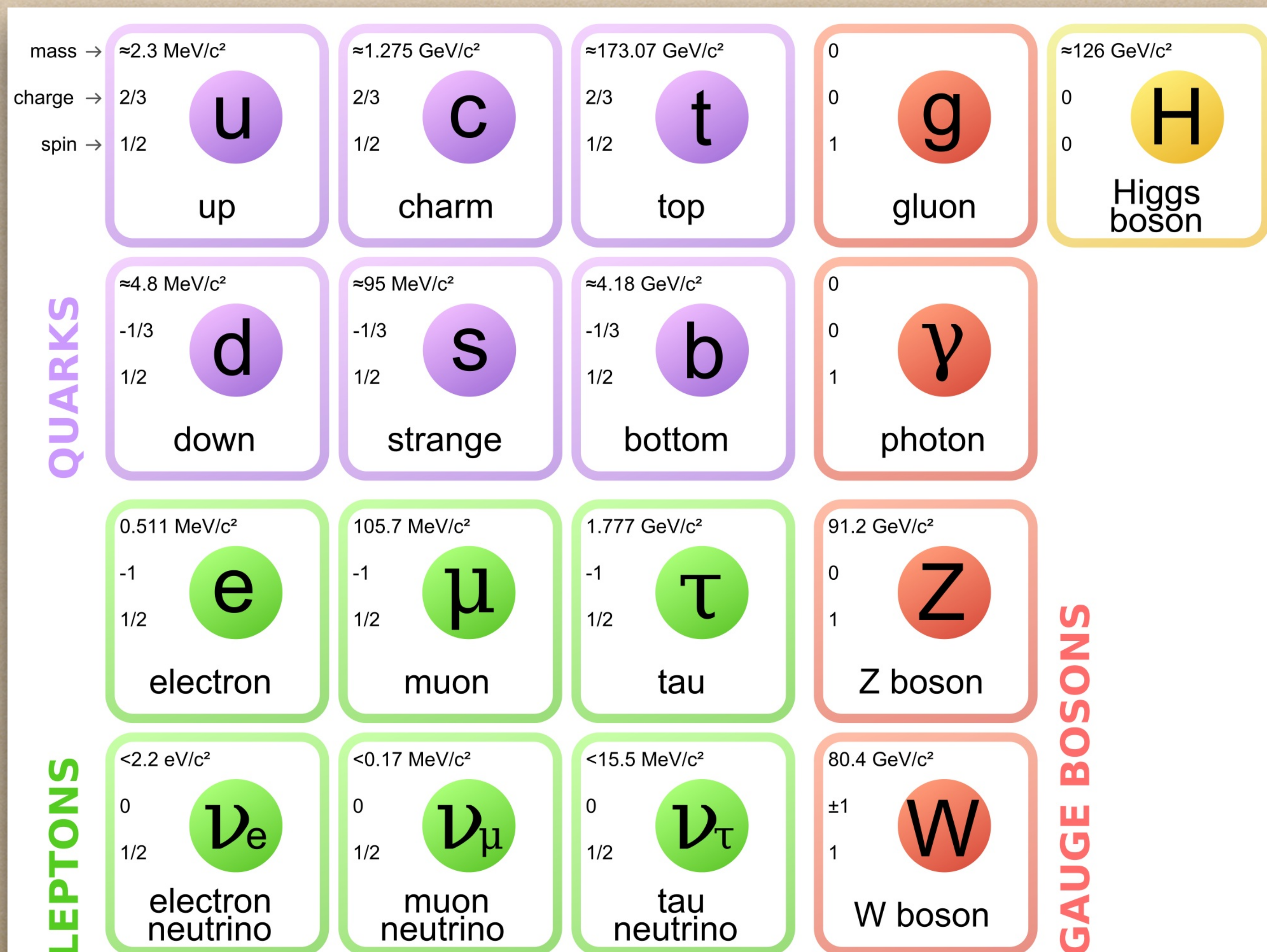
Three very cool and quantisable and not 'totally ignorable'

- ~~Four fundamental~~ forces:
  - Electromagnetic: exchanged by photon
  - Weak: exchanged by $W^+$, $W^-$, $Z^0$
  - Strong: exchanged by gluons
  - ~~Gravity: exchanged by graviton~~

# Particle Properties

- Every force comes with an associated charge. If a certain particle does not have this charge, it will not interact with this force.
    - Electromagnetic charge
    - Weak hypercharge
    - Colour (strong force)
- Fermions come in 3 families, the difference between the families being the mass.

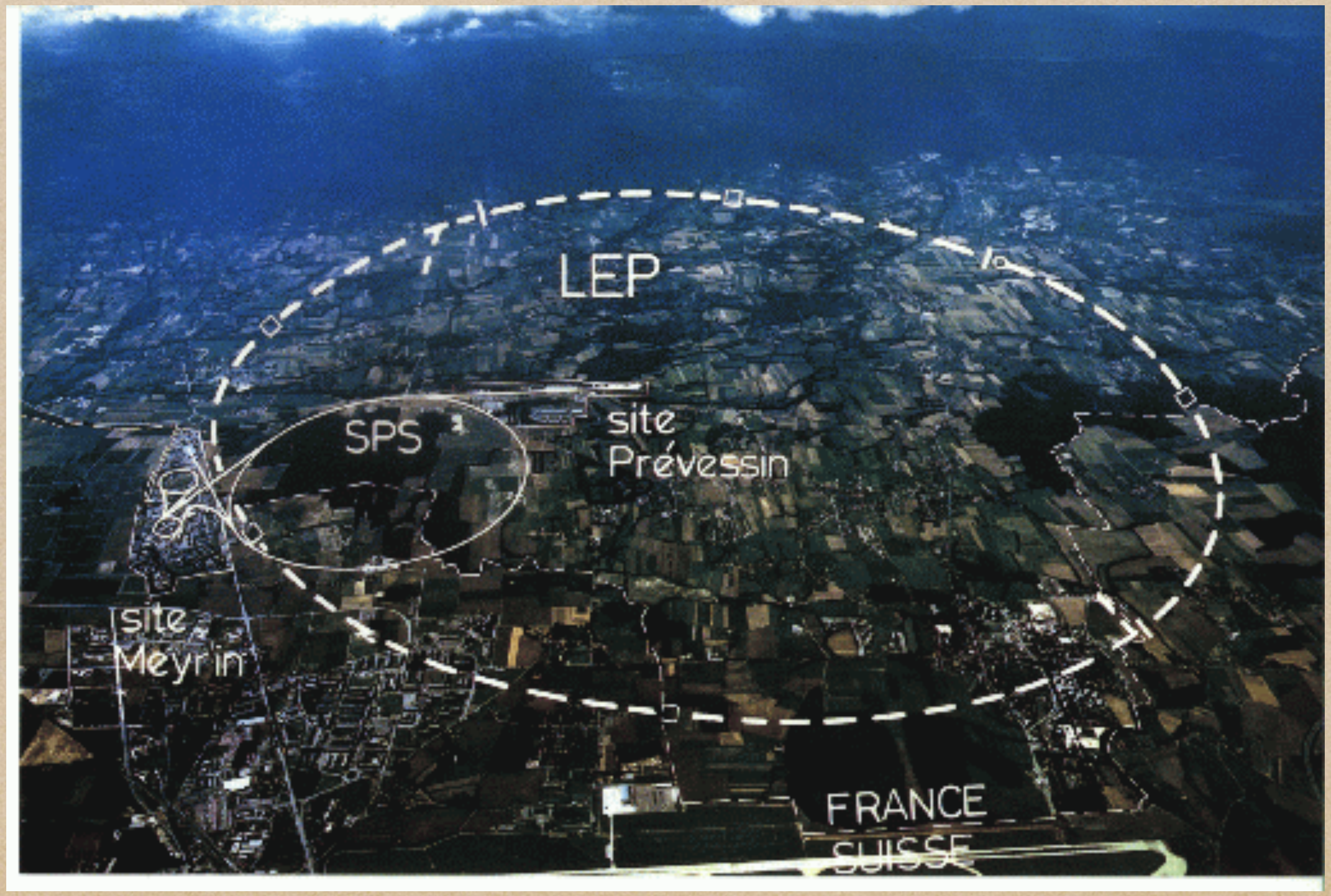
# Elementary: The SM



# What Are Feynman Diagrams

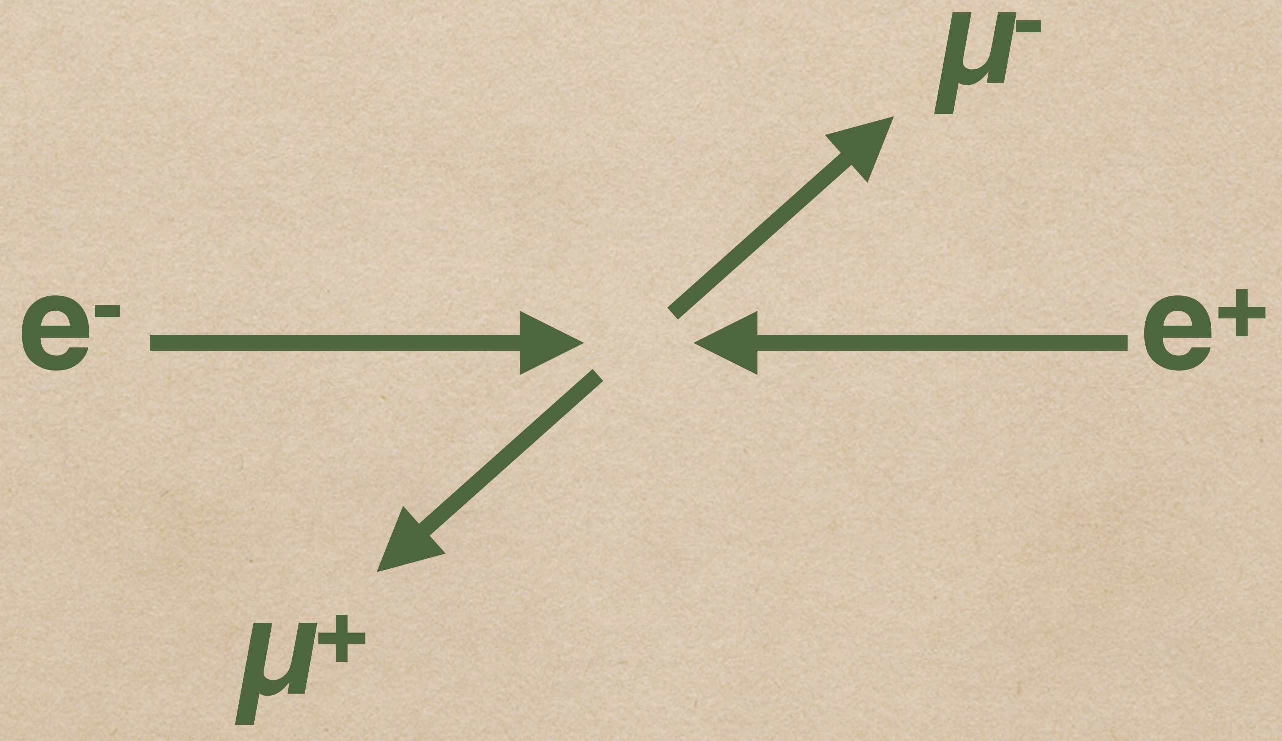
# Feynman Diagrams

- Are an easy visual way to calculate elementary processes



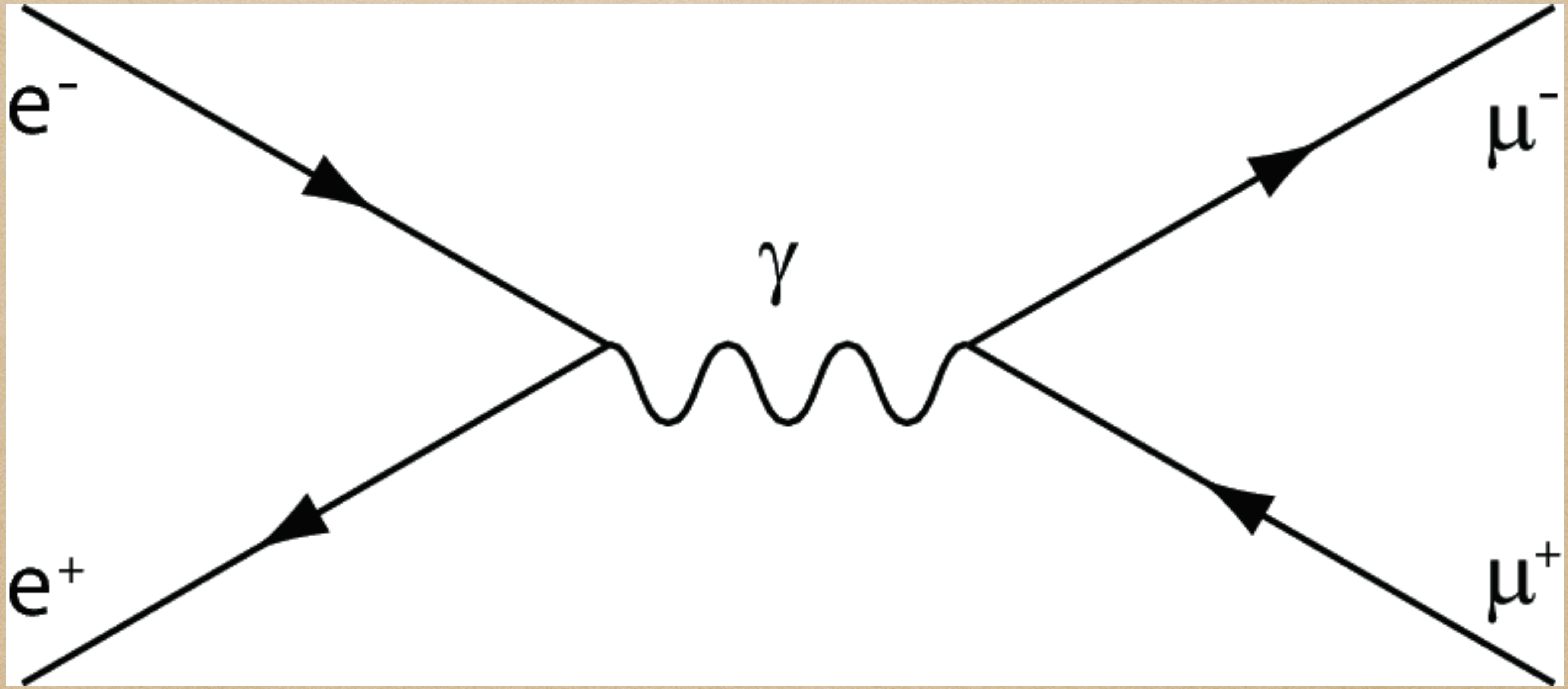
# Feynman Diagrams

- Are an easy visual way to calculate elementary processes



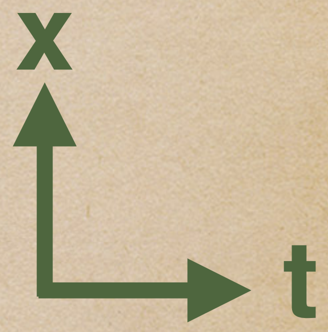
# Feynman Diagrams

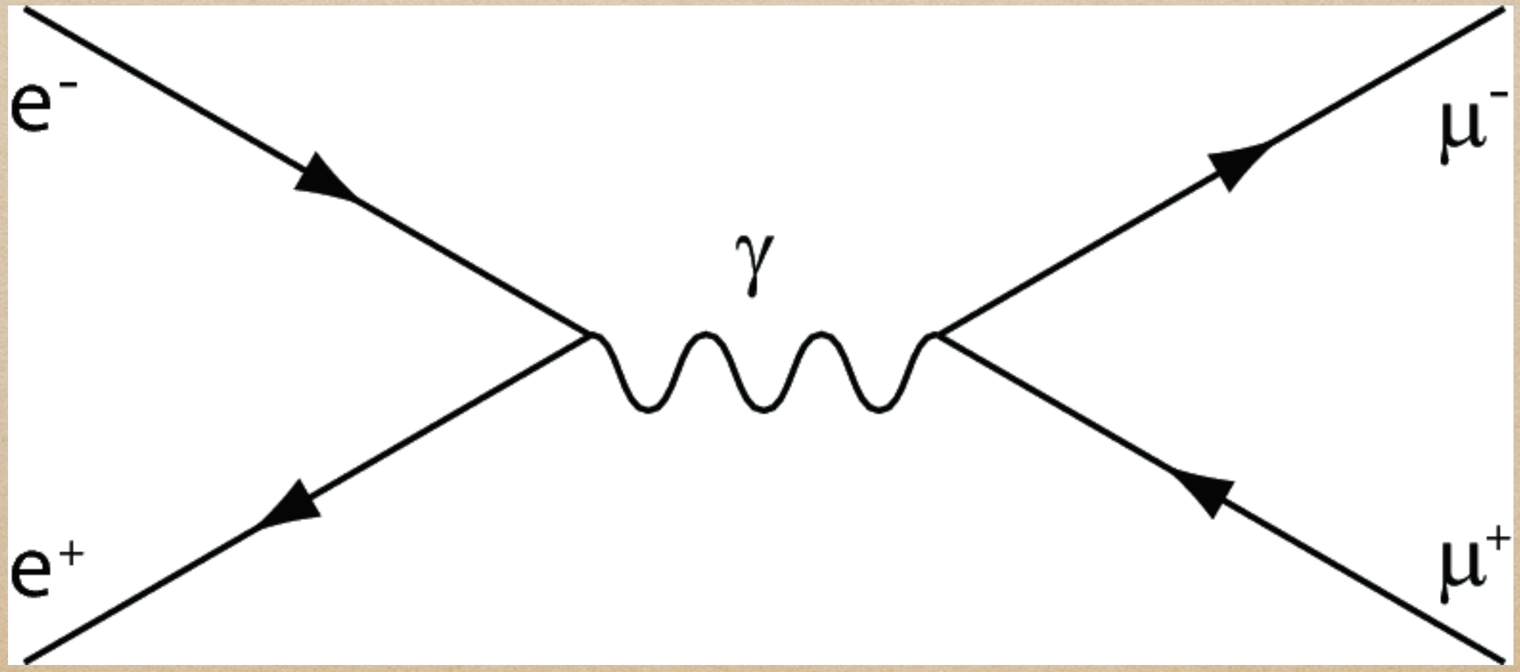
- Are an easy visual way to calculate elementary processes



# Feynman Diagrams

- Are an easy visual way to calculate elementary processes
- Particles are drawn on space-time plane



# How to Draw Feynman Diagrams

# Feynman Diagrams

Different lines for different particle types:

- fermion (matter particle)


- antifermion (antimatter particle)

# Feynman Diagrams

Different lines for different particle types:

- fermion (matter particle)


- antifermion (antimatter particle)

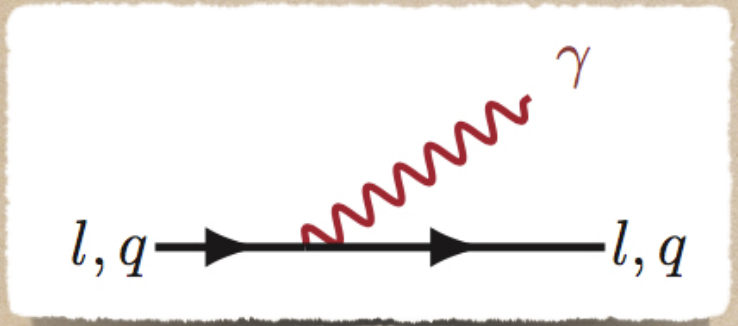

- photon

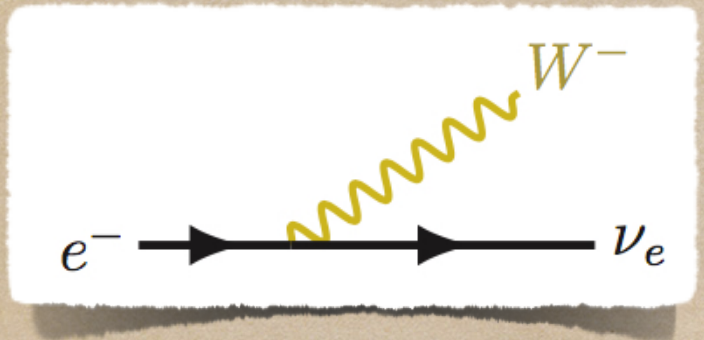

- gluon

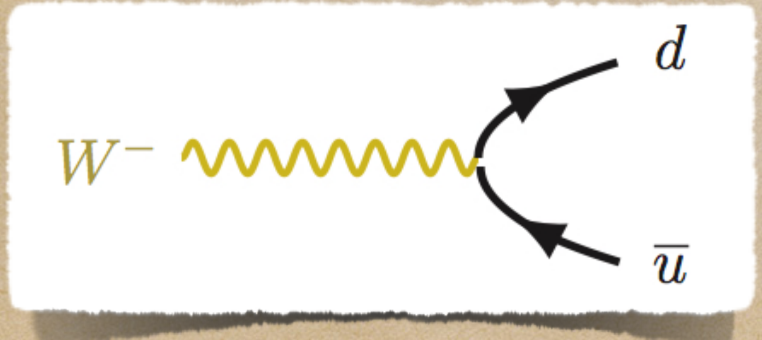

- weak boson

# Feynman Diagrams

## boson - fermion interactions

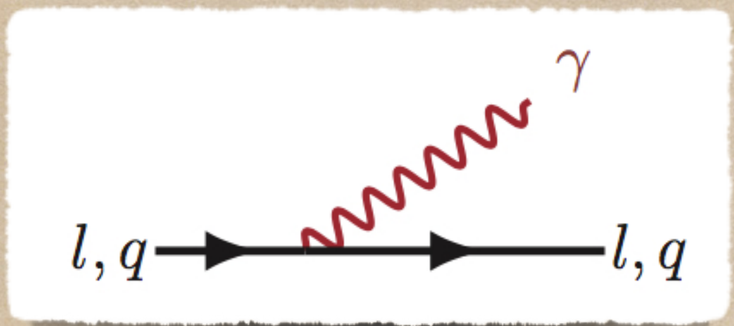


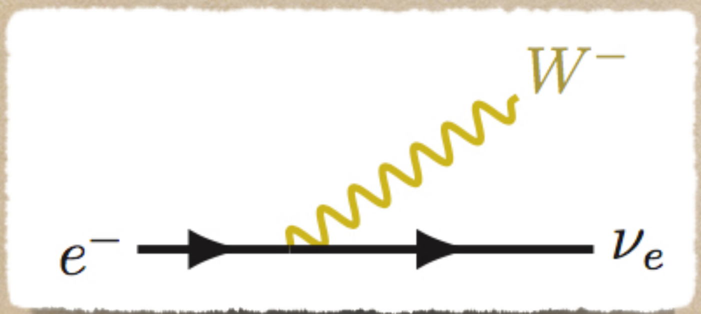



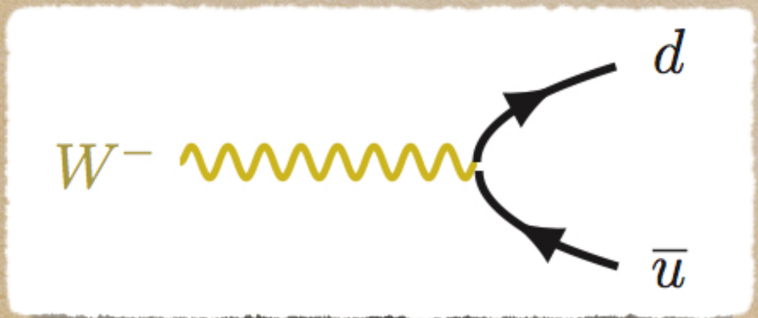



# Feynman Diagrams

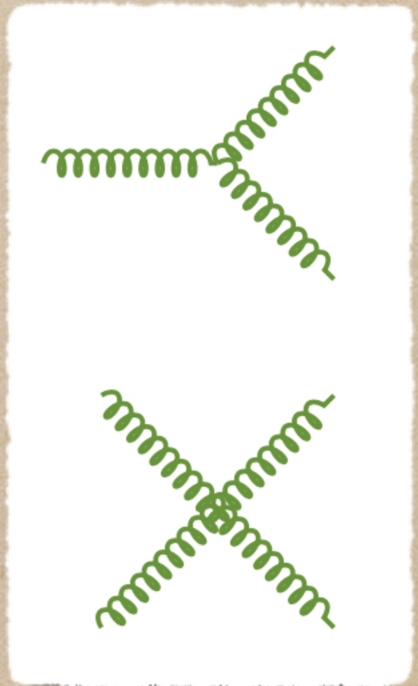
boson - fermion interactions




gluon self-interactions



# Electromagnetic Interactions

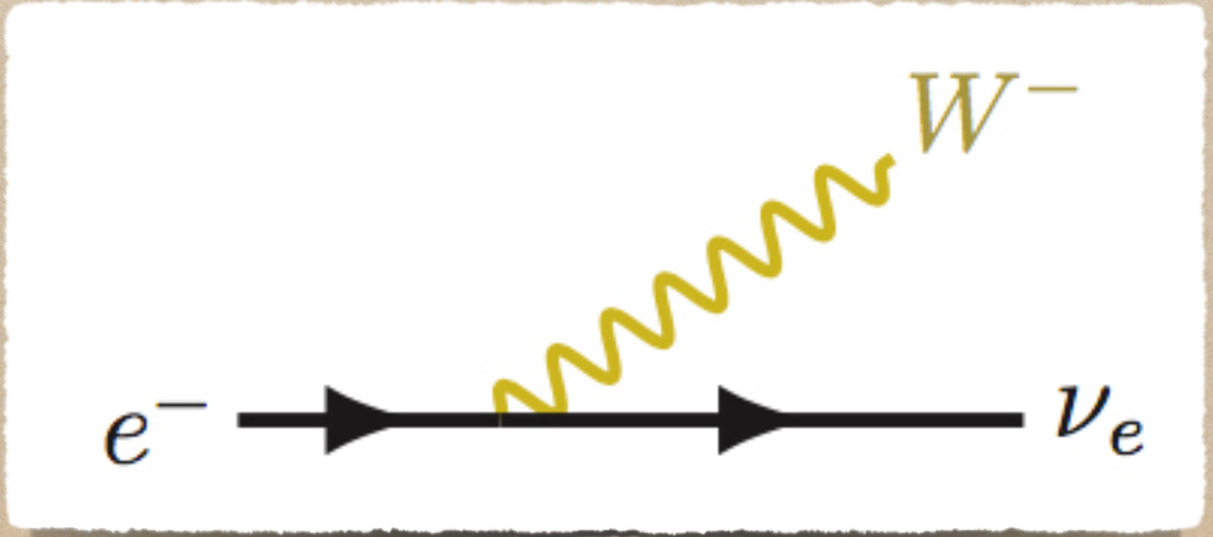
- Photons only interact with **charged** particles
- Electromagnetic charge is **always** conserved

Exercises:

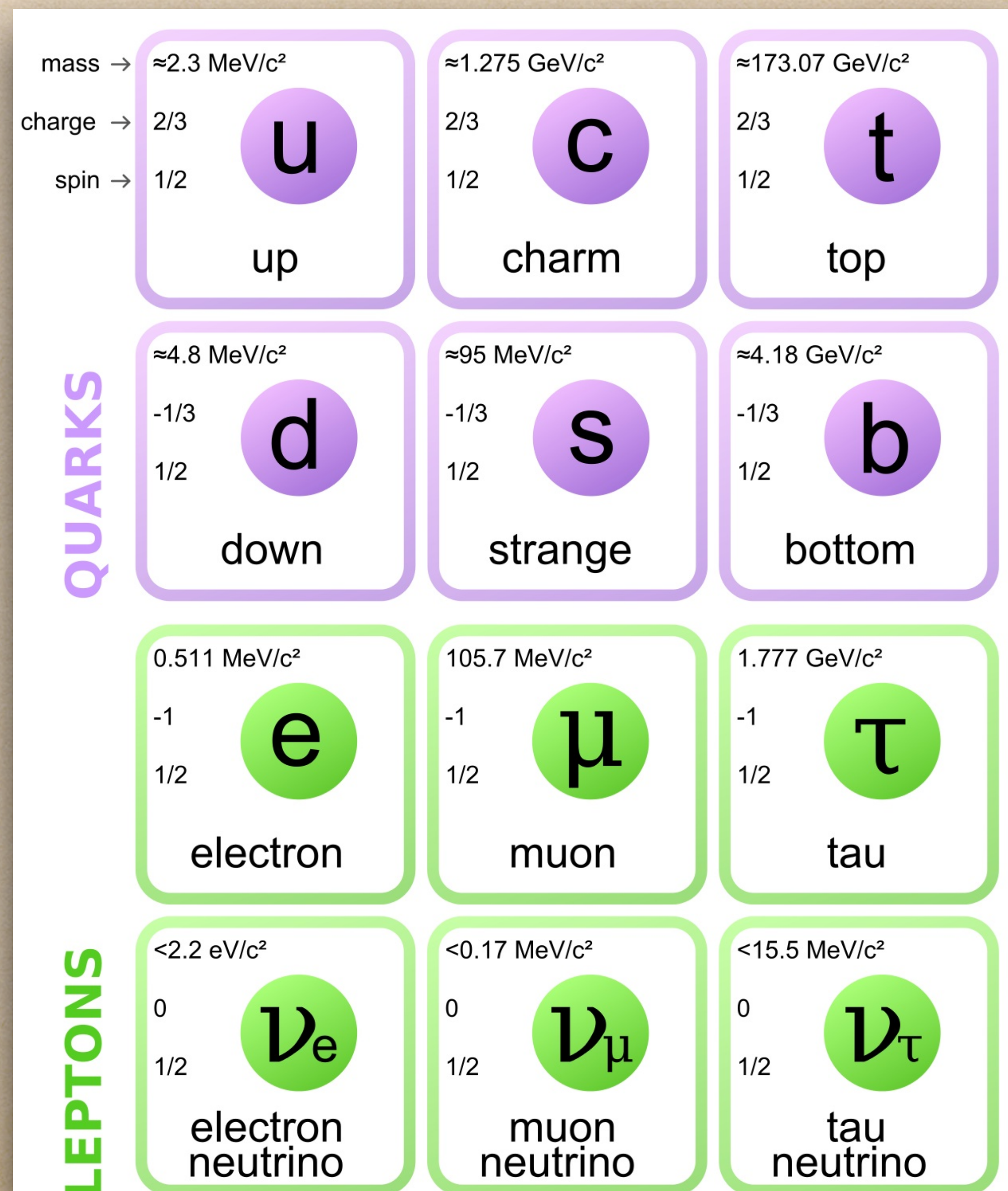
- $e^-e^- \longrightarrow e^-e^-$
- $e^-e^+ \longrightarrow \mu^-\mu^+$
- $e^-e^+ \longrightarrow e^-e^+$
- $\pi^0 \longrightarrow \gamma\gamma$
- $\gamma \longrightarrow e^-e^+ \longrightarrow \gamma$

# Weak Interactions

- The weak interaction is carried by $Z^0$, $W^+$, $W^-$
- The weak interaction is special because it's the only interaction that changes particle types



# The Standard Model



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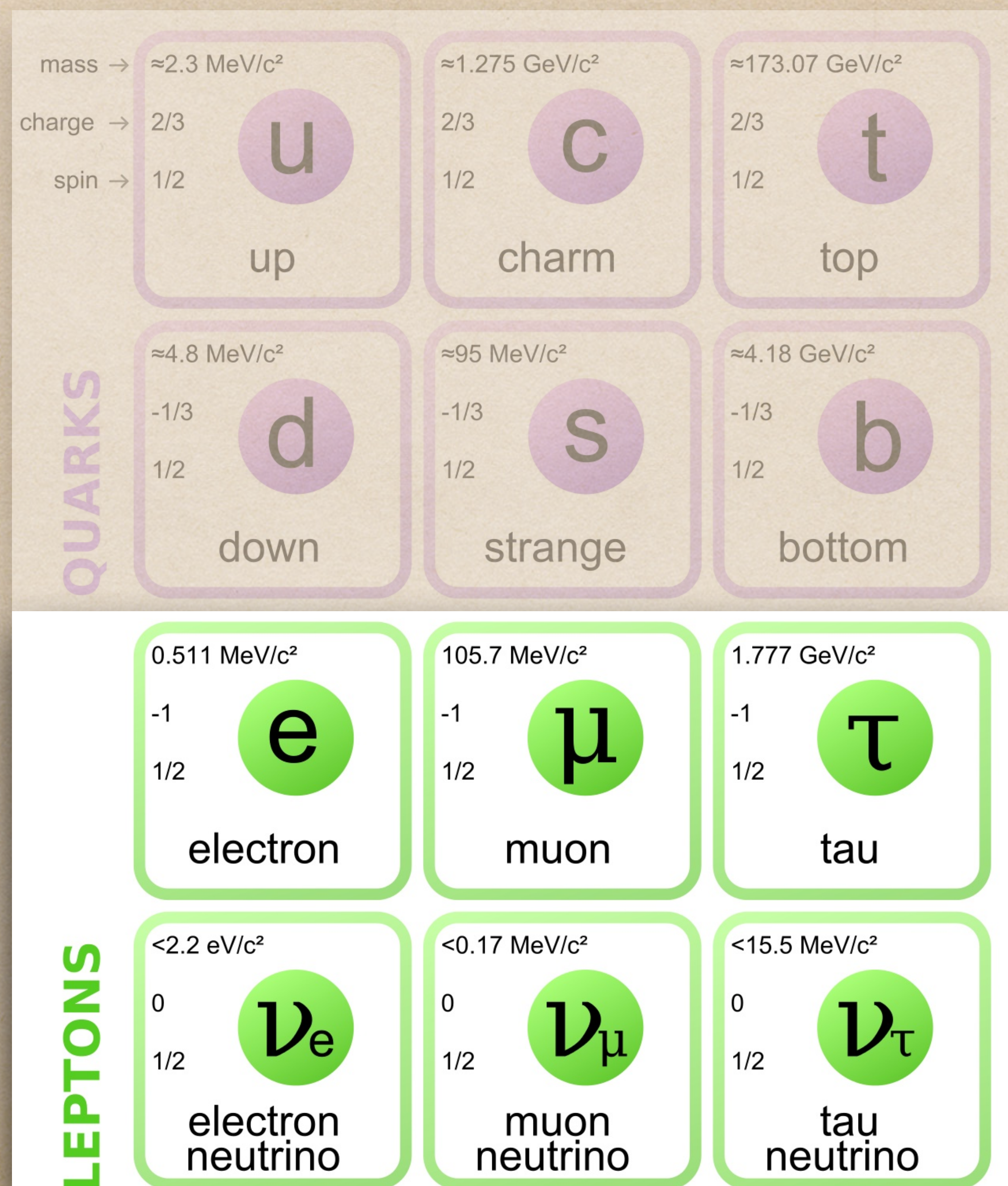

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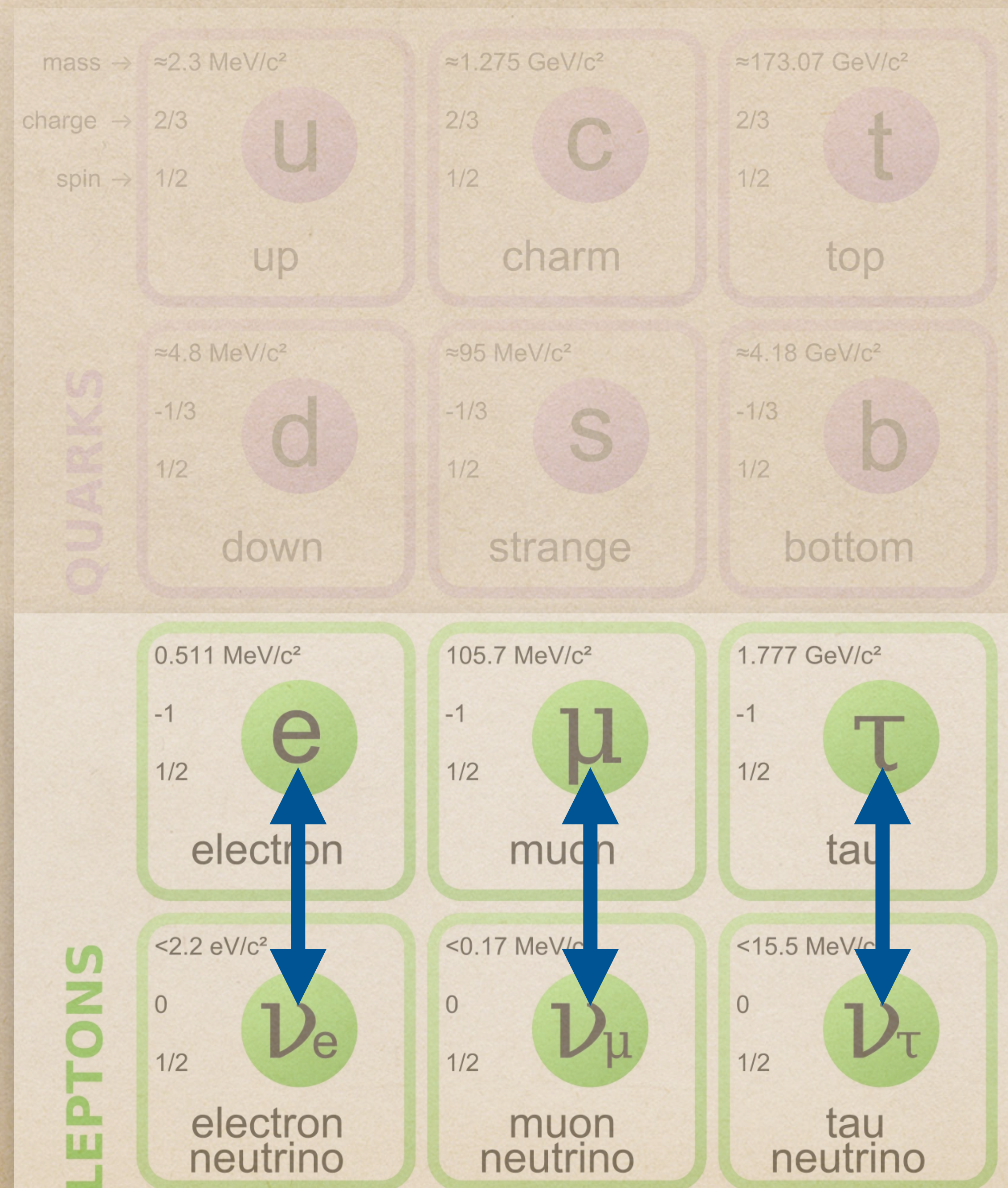
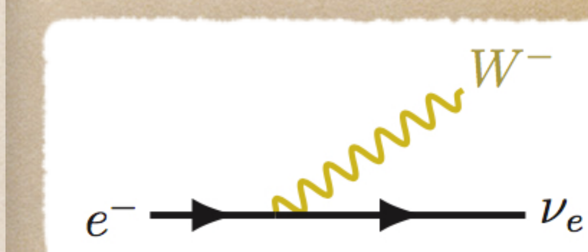



**W+**
**W-**



# Leptons

- The lepton number of a system is the total number of leptons minus the total number of anti-leptons. Lepton number is always conserved, **even per lepton family**!

- Exercise:

$\mu^- \longrightarrow e^- + \ldots$

$\mu^- \longrightarrow e^- + e^+ + e^-$

$0 \neq 1 - 1 + 1$ NOK

$1 \neq 0 + 0 + 0$ NOK

$1 = 1 - 1 + 1$ OK

# Leptons

- The lepton number of a system is the total number of leptons minus the total number of anti-leptons. Lepton number is always conserved, even per lepton family!

- Exercise:

$\mu^- \longrightarrow e^- + \overline{\nu_e} + \nu_\mu$

| | |
|---|---|
| $L_e$: | $0 = 1 - 1 + 0$ OK |
| $L_\mu$: | $1 = 0 + 0 + 1$ OK |
| $L$ : | $1 = 1 - 1 + 1$ OK |

$\mu^- \longrightarrow e^- + e^+ + e^-$

| | |
|---|---|
| $L_e$: | $0 \neq 1 - 1 + 1$ NOK |
| $L_\mu$: | $1 \neq 0 + 0 + 0$ NOK |
| $L$ : | $1 = 1 - 1 + 1$ OK |

# Quarks

- Number of baryons (3 quarks) is conserved

$n \rightarrow p + e^- + \overline{\nu_e}$

B: 1 = 1 + 0 + 0 OK

$p^+ \rightarrow \pi^+ + \pi^0$

B: 1 = 0 + 0 NOK

- Number of mesons ($q + \bar{q}$) is not conserved

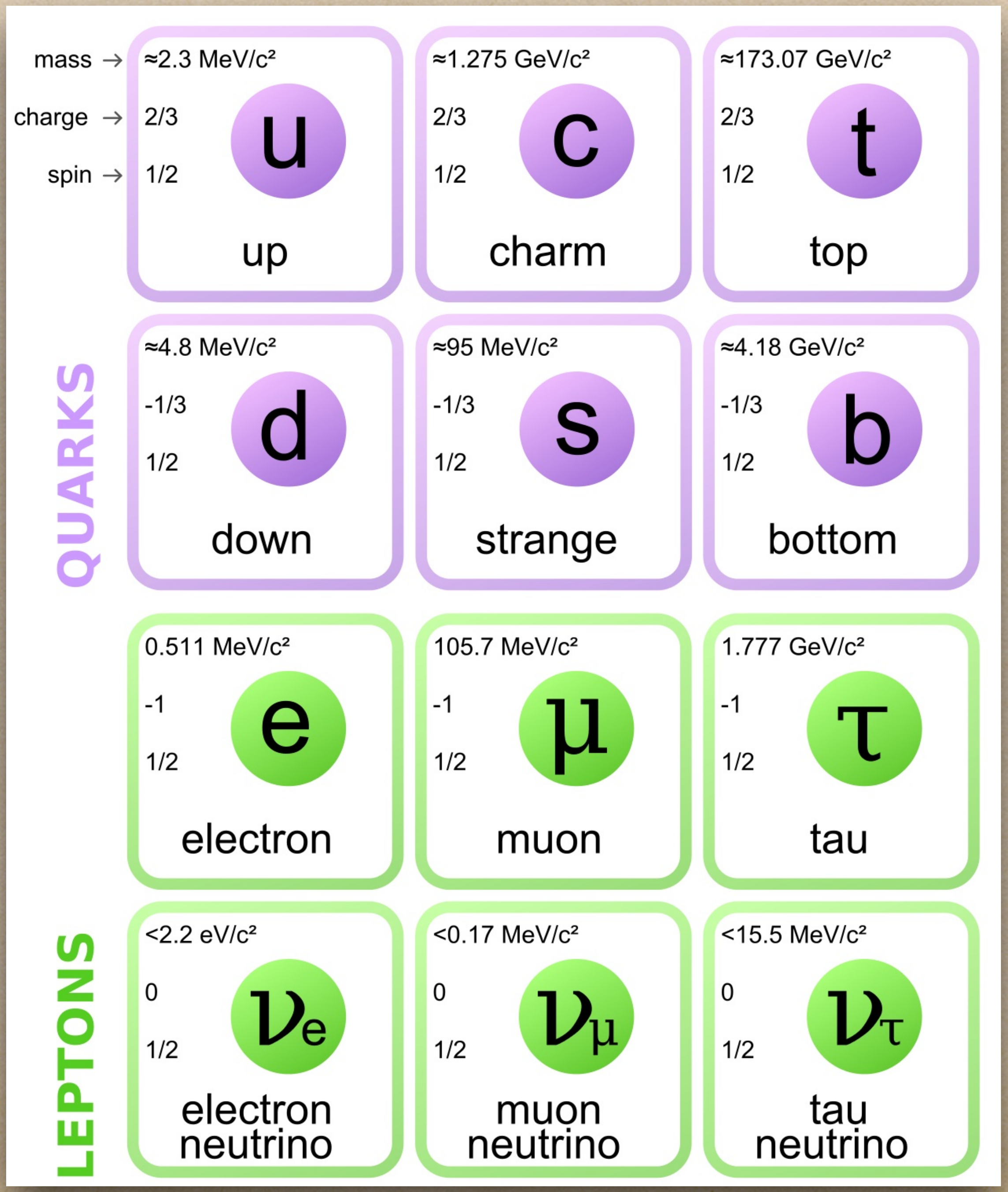
Exercise:

- $pp \rightarrow \Delta^{++} \overline{\Delta^0}$ ... (add missing + draw diagram)

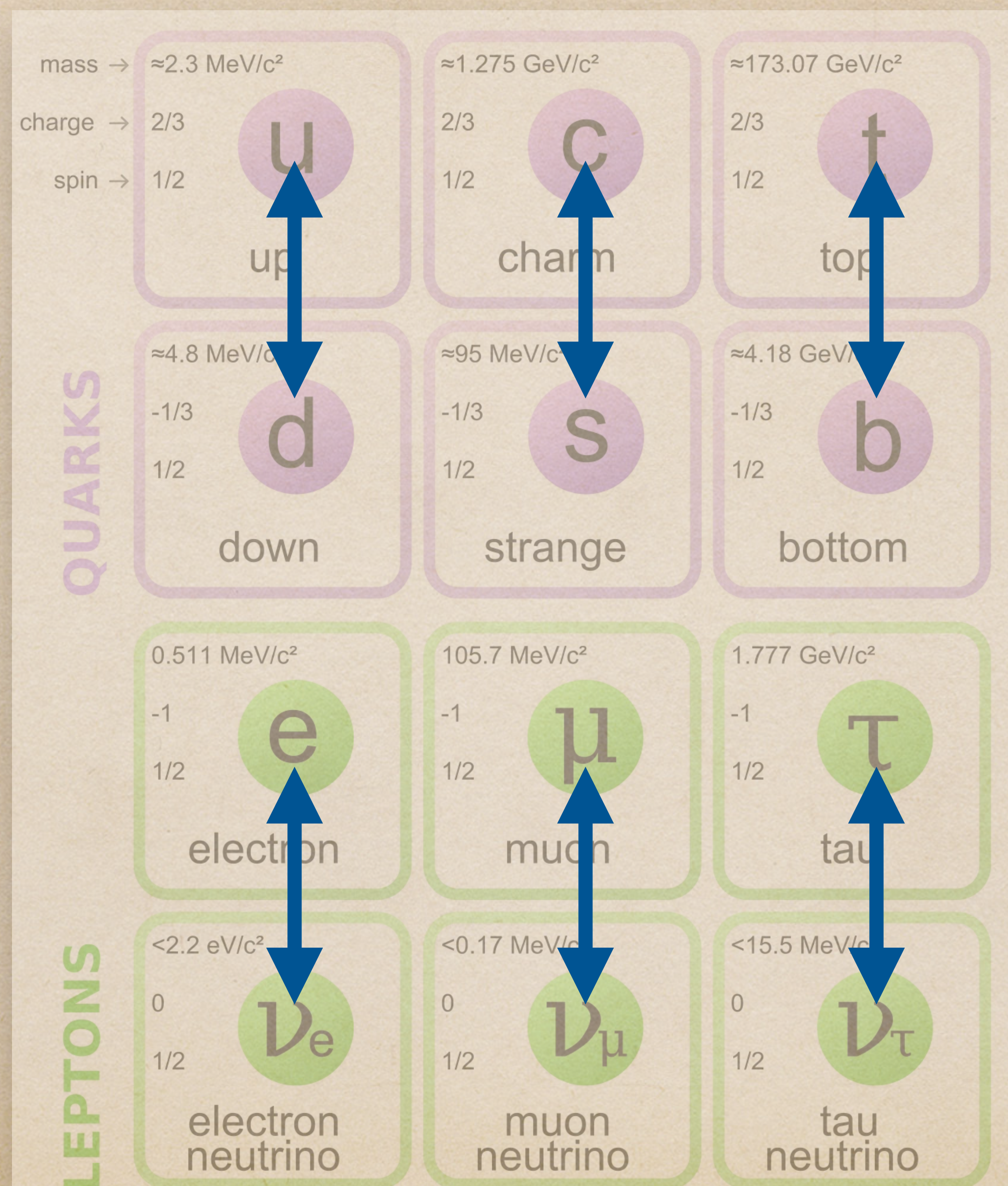
# Quarks

- In the weak interaction, quarks behave different than leptons, as they can **mix** between each other

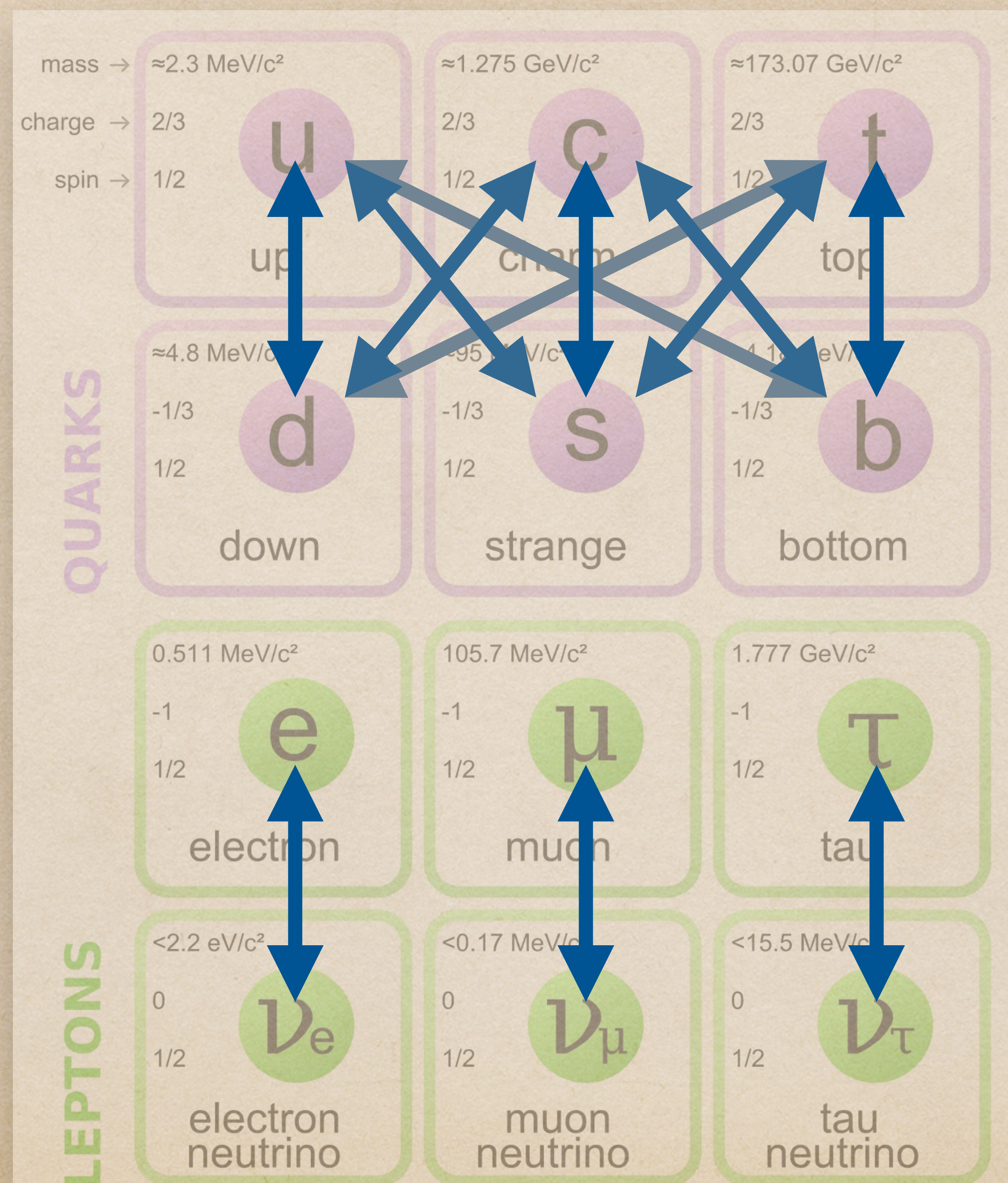
# The Standard Model



# The Standard Model



# The Standard Model



# Let's Try

**Exercise:**

- $n \longrightarrow p\ e^-$ … (add missing + draw diagram)
- $\pi^+ \longrightarrow \mu^+$ … (add missing + draw diagram)
- $K^- \longrightarrow \pi^-$ … (add missing + draw diagram)
- $Z^0 \longrightarrow \gamma\gamma$ (draw diagram, be careful!)
- $K^0 \longrightarrow$ … $\longrightarrow \gamma\gamma$ (add missing + draw diagram)

# Weak Bosons

- Weak bosons can interact with themselves (like gluons), as long as charge is conserved
  - Diagram with $W^+W^-Z^0$ (try)
  - Diagram with $W^+W^-Z^0\gamma$ (try)
- LEP100 vs LEP200

# Exercises

- Draw Feynman diagrams for the following processes using the weak interaction:

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\Lambda \to p + e^- + \bar{\nu}_e$$

$$K^0 \to \pi^+ + \pi^-$$

$$\pi^+ \to \pi^0 + e^+ + \nu_e$$

- Draw Feynman diagrams for the following processes using the strong interaction:

$$\omega^0 \to \pi^+ + \pi^- + \pi^0$$

$$\rho^0 \to \pi^+ + \pi^-$$

$$\Delta^{++} \to p + \pi^+$$

# Order in the Particle Zoo

# Spin

## Wikipedia:

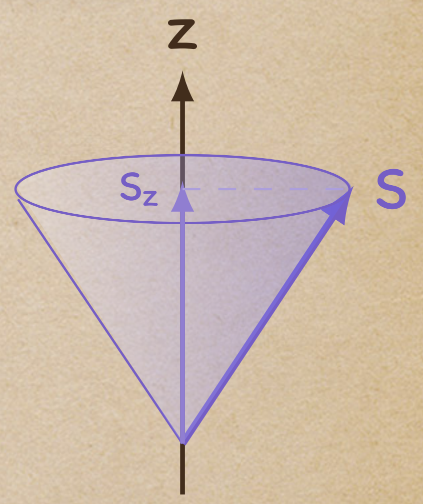
"In quantum mechanics and particle physics, spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (hadrons), and atomic nuclei.

In some ways, spin is like a vector quantity; it has a definite magnitude, and it has a 'direction' (but quantisation makes this 'direction' different from the direction of an ordinary vector).

All elementary particles of a given kind have the same magnitude of spin angular momentum, which is indicated by assigning the particle a spin quantum number."

# Spin

- Spin is a vector, however, due to uncertainty in quantum mechanics, we cannot know all three components $S_x$, $S_y$, and $S_z$ at the same time




- But we can know the length S and the z-component $S_z$ simultaneously

- But spin is a quantum vector, which puts some restrictions on its possible values, as they are quantised (which means values go in steps)..

# Spin

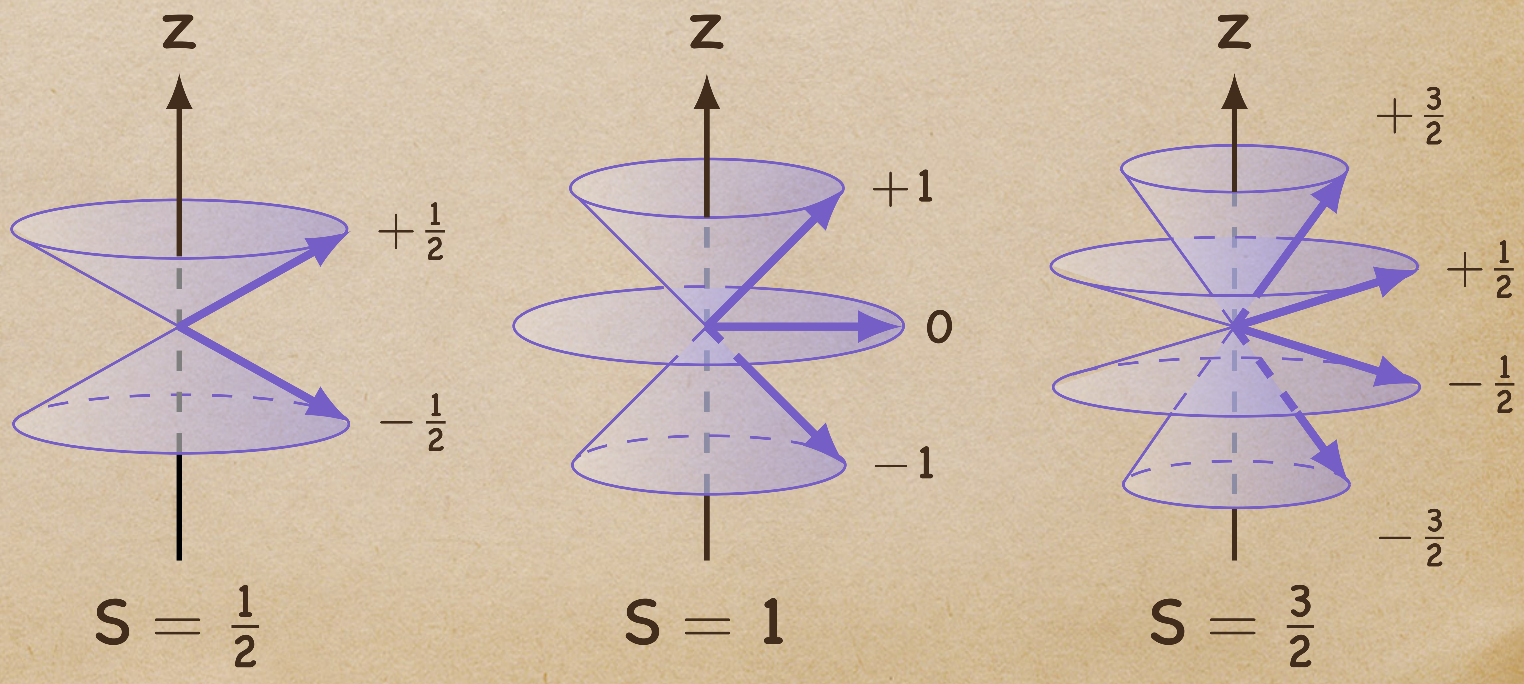
- The length needs to be a positive multiple of 1/2, so $S = 0, 1/2, 1, 3/2, \ldots$

- $S_z$ can be anything between $-S, -S+1, \ldots, S-1, S$
  This means that spin states come in multiplets.

$S = 0 \rightarrow S_z = 0$

$S = 1/2 \rightarrow S_z = -1/2, +1/2$

$S = 1 \rightarrow S_z = -1, 0, +1$



# Spin

- Typical example is the electron: it has spin 1/2, which means it has two possible states:

  -1/2 or +1/2

  also known as ‘up’ or ‘down’

- Now back to elementary particles..

# Elementary Particles

- Three types:
  - Fermions: matter particles => spin 1/2
  - Bosons: force carriers => spin 1
  - Higgs: special guy => spin 0

# Baryons

- So, using only u and d quarks, we can make a proton (uud) or a neutron (udd), but also two other particles which have the same quarks but different spin:
  - $\Delta^{+}$: uud but spin 3/2
  - $\Delta^{0}$: udd but spin 3/2

- We can even make two more combinations:
  - $\Delta^{++}$: uuu (spin 3/2)
  - $\Delta^{-}$: ddd (spin 3/2)

# Baryons

- The other quarks are way heavier than u and d:

  $m_s = 20\ m_d = 40\ m_u\ ,\ m_c = 250\ m_d = 500\ m_u$

  which means that the resulting baryons will be much heavier as well

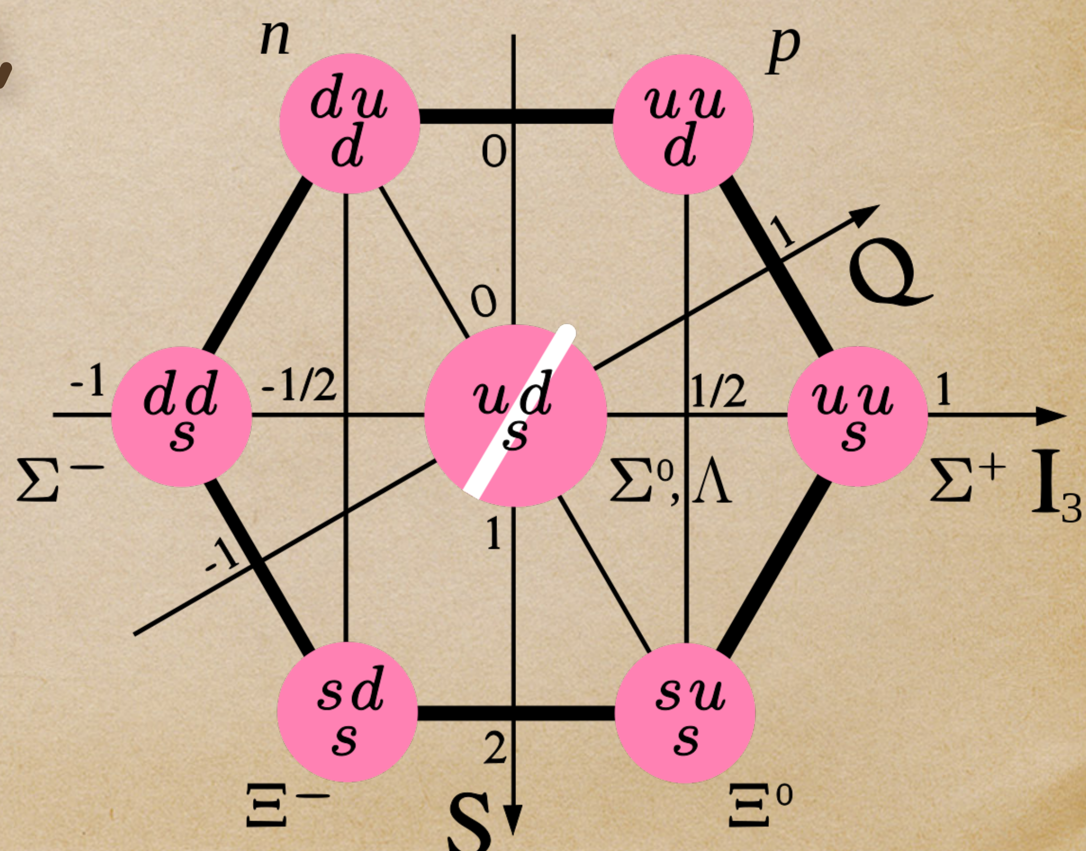
- Before quarks were discovered, only hadrons built from u, d, and s quarks were found. Some were acting 'normal', like a proton, but some were acting 'strange' (because - we know now - they contain an s quark). They were given a Strangeness

# Baryons

- We know today that a hadron with Strangeness -1 contains exactly one s quark (similarly, Strangeness -2 implies two s quarks etc).

- The simplest spin 1/2 baryons can be organised in an octet, called "The eightfold way"

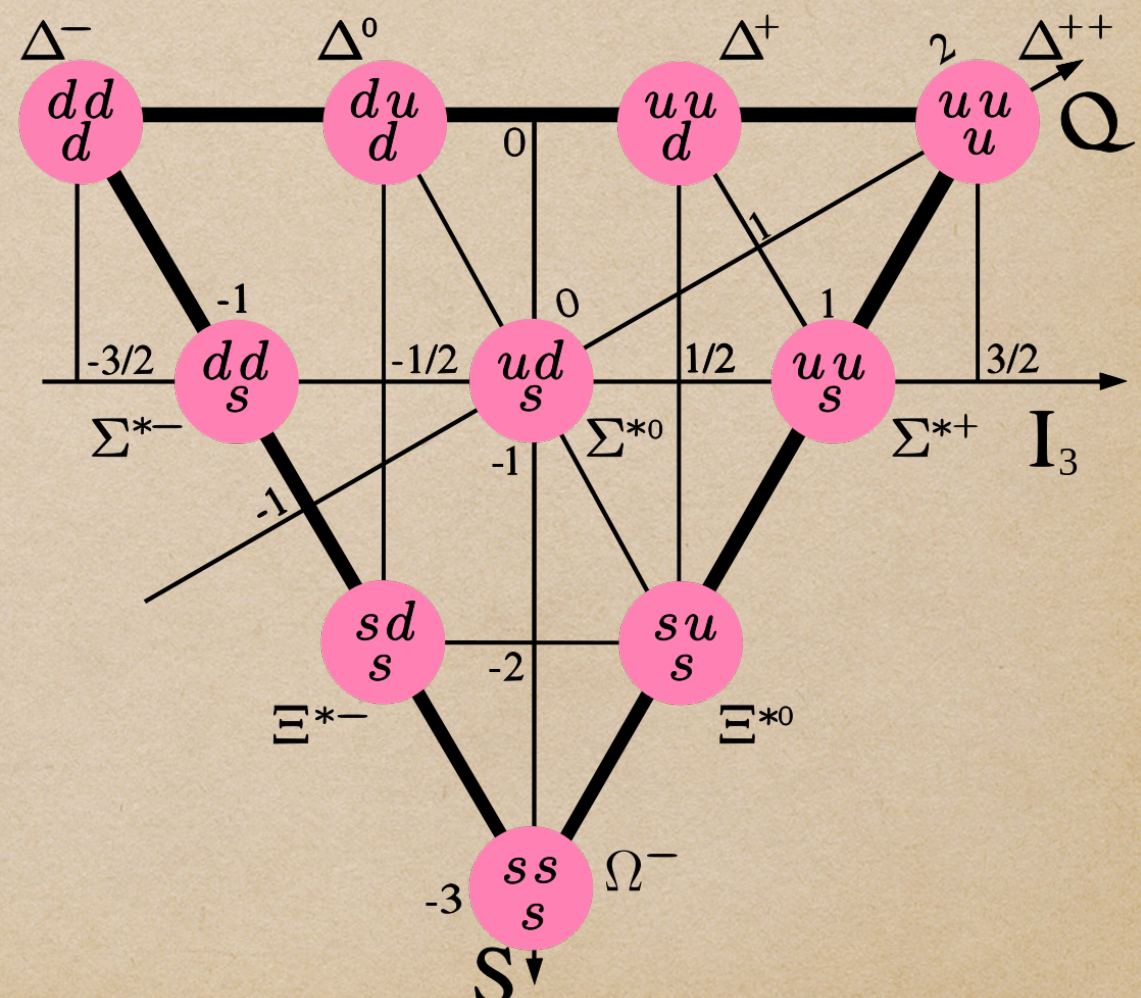
- Strangeness 0: n, p
  Strangeness -1: Σ, Λ
  Strangeness -2: Ξ



# Baryons

- Similarly, the simplest spin 3/2 baryons can be organised in a decuplet

- Strangeness 0: Δ
  Strangeness -1: Σ*
  Strangeness -2: Ξ*
  Strangeness -3: Ω



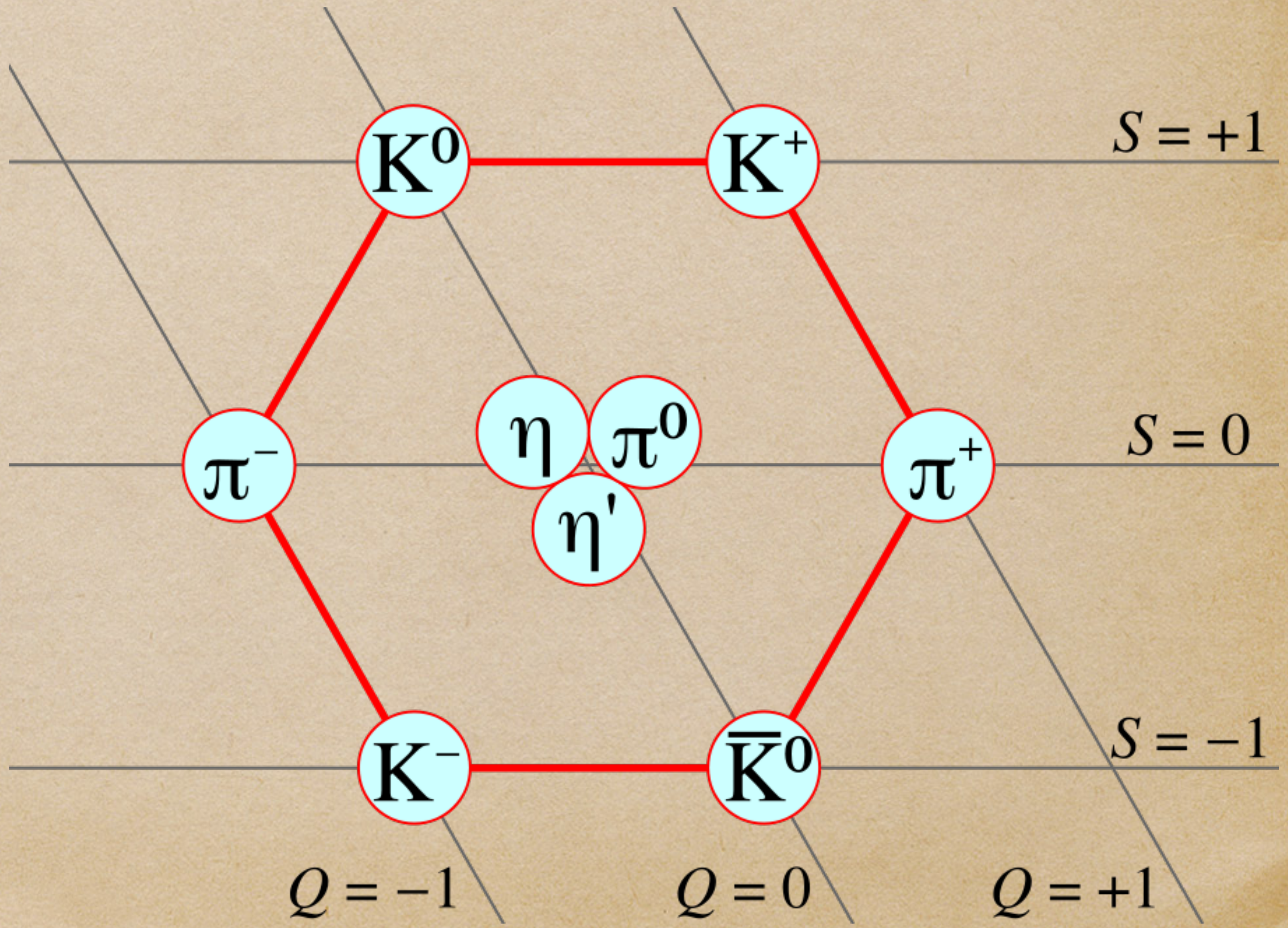
# Mesons

- Mesons are built from a quark and an antiquark, and hence lighter dan baryons.
- As they are built from two quarks, their spin is 1/2 + 1/2 = 0 or 1.
- They are classified similarly to baryons, in function of their Strangeness.

# Mesons

- The simplest spin 0 mesons can be organised in a nonet, originally called "The eightfold way" as well (because η′ wasn't found yet)

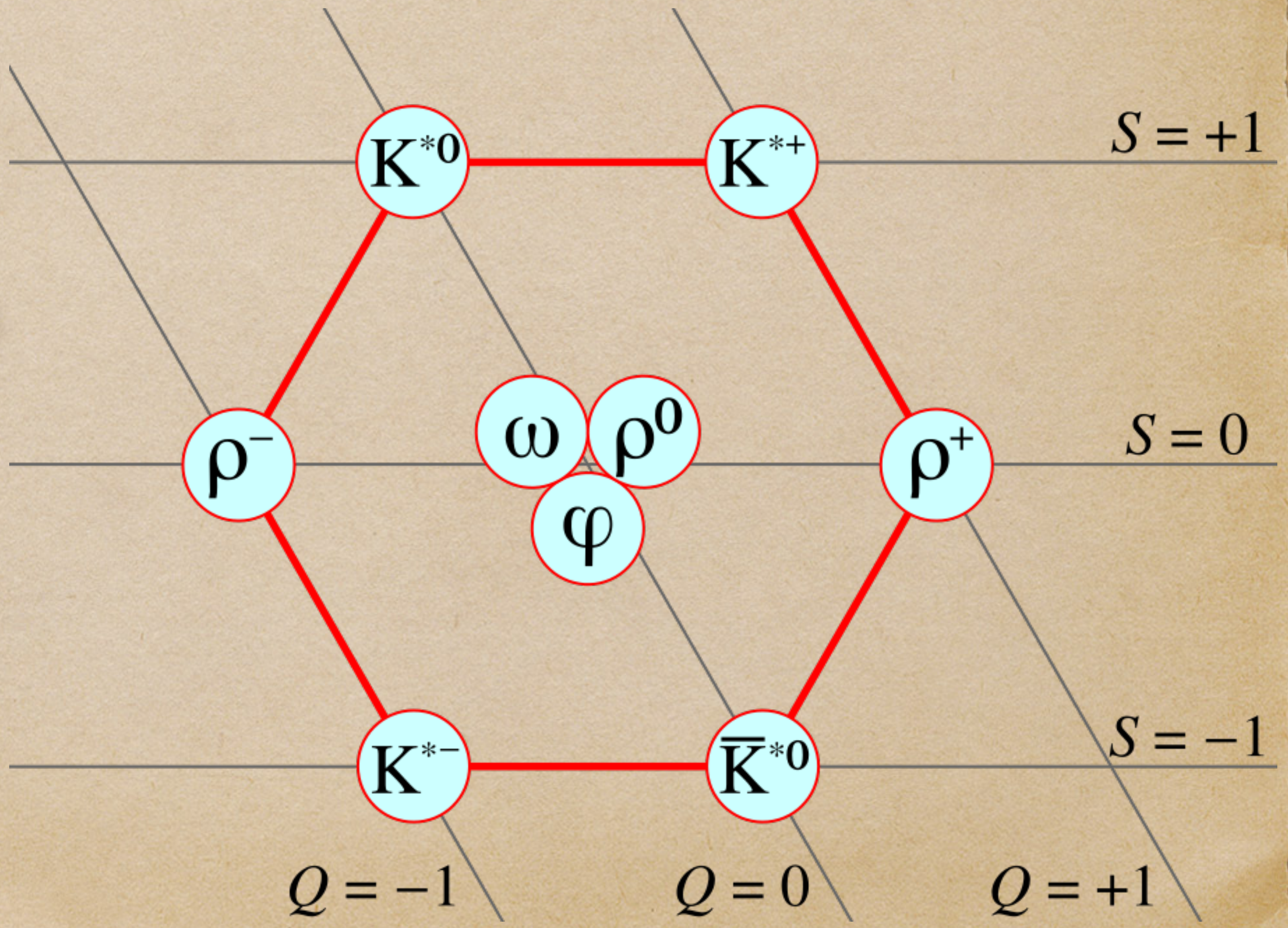
- Strangeness +1: K
  Strangeness 0: π, η, η′
  Strangeness -1: K



# Mesons

- And the simplest spin 1 mesons can be organised in another **nonet**

- Strangeness +1: $K^*$
  Strangeness 0: $\rho$, $\omega$, $\varphi$
  Strangeness -1: $K^*$



# Recap: Conservation Laws

# Conservation Laws

- Conservation laws are an important concept in quantum physics. They tell us that a certain quantity is conserved
- This means that its values before and after an interaction have to be the same
- For example EM charge is conserved. Not for each particle separately, but the sum of all particles' charges before an interaction has to equal the sum of all particles' charges after that interaction

# Conservation Laws

- Conservation laws help us determine if a certain process can take place or not

- Example: $p + p \rightarrow n + \pi^+ + \pi^- + p$ is forbidden (initial charge is 2, final charge is 1)

- Certain laws are exact: it is believed that they always hold. Others are approximately exact (they hold in say 99% of cases), or are valid under certain conditions only (for example only when the process is without the weak force)

# Conservation Laws

- Conservation of 4-momentum
- Conservation of charges (EM, weak, colour)
- Conservation of baryon number
- Conservation of lepton number (total & individual)
- Conservation of flavour
- ……

# Mass

- Important for decays (where one particle transforms into several). In rest frame of initial particle: mass of initial particle equals sum of energies of final particles. This gives the following condition:

$$m_{initial} \geq \sum m_{final}$$

- Probability of decay becomes larger, the larger the mass difference!

# Charge Conservation

- All charges are always 100% conserved!
- Conservation of electromagnetic charge is extremely important and an easy check of process validity
- Conservation of colour charge is automatically satisfied as long as quarks are combined correctly
- Conservation of weak charge is more complex to check, use rules of weak interaction

# Weak interaction?

- Weak interaction changes flavour

- This means between one family:

  $e^- \leftrightarrow \nu_e$ u <-> d etc

- Charge is not the same => need other particles to correct this

- Quarks can show mixing between families:

  u <-> s or u <-> b

  but probability is rather small

  No mixing between leptons!

# Weak interaction?

- No other interaction can change flavour, so if we see a flavour change in a certain process, we know that this process is governed by the weak force
- We say that all interactions except the weak conserve flavour

# Summary

- In decays, the sum of masses of final products cannot be larger than the initial mass
- EM charge is conserved
- Baryon number is conserved
- Lepton number is conserved (total & individual)
- Flavour is conserved unless the process is weak
- Antiparticles have opposite numbers and charges

# Exercises

- **Determine if the following processes are possible, and if yes, with which interaction:**

$$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0 + \pi^+ + \pi^-$$

$$p + K^- \rightarrow \Sigma^+ + \pi^- + \pi^+ + \pi^- + \pi^0$$

$$p \rightarrow \Lambda^0 + \bar{\Sigma}^0 + \pi^+$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

$$\bar{\nu}_e + p \rightarrow e^+ + \Lambda^0 + K^0$$

$$\Sigma^0 \rightarrow \Lambda^0 + \gamma$$

# The Higgs Boson

# Production

Higgs boson production at LEP

- Direct production
- Higgs strahlung

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# Production

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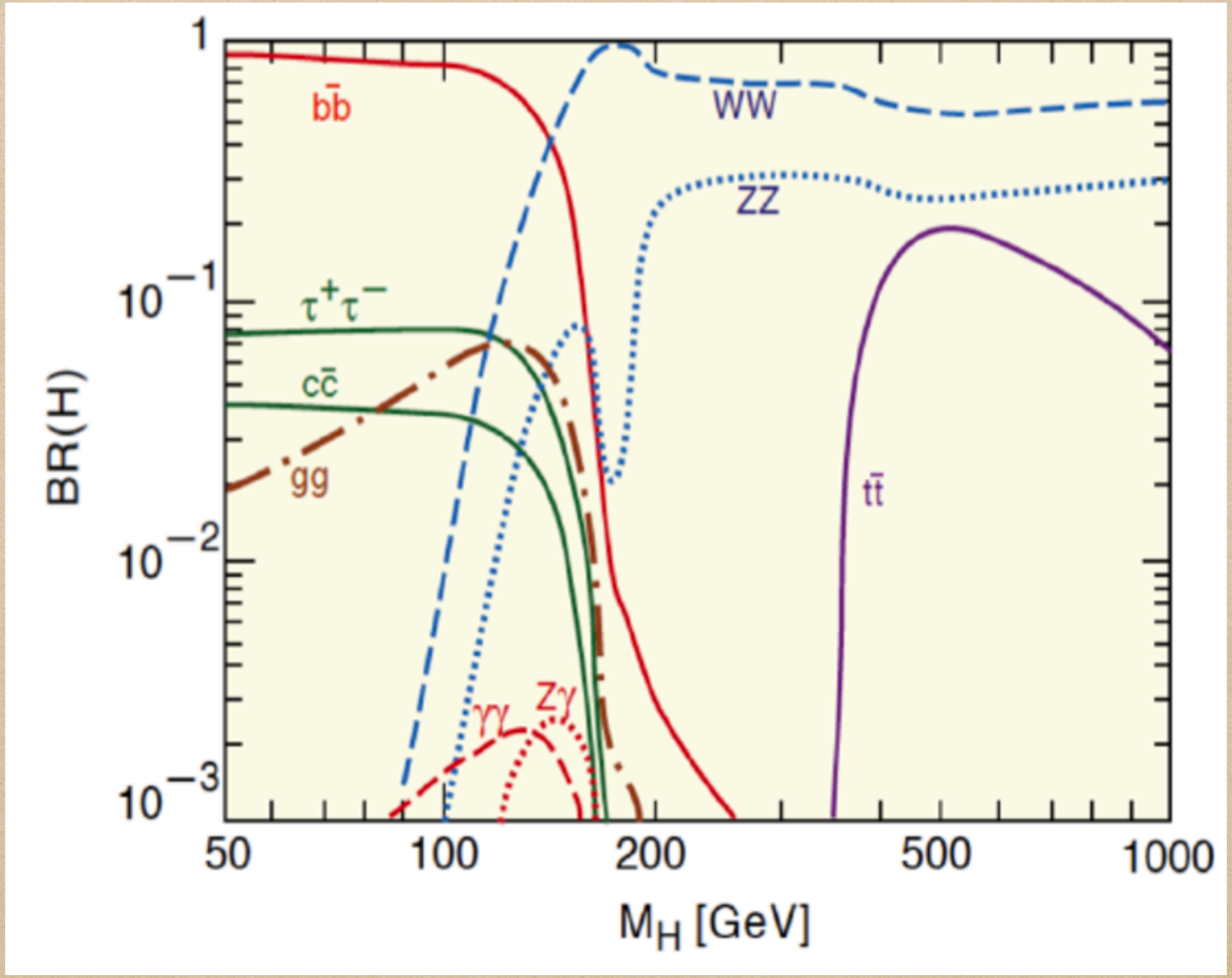
Higgs boson production at LEP

- Direct production
- Higgs strahlung

Higgs boson production at LHC

- Gluon fusion
- Vector boson fusion
- Higgs strahlung
- Associated tt production

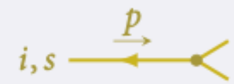
# Decay


BR(H)
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
50
100
200
500
1000
$M_H$ [GeV]
$b\bar{b}$
WW
ZZ
$t\bar{t}$
$\tau^+\tau^-$
$c\bar{c}$
gg
$\gamma\gamma$
$Z\gamma$

# Feynman Rules


$= u_i^s(p)$ (initial)


$= \bar{u}_i^s(p)$ (final)

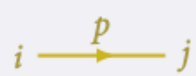



$= \bar{v}_i^s(p)$ (initial)


$= v_i^s(p)$ (final)


$= \varepsilon_\mu^a(k)$ (initial)


$= \bar{\varepsilon}_\mu^a(k)$ (final)




$$= \mathrm{i}\,\delta^{ij}\,\frac{\not{p}+m}{p^2-m^2+\mathrm{i}\epsilon}$$

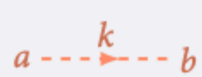

$$= \delta^{ij}\,\delta^+(p^2-m^2)\,(\not{p}+m)$$


$$\overset{\text{Lorentz}}{=} \frac{-\mathrm{i}\,\delta^{ab}}{k^2+\mathrm{i}\varepsilon}\left[g^{\mu\nu}-(1-\xi)\,\frac{k^\mu k^\nu}{k^2}\right]$$

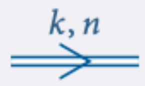

$$\overset{\text{LC}}{=} \frac{-\mathrm{i}\,\delta^{ab}}{k^2+\mathrm{i}\varepsilon}\left[g^{\mu\nu}-2\frac{k_{(\mu}n_{\nu)}}{k\cdot n}+\xi\frac{k^2\,k_\mu k_\nu}{(k\cdot n)^2}\right]$$


$$\overset{\text{Lorentz}}{=} -\delta^{ab}\,\delta^+(k^2)\,g^{\mu\nu}$$

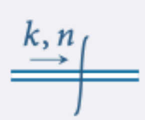

$$\overset{\text{LC}}{=} -\delta^{ab}\,\delta^+(k^2)\left(g^{\mu\nu}-2\frac{k_{(\mu}n_{\nu)}}{k\cdot n}\right)$$




$$= \frac{\mathrm{i}\,\delta^{ab}}{k^2+\mathrm{i}\varepsilon}$$ (only Lorentz gauges)

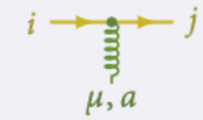



$$= \frac{\mathrm{i}}{n\cdot k+\mathrm{i}\eta}$$

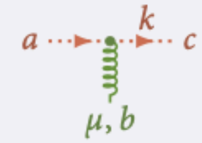



$$= \delta(n\cdot k+\mathrm{i}\eta)$$

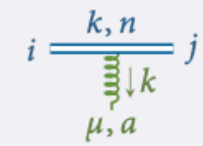

$$= \mathrm{i}\,g_{\mathrm{EM}}\,\mu_{\mathrm{EM}}^{\epsilon}\,\gamma^\mu\,\delta_{ij}$$




$$= \mathrm{i}g\mu^\epsilon\,\gamma^\mu\,(t^a)_{ji} \qquad \text{(A.99q)}$$

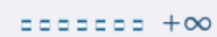



$$= g\mu^\epsilon f^{abc}\,k^\mu \quad \text{(only Lorentz gauges)} \qquad \text{(A.99r)}$$



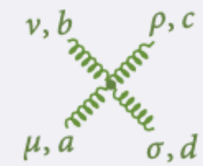

$$= \mathrm{i}g\mu^\epsilon\,n^\mu\,(t^a)_{ji} \qquad \text{(A.99s)}$$


$$= e^{\mathrm{i}r\cdot k} \qquad \text{(A.99t)}$$




$= 1$ (no momentum flow) (A.99u)


$$= g\mu^\epsilon f^{abc}\left[g^{\mu\nu}(k-p)^\rho+g^{\nu\rho}(p-q)^\mu + g^{\rho\mu}(q-k)^\nu\right] \qquad \text{(A.99v)}$$




$$= -\mathrm{i}g^2\mu^{2\epsilon}\left[f^{abx}f^{xcd}\,(g^{\mu\rho}g^{\nu\sigma}-g^{\mu\sigma}g^{\nu\rho}) - f^{acx}f^{xbd}\,(g^{\mu\sigma}g^{\nu\rho}-g^{\mu\nu}g^{\rho\sigma}) + f^{adx}f^{xbc}\,(g^{\mu\nu}g^{\rho\sigma}-g^{\mu\rho}g^{\nu\sigma})\right] \qquad \text{(A.99w)}$$

Furthermore:

A. Momentum conservation is imposed at every vertex.

B. Loop momenta have to be integrated with an additional factor $1/(2\pi)^4$.

C. Fermion loops (hence ghost loops as well) add an additional factor -1.

D. All Feynman rules are complex conjugated when on the right side of a final-state cut. Additionally, the 3-gluon vertex and the ghost vertex change sign if on the right side of a final-state cut.

E. The final result has to be divided by the symmetry factor of the diagram. For a cut diagram: multiply with a symmetry factor for each side.

F. For each set of $k$ indistinguishable particles in the final state, divide by $k!$.

G. Impose momentum conservation between initial and final states.

H. Divide by the flux factor. It is $4\sqrt{(p_1\cdot p_2)^2-m_1^2m_2^2}$ when there are exactly two incoming particles.

# Symmetries:

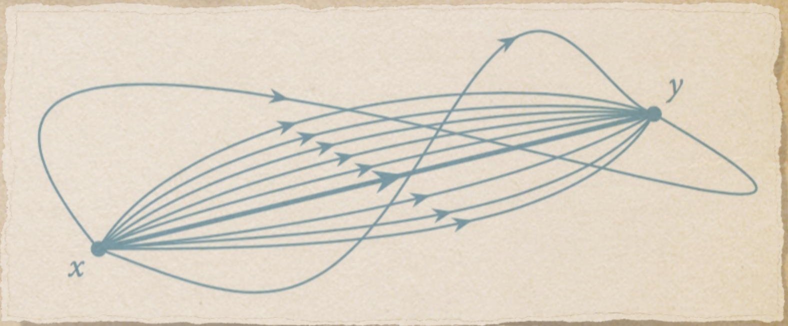
## Building the Lagrangian

# Basics

- basic components are **fields**
    - just mathematical tools
    - will give rise to particles

- principal quantity is the **action**, which is the integral of the Lagrangian:

$$S = \int d^4x \, \mathcal{L}(x, \phi, \partial\phi)$$




- all paths possible (simultaneous), but path with **least action** is favoured
- minimising action leads to **equations of motion**

# Lagrangian?

- is kinetic energy minus potential energy

$$\mathcal{L} = T - V$$

- classical example: spring

$$\mathcal{L} = \frac{1}{2}m\left(\frac{dx}{dt}\right)^2 - \frac{1}{2}kx^2 \quad \Rightarrow \quad x = x_0 \cos\sqrt{\frac{k}{m}}t$$

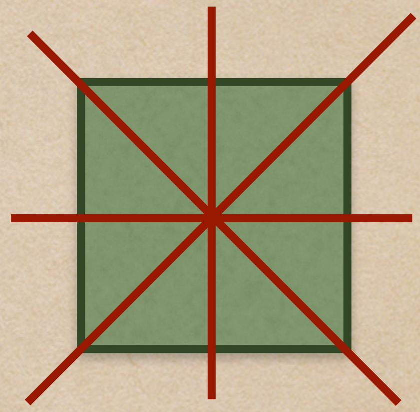
- field example: free electron field

$$\mathcal{L} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi \quad \Rightarrow \quad \left(i\partial\!\!\!/ - m\right)\psi = 0 \quad \text{(QM)}$$

# Lagrangian!

- kinetic terms are quadratic and have derivatives $\bar{\psi}\partial\!\!\!/\psi, \quad \partial_\mu\phi\partial^\mu\phi, \quad \ldots$
- potential terms are what is left
  - special type: mass terms: $m\bar{\psi}\psi, \quad m^2|\phi|^2, \quad \ldots$ quadratic without derivatives
  - others are interaction terms $\bar{\psi}A\!\!\!/\psi, \quad \ldots$

# Symmetries



- leave theory unchanged
- symmetry => conservation

  Emmy Noether

- homogeneity of space

  => translational invariance

  => momentum conservation
- isotropy of space

  => rotational invariance

  => angular momentum conservation

# Symmetries

- in quantum mechanics, $\psi$ is an amplitude
  - not physical
  - $|\psi|^2$ is probability, physical

- phase is undetermined, because we can scale $\psi \to e^{i\alpha}\psi$, then $\bar{\psi} \to e^{-i\alpha}\bar{\psi}$, such that $|\psi|^2 \to |\psi|^2$

=> invariant!

# Symmetries

- similar in quantum field theories:

$$i\bar{\psi}\partial\!\!\!/\psi \rightarrow i\bar{\psi}\partial\!\!\!/\psi \qquad m\bar{\psi}\psi \rightarrow m\bar{\psi}\psi$$

in other words $\mathcal{L} = \mathcal{L}'$

- free electron field

=> conservation of electric charge

- BUT... phase $\alpha$ can depend on spacetime coordinates: $\alpha = \alpha(x)$

$$i\bar{\psi}\partial\!\!\!/\psi \rightarrow i\bar{\psi}\partial\!\!\!/\psi - \bar{\psi}(\partial\!\!\!/\alpha)\psi \qquad \mathcal{L}' = \mathcal{L} - \bar{\psi}(\partial\!\!\!/\alpha)\psi$$

=> no longer invariant!

# Lagrangian

- add term $g\bar{\psi}\not{A}\psi$ to the Lagrangian
  - with property $A_\mu \rightarrow A_\mu + {}^1/_g\, \partial_\mu a$
  - because then $g\bar{\psi}\not{A}\psi \rightarrow g\bar{\psi}\not{A}\psi + \bar{\psi}(\not{\partial} a)\psi$
  - invariant !

- but new field also needs kinetic terms
  - symmetry => conserved tensor:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

  - its square will be kinetic term:

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

# QED:

## From the Lagrangian to a full theory

# QED

**Full Lagrangian for Quantum Electro Dynamics:**

$$\mathcal{L}_{QED} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi + g\bar{\psi}A\!\!\!/\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

**electron kinetic term**

**electron mass term**

**electron-photon interaction term**

**photon kinetic term**

# QED

**Full Lagrangian for Quantum Electro Dynamics:**

$$\mathcal{L}_{\mathrm{QED}} = i\bar{\psi}\partial\!\!\!/\psi - m\bar{\psi}\psi + g\bar{\psi}A\!\!\!/\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

**'free' theory**

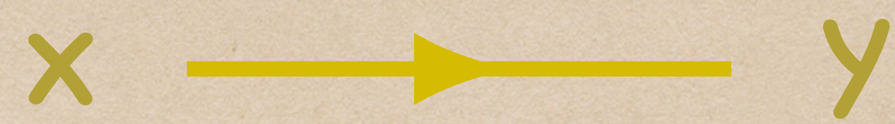
**'interaction' theory**

$$\mathcal{L}_{\mathrm{QED}} = \mathcal{L}_0 + \mathcal{L}_I$$

**Keep $\mathcal{L}_0$ exact, but expand $\mathcal{L}_I$ => perturbation theory**

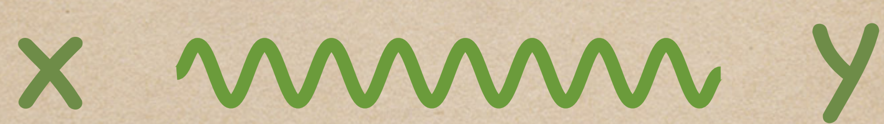
# Free Theory

**Propagation of an electron from x to y:**




$$\langle 0|\psi(y)\bar{\psi}(x)|0\rangle = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \;\; \psi(y)\bar{\psi}(x)\; e^{iS_0}$$

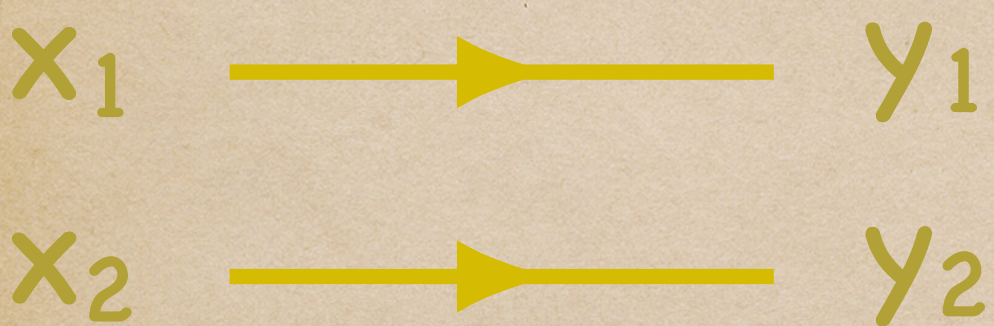
**Propagation of a photon from x to y:**



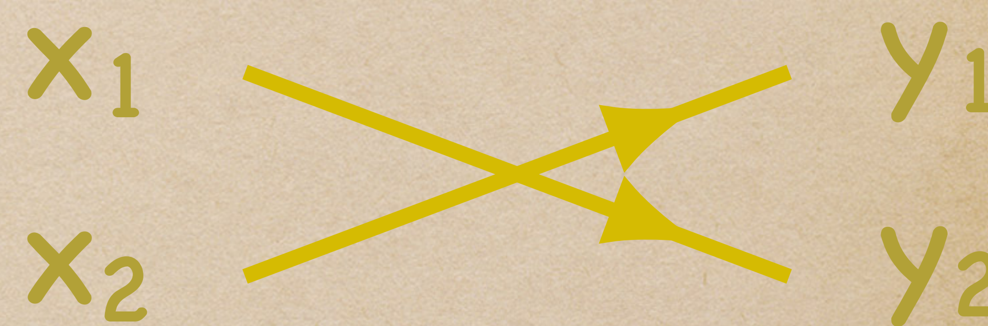

$$\langle 0|A_\mu(x)A_\mu(y)|0\rangle = \int \mathcal{D}A_\mu \;\; A_\mu(x)A_\mu(y)\; e^{iS_0}$$

# Free Theory

**Easily generalised to more points:**




**and**




$$\langle 0|\psi_{y_1}\psi_{y_2}\bar{\psi}_{x_1}\bar{\psi}_{x_2}|0\rangle = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \;\; \psi_{y_1}\psi_{y_2}\bar{\psi}_{x_1}\bar{\psi}_{x_2}\, e^{S_0}$$

# Interaction

- Add interaction part from action (Lagrangian) to the exponential $e^{S_0+S_I}$
- Equations are not solvable anymore

=> expand interaction part:

$$e^{S_I} \approx 1 + S_I + \frac{1}{2}S_I^2 + \ldots$$

- Propagation of electron from x to y is now:

$$\langle \psi(y)\bar{\psi}(x)\rangle = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu\, \psi(y)\bar{\psi}(x)\, e^{S_0}\left(1 + S_I + \frac{1}{2}S_I^2 + \ldots\right)$$

# Interaction

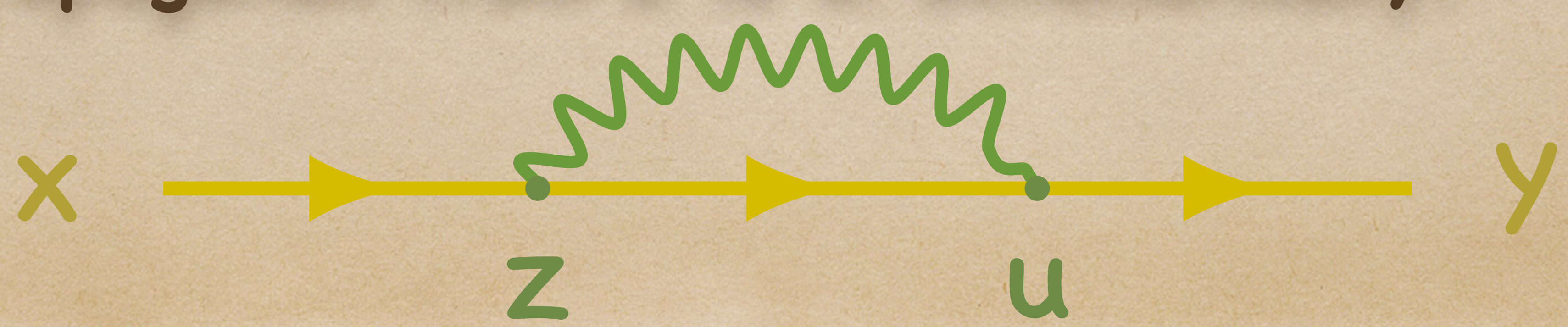
- Propagation of electron from x to y is now:

$$\langle \psi(y)\bar{\psi}(x)\rangle = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A_\mu \, \psi(y)\bar{\psi}(x)\, e^{S_0}\left(1+S_I+\frac{1}{2}S_I^2+\ldots\right)$$

- Take the second order as example:

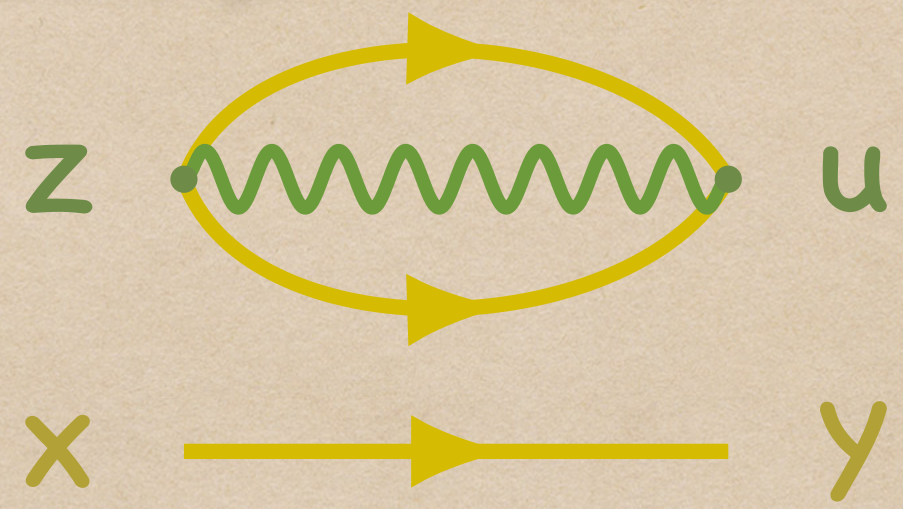
$$S_I^2 = g^2\int dz\, du\, \left(\bar{\psi}\not{A}\psi\right)_z \left(\bar{\psi}\not{A}\psi\right)_u$$

- So we have electron propagation from x to z, from z to u, and from u to y. We also have photon propagation from z to u. Schematically:



# Interaction

- Other possibility:




- Vacuum diagrams

=> These are unwanted and have to be cancelled:

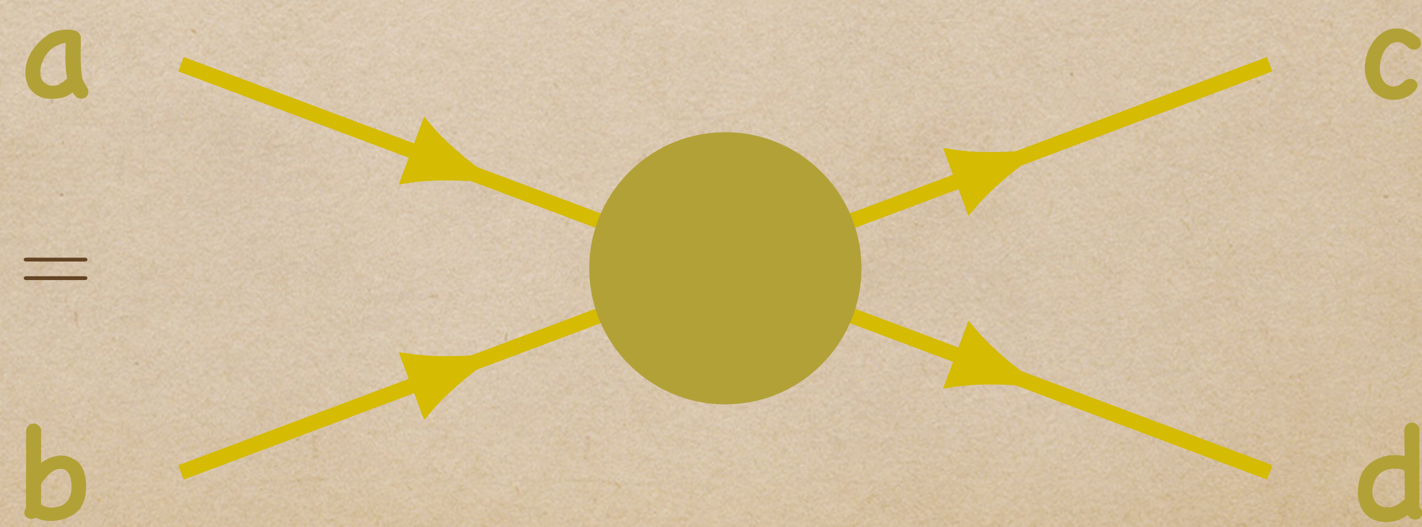
$$\langle \psi(y)\bar{\psi}(x) \rangle = \frac{\int \mathcal{D}\bar{\psi}\mathcal{D}\psi \;\; \psi(y)\bar{\psi}(x)\, e^{S}}{\int \mathcal{D}\bar{\psi}\mathcal{D}\psi \; e^{S}}$$

# Interaction

- So the full propagator is:

- This can be extended to any number of particles, i.e. electron-electron collision:

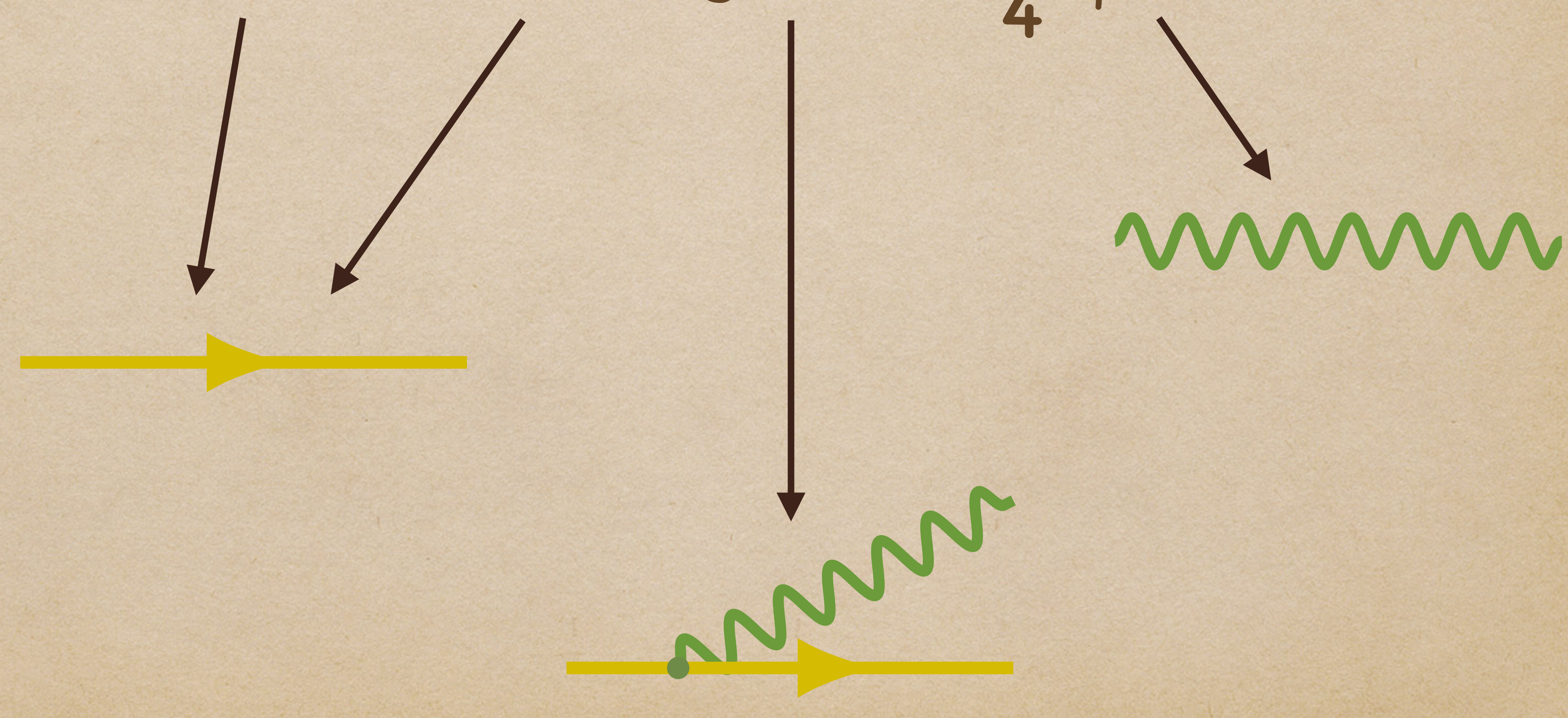
$$\langle \psi_c \psi_d \bar{\psi}_a \bar{\psi}_b \rangle =$$



# Feynman Rules

**Full Lagrangian for Quantum Electro Dynamics:**

$$\mathcal{L}_{QED} = i\bar{\psi}\not{\partial}\psi - m\bar{\psi}\psi + g\bar{\psi}\not{A}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$



# SM:

# The Standard Model of particle physics

# Lagrangian

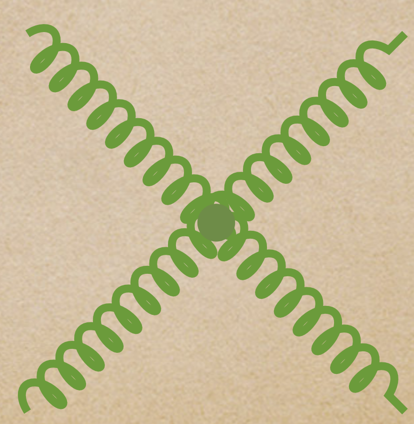
- We can easily extend our theory by adding new parts to our Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QFD}} + \mathcal{L}_{\text{QCD}} + \ldots$$

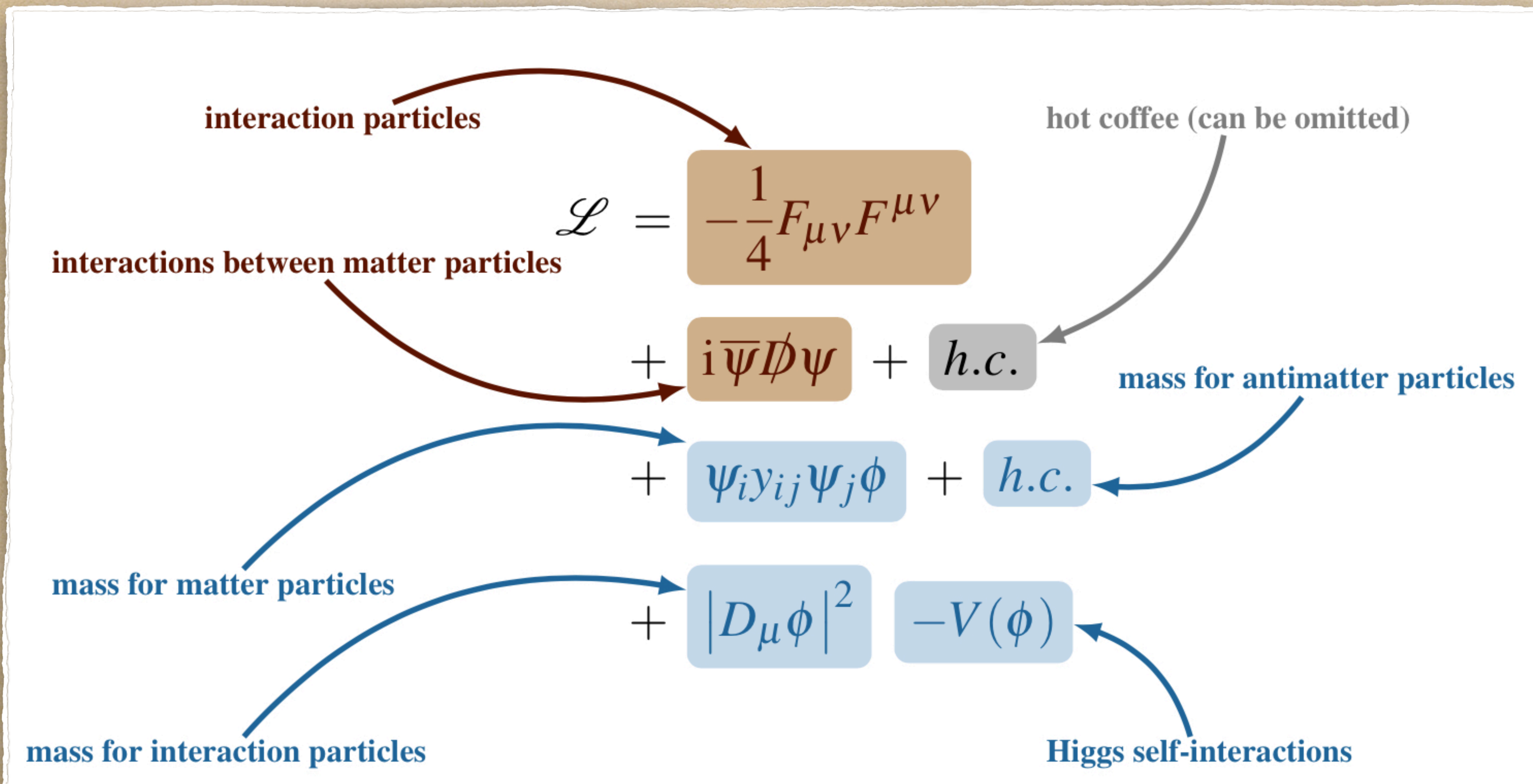
- QFD (weak force) and QCD (strong force) are very similar to QED. They only add two different types of interaction terms:

$A_\mu A_\nu \partial^\mu A^\nu$

$A_\mu A_\nu A^\mu A^\nu$



# Lagrangian




Let's have a coffee with the Standard Model of particle physics!

J Woithe, GJ Wiener, FF VdV, Phys Educ 52 (2017) no 3, 034001