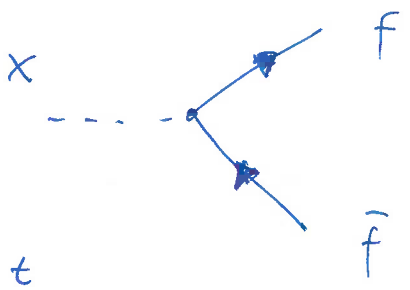
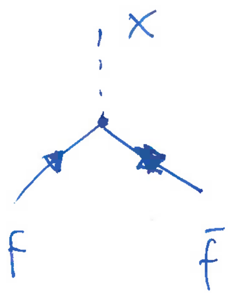
Feynman diagrams

time direction $\rightarrow t$



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

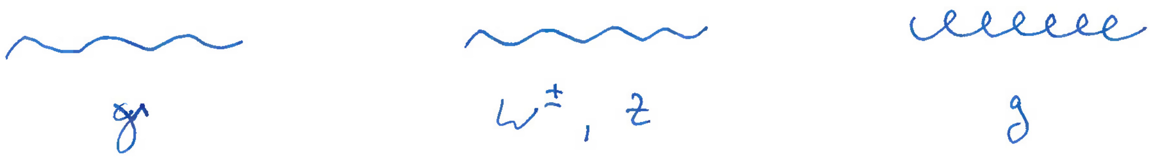
$\rightarrow t$



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

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

Vector bosons (Spin 1)



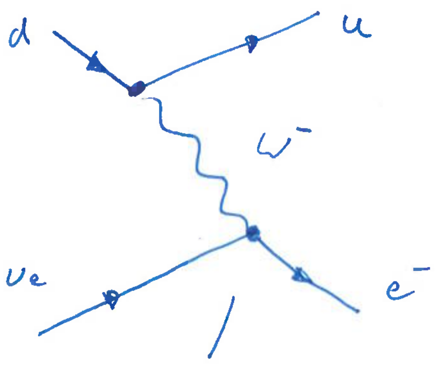
Scalar boson (spin 0)

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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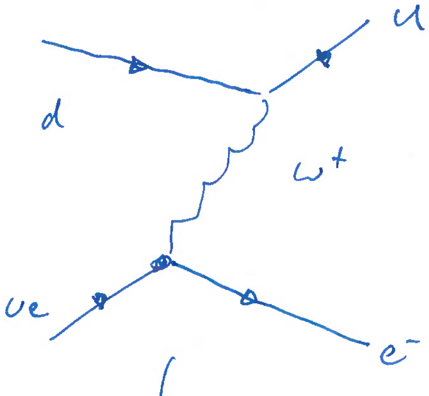

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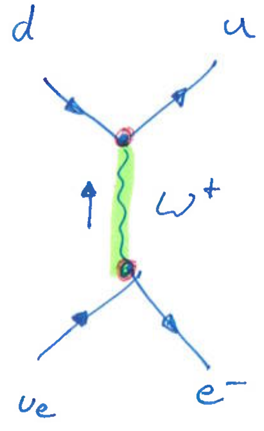


$d\nu_e \to u\nu_e W^- \to u e^-$

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

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

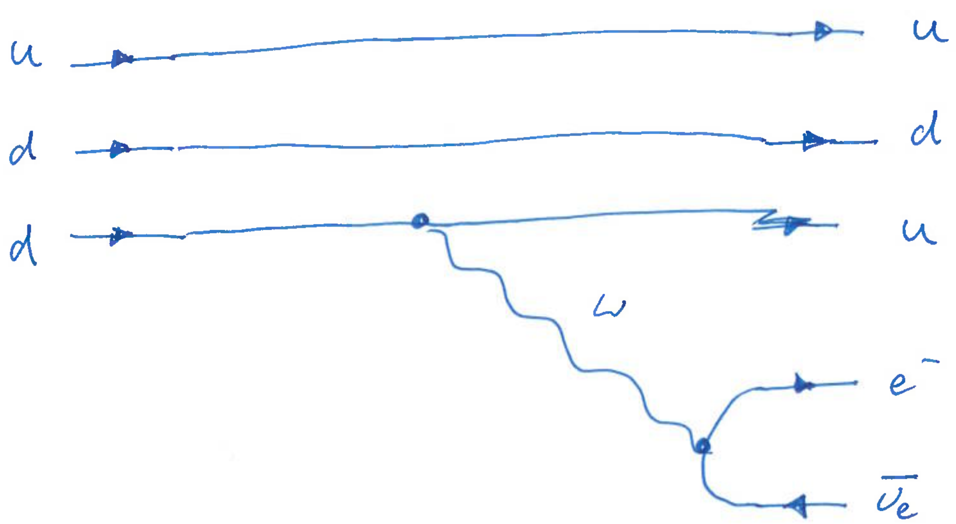
How to draw a Feynman diagram

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

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

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.

$$\frac{1}{p^2 - M^2 - iM\Gamma}$$

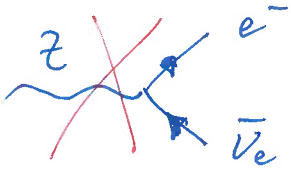
Γ = width of the exchanged particle

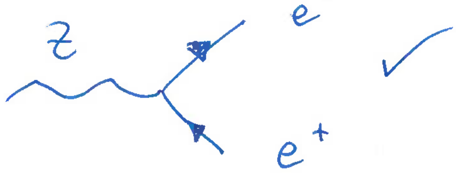
$$\sigma(d\nu_e \to u e^-) \propto |\mathcal{M}|^2$$

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

Conserved quantum numbers at all vertices:

- el. charge

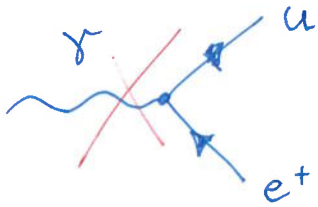


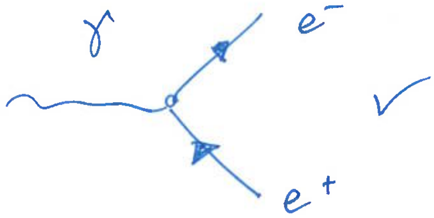


- lepton number L

$L[e^-] = +1$

$L[e^+] = -1$

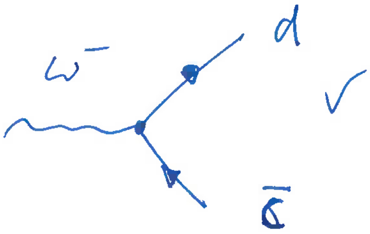


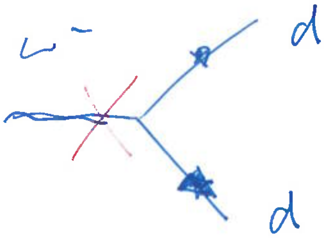


- Baryon number B

$B[q] = 1/3$

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





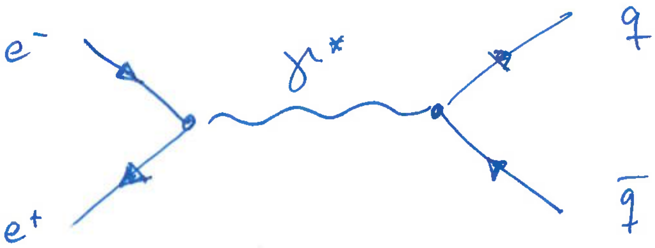
Quarkonia

Similar to e/m bond states,

H　　　Positronium　　　Mesons

q and $\bar{q}$ states can form a $q\bar{q}$ bond state.
In contrast to positronium these states are bond by the strong force.

These states can be produced at colliders



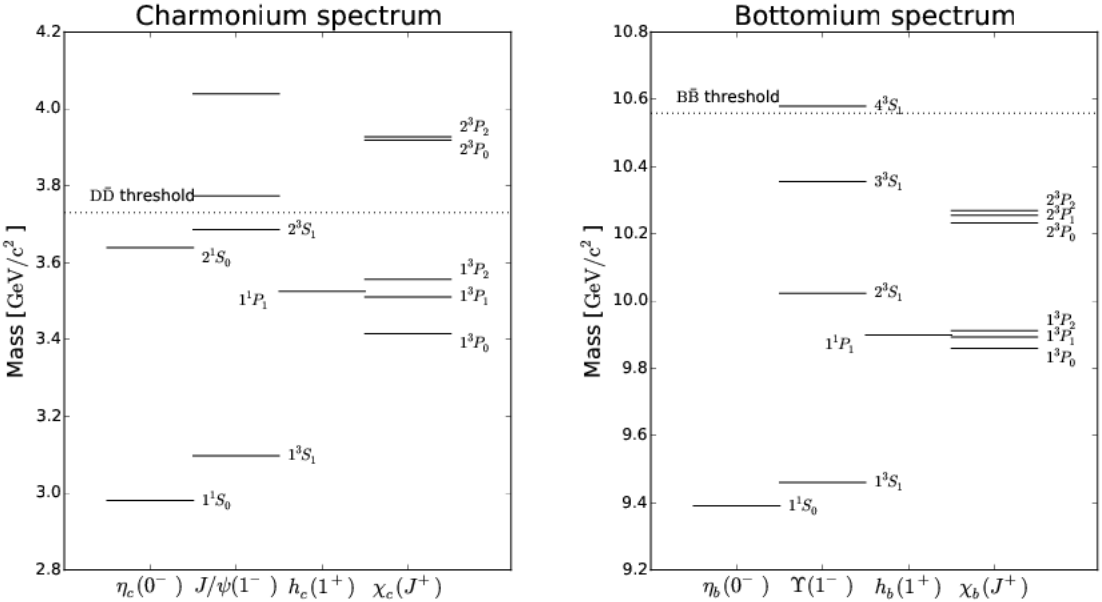
$e^+e^- \to \gamma^* \to q\bar{q}$

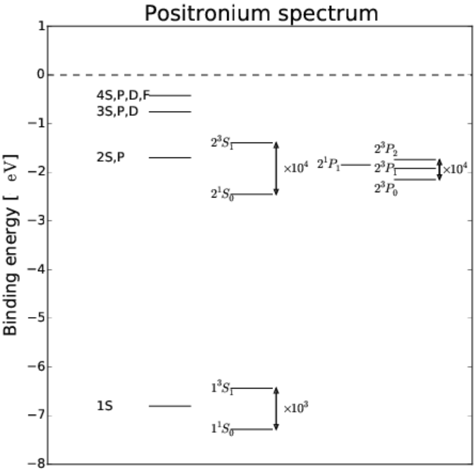
We will focus on heavy quarks (c and b), because their relative motion is non-relativistic.

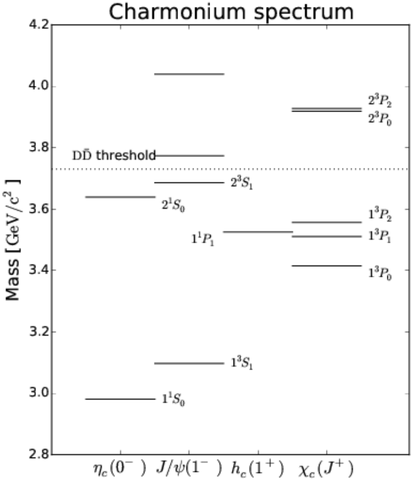
Compare Spectrum:

Quantum numbers of the mesons　　$n\,^{2S+1}L_J$

$1\,^1S_0$


Charmonium spectrum
Mass [GeV/c^2]
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
DD̄ threshold
2^3S_1
2^1S_0
2^3P_2
2^3P_0
1^3P_2
1^3P_1
1^1P_1
1^3P_0
1^3S_1
1^1S_0
$\eta_c(0^-)$
$J/\psi(1^-)$
$h_c(1^+)$
$\chi_c(J^+)$
Bottomium spectrum
Mass [GeV/c^2]
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
9.2
BB̄ threshold
4^3S_1
3^3S_1
2^3P_2
2^3P_1
2^3P_0
2^3S_1
1^3P_2
1^3P_1
1^1P_1
1^3P_0
1^3S_1
1^1S_0
$\eta_b(0^-)$
$\Upsilon(1^-)$
$h_b(1^+)$
$\chi_b(J^+)$


Positronium spectrum
Binding energy [eV]
1
0
−1
−2
−3
−4
−5
−6
−7
−8
4S,P,D,F
3S,P,D
2S,P
1S
2^3S_1
2^1S_0
$\times 10^4$
2^1P_1
2^3P_2
2^3P_1
2^3P_0
$\times 10^4$
1^3S_1
1^1S_0
$\times 10^3$


Charmonium spectrum
Mass [GeV/c^2]
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
D$\bar{D}$ threshold
2^3P_2
2^3P_0
2^3S_1
2^1S_0
1^3P_2
1^1P_1
1^3P_1
1^3P_0
1^3S_1
1^1S_0
$\eta_c(0^-)$
$J/\psi(1^-)$
$h_c(1^+)$
$\chi_c(J^+)$

- binding energy and mass splittings for quarkonia is many orders of magnitude larger as for e^+e^- bound states.
- Spectrum for low lying modes looks similar

$$e^+e^- \longrightarrow V(r) \sim \frac{\alpha}{r}$$

$$q\bar{q} \longrightarrow V(r) \sim \frac{\alpha_s}{r}$$

→ for heavier states the spectrum is different and we expect a deviation from the $1/r$ potential

- Strong force seems to be insensitive to quark masses and electric charges.