COLOUR

u, d and s quarks have been introduced to help understand the properties of baryons (hadrons made from 3 quarks).

The force that binds quarks is called the strong force and it is mediated by gluons.

$p \sim uud$	$n \sim ddu$	$\Delta^{++} \sim uuu$
spin $\frac{1}{2}$	spin $\frac{1}{2}$	spin $3/2$
el. charge $+1$	el. charge 0	el. charge $+2$

Wave-functions of baryons have to be anti-symmetric under the exchange of any two quarks. This is a consequence of the Pauli-principle.

$$\underset{\text{AS}}{\Psi} = \underset{\text{SYM}}{\Psi_{space}} \otimes \underset{\uparrow\uparrow\uparrow}{\Psi_{spin}} \otimes \underset{uuu}{\Psi_{flavour}} \otimes \underset{\text{AS}}{\Psi_{colour}}$$

The Δ^{++} puzzle can be explained by adding a new quantum number : colour.

Quarks can carry 3 colours r, g, b $\quad r+g+b=w$

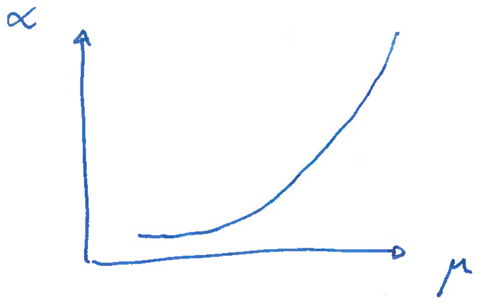
Anti-quarks carry anti-colour $\bar{r}, \bar{g}, \bar{b}$

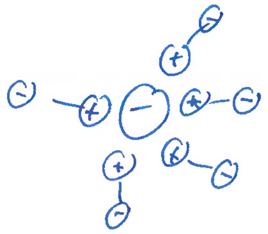
gluons carry a colour-anticolour combination $r\bar{g}, \bar{b}g, \ldots$

Because gluons carry colour as well, the strong force has different properties to the e/m force:

- only colour-neutral objects ($\gtrsim$ fm)

- screening in e/m

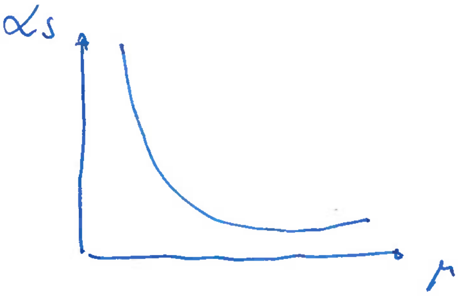




$$\alpha = \frac{e^2}{4\pi}$$

- anti-screening in the strong force

$$\alpha_s = \frac{g_s^2}{4\pi}$$



Scaling violation

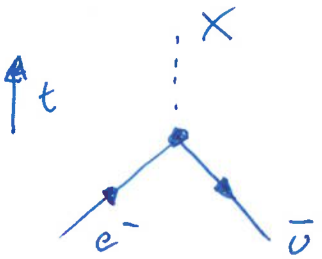
Gluons can split into sea-quarks for a short period of time. At large Q^2 the distance scale probed by the electron is small, so short-lived sea-quarks are visible, more scattering occurs and the structure function rises. The more $q\bar{q}$-pairs the smaller is the momentum fraction carried by each of them.

PARTICLE PHYSICS

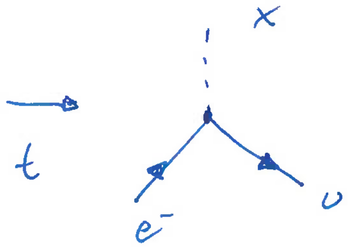
Feynman diagrams

Feynman diagrams are a pictorial way of representing interactions in particle physics. They also provide a recipe to calculate the amplitude.

Possible ambiguity: Direction of time

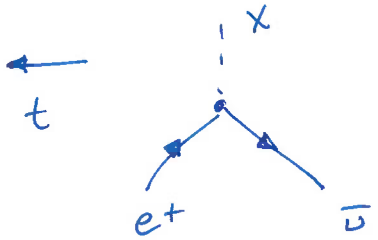


$$e^- + \bar{\nu} \to X$$

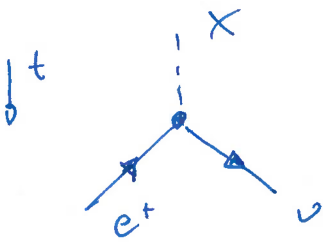


$$e^- \to X + \nu$$

In this lecture time flows from left to right.



$$\bar{\nu} \to X + e^+$$



$$X \to e^+ + \nu$$

- Fermions (spin $\frac{1}{2}$)

$\xrightarrow{t}$

f $\qquad\qquad$ $\bar{f}$

In the standard Model (SM): $q = u, d, s, c, b, t$

$\ell^- = e^-, \mu^-, \tau^-$

$\nu = \nu_e, \nu_\mu, \nu_\tau$

Anti-fermions have a bar: $\bar{q} = \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, \bar{t}$

$\ell^+ = e^+, \mu^+, \tau^+$

$\bar{\nu} = \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

- Bosons (spin 1 or spin 0)

γ  photon

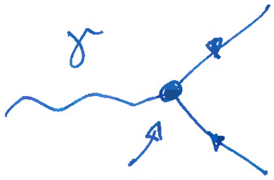
Z, W^+, W^- 

g  gluons

h 

Higgs $\leftarrow$ only spin-0 boson

- Vertices

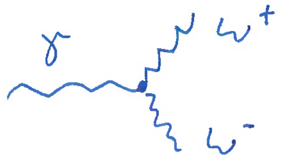


There are quantum numbers conserved at all vertices:

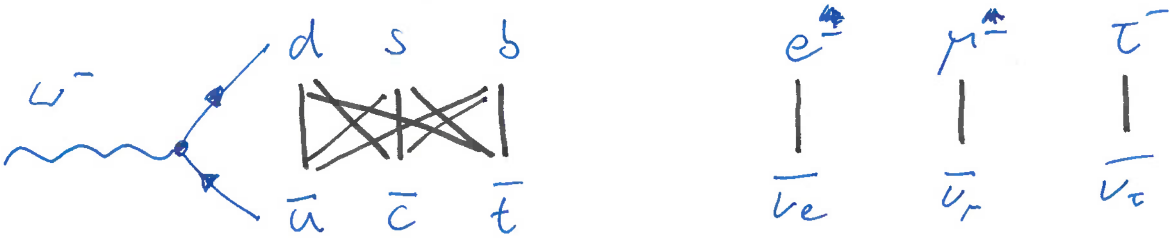
- el. charge
- lepton number
- Baryon number ($+\frac{1}{3}$ for quarks, $-\frac{1}{3}$ for anti-quarks)
  0 for leptons

- Photons couple only to electrically charged particles

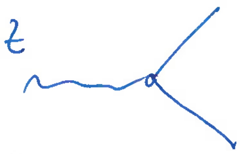
$\mu, \tau, u, d, s, c, b, t$ no νs!



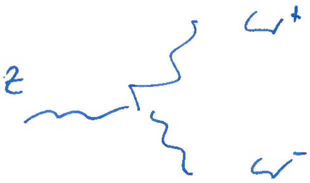
- W bosons
interact with a pair of charged and uncharged fermions.



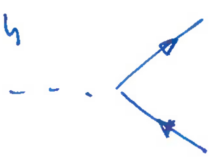
- Z boson
couples to all charged particles and the neutrinos



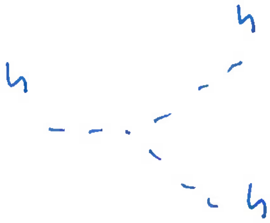
ν_e, ν_μ, ν_τ
e, μ, τ
u, c, t
d, s, b



- Higgs boson couples all massive particles

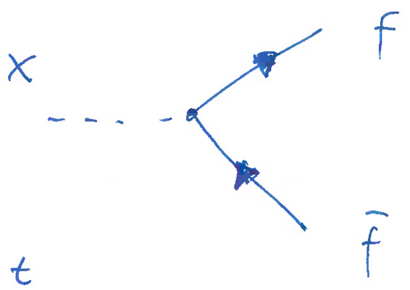


e, μ, τ
u, c, t
d, s, b

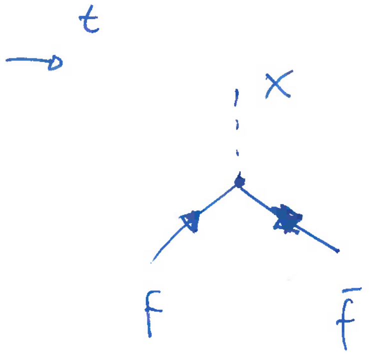


Feynman diagrams

time direction $\rightarrow t$



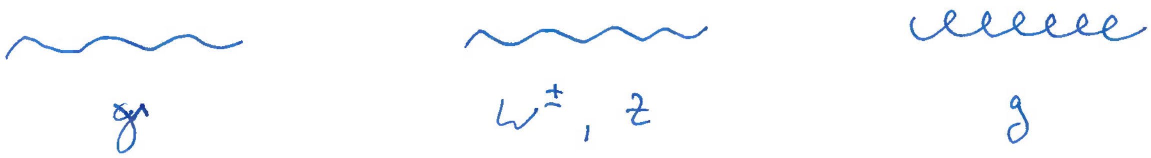
$X \rightarrow f + \bar{f}$



$f \rightarrow X + \bar{f}$

Fermion lines (all SM fermions have spin ½)
plain lines with arrow indicating fermion / anti-fermion

Vector bosons (Spin 1)



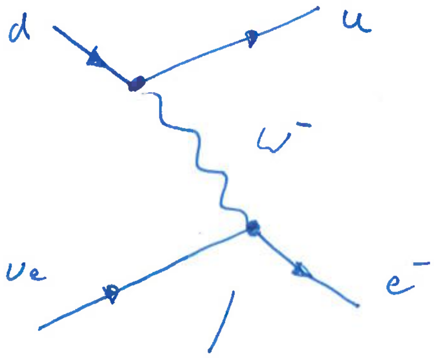
Scalar boson (spin 0)

Vertices

- photons interact only with particles that are electrically charged.
- gluons interact only with particles that are colour charged.
- Z bosons interact with all el. charged particles and the neutrinos.
- $W^\pm$ bosons interact with quark anti-quark pairs with different el. charges (e.g. $u\bar{d}$ or $c\bar{b}$) or with charged and uncharged leptons ($e^-\bar{\nu}_e$, $\mu^-\bar{\nu}_\mu$ ..)
- The Higgs boson interacts with all massive particles.

Internal particles

Internal particles cannot be observed:



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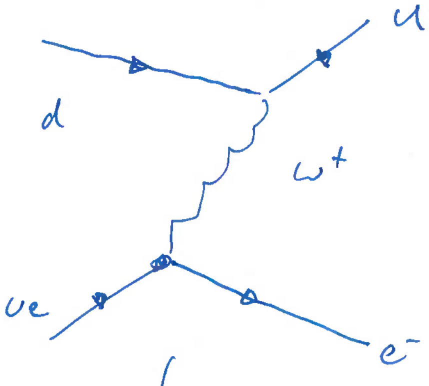

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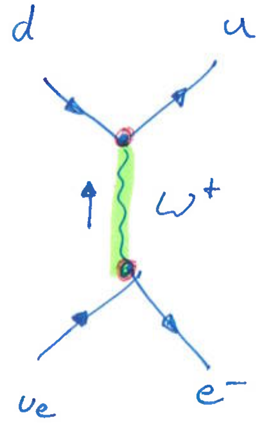


$d\nu_e \to u\nu_e W^- \to u e^-$

$d\nu_e \to e^- W^+ d \to u e^-$

Some processes are therefore indistinguishable.
The internal line contribute a propagator to the amplitude.

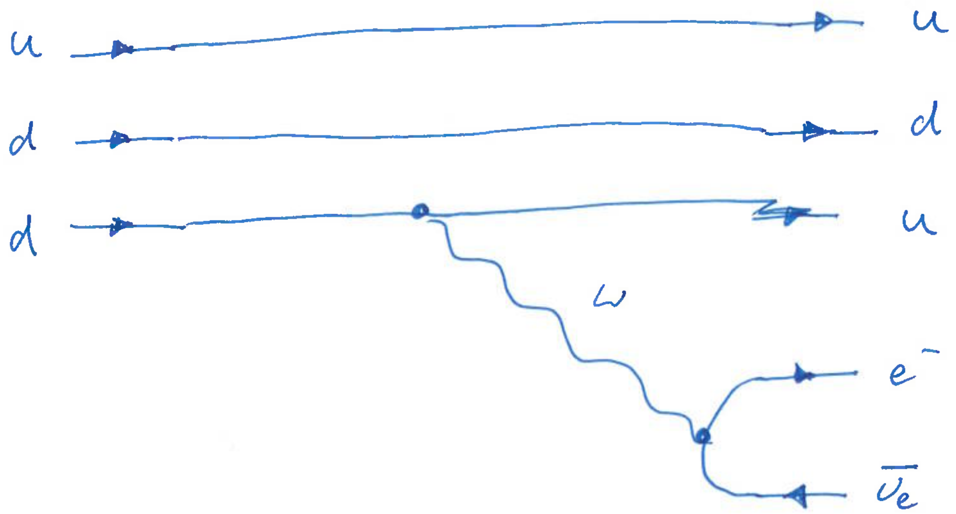
How to draw a Feynman diagram

If you respect all these rules, the question of whether a physical process is allowed or not allowed can be answered if the Feynman diagram exists.

β- decay $\quad n \to p\, e^- \bar{\nu}_e$

$\quad\quad (udd) \quad (uud)\, e^- \bar{\nu}_e$

1. Draw the external lines



2. Connect the lines that don't change.
3. Connect all lines that are allowed to be connected.
4. Connect the vertices with an appropriate boson.

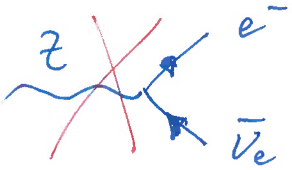
$$\frac{1}{p^2 - M^2 - iM\Gamma}$$ Γ = width of the exchanged particle

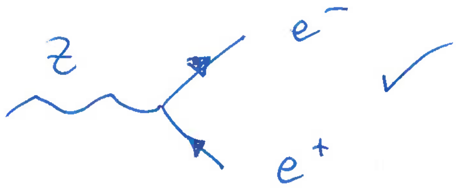
$$\sigma(d\nu_e \to u e^-) \propto |\mathcal{M}|^2$$

$= \Big|$  $\Big|^2 \propto \left| \dfrac{g^2}{p^2 - M^2 - iM\Gamma} \right|^2$

Conserved quantum numbers at all vertices:

- el. charge

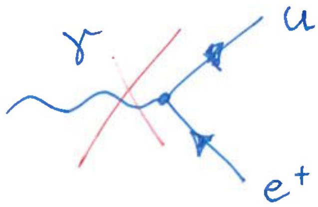


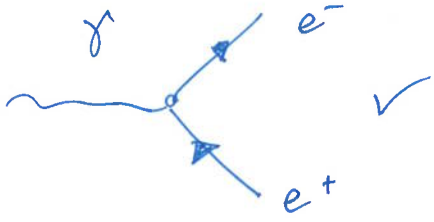


- lepton number L

$L[e^-] = +1$

$L[e^+] = -1$





- Baryon number B

$B[q] = 1/3$

$B[\bar{q}] = -1/3$