PHY 489 : HEP

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Introduction to SM:

Particles:

- Fundamental particles: "point-like"
- QFT / RQM: particles are quanta of field excitations.
- Represented by a state ket/ superposition of states:

$$|\psi_1\rangle, \; |\psi_2\rangle, \; |\phi\rangle = \alpha|\psi_1\rangle + \beta|\psi_2\rangle$$

- SM: describes fundamental particles and their interactions.

  Forces mediated by scattering/ particle exchange.

FORCE	EFFECTIVE STRENGTH	PHYSICAL PROCESS	
STRONG	10^0	NUCLEAR BINDING	(massless carrier)
ELECTROMAGNETIC	10^{-2}	ELECTRON-NUCLEUS BINDING	
WEAK	10^{-5}	β - DECAY	(massive)

FERMIONS
SPIN $\frac{1}{2}$
"MATTER PARTICLES"
WEAK INTERACTIONS

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

Charged leptons, $q = -1$
neutral leptons

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

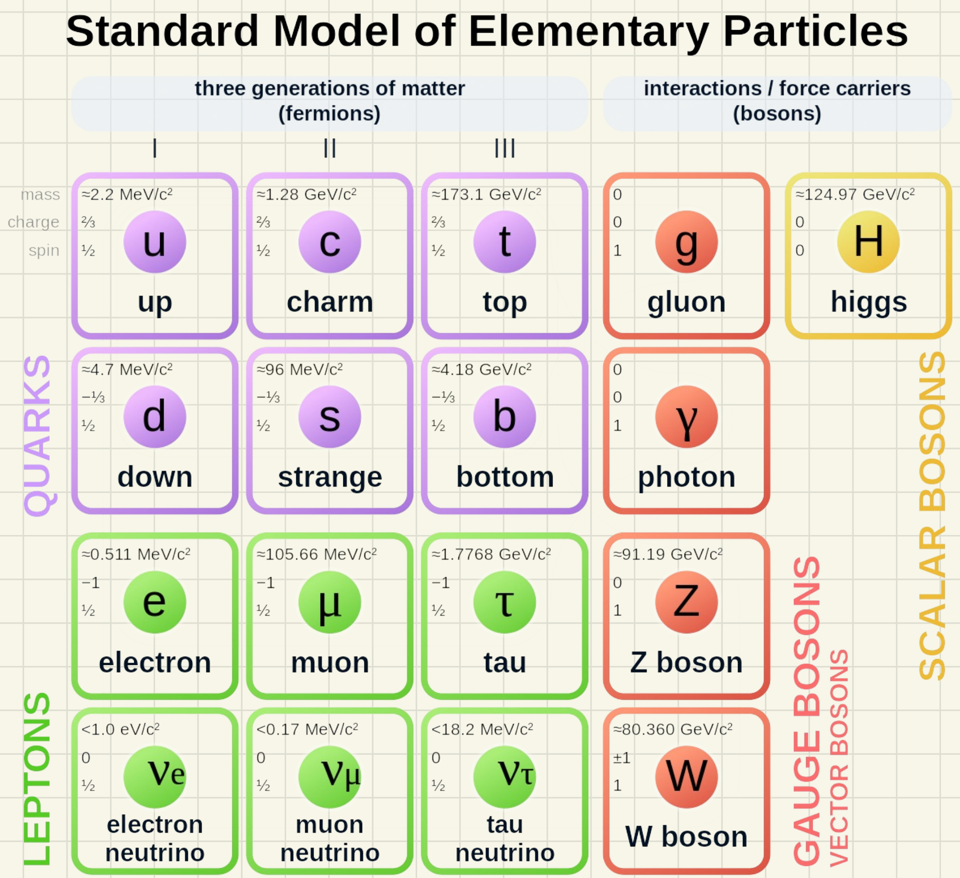
quarks $q = +\frac{2}{3}$
$q = -\frac{1}{3}$
(can be strong interactions)

BOSONS
SPIN 1
FORCE CARRIERS

γ EM-Interactions
$W^{\pm}$, Z^{0} Weak Interactions
Strong interactions g

H

BOSONS
SPIN 0
"HIGGS"



DOES NOT ACCOUNT FOR GRAVITY.

Particle masses (shown above)

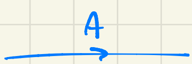
- Inverse mass of force carrier $\left(\frac{1}{m}\right)$ determines the range of the force $r \sim \frac{\hbar}{mc}$ ($\hbar = c = 1$ in HEP)
- Massless photon $\Rightarrow$ EM force has infinite range
- Massive weak gauge bosons $\Rightarrow$ weak force, short range

- Anti-particles: consequence of RQM:

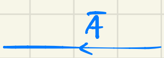
$$E^2 = m^2 + p^2 \Rightarrow E = \pm\sqrt{m^2 + p^2} \quad (\exists \text{ negative energies})$$

* Negative particle energies $\Rightarrow$ opposite particle charges which move "backwards" in time.

Feynman Diagrams:

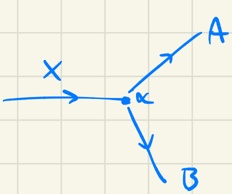


A - particle, stable, forwards in time



$\bar{A}$ - antiparticle, stable, backwards in time

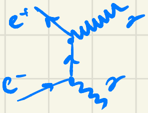
- Vertices: "Coupling constants"

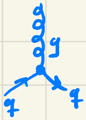


$X \rightarrow A + B$ (decay)

Strength of interaction given by α

These coupling constants change with energy, differently for three fundamental interactions:





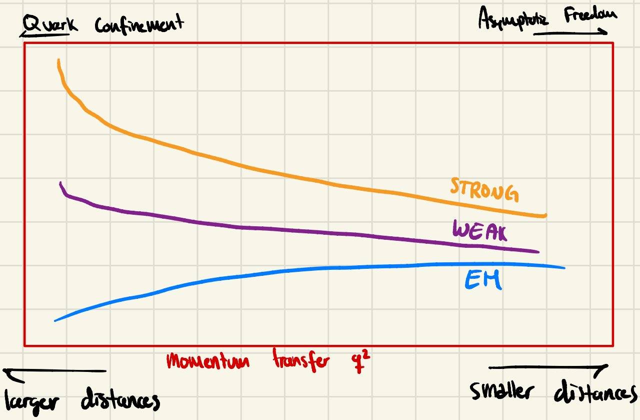
(i) QED : photon interaction, γ's don't interact with each other.

(ii) QCD : gluon interactions, g's carry (anti-) colour so they interact

(iii) Weak Interaction: electroweak gauge bosons carry "weak charge" so they interact.

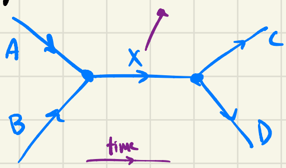
- Momentum, energy conserved in feynman diagrams. ie some diagrams impossible due to $E, \vec{k}$ violation.

- Running of coupling constants:



- Feynman diagrams:

Internal lines : field contractions, "virtual particle exchange" (momenta)

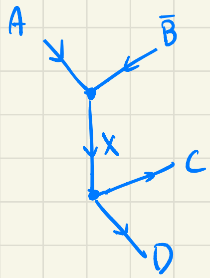


Process $A+B \to C+D$.

Crossing symmetry: $A + \bar{C} \to \bar{B} + D$, $\bar{C} + \bar{D} \to \bar{A} + \bar{B}$, etc.

EACH correspond to different Feynman diagrams.

Describes processes allowed by dynamics, may not be allowed kinematically. ie:



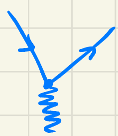
$A \to \bar{B} + C + D$ isn't possible unless

$M_A > M_B + M_C + M_D$.

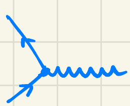
Feynman diagrams correspond to scattering amplitudes.

- **Processes in QED:** photon interaction.

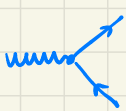
Illegal processes: by momentum conservation, Lorentz Invariance, Energy conservation, the following processes are considered illegal in QED:



$e^- \to e^- \gamma$



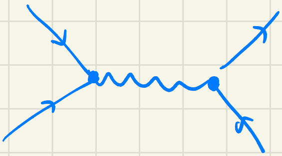
$e^+ e^- \to \gamma$



$\gamma \to e^+ e^-$

Are forbidden!

However, all allowed QED processes are made up of this fundamental vertex:

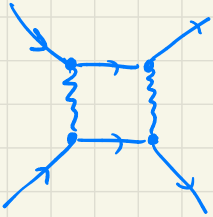
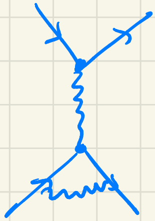
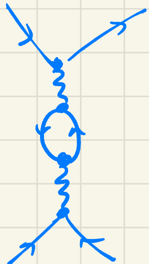


$e^+e^- \to e^+e^-$

Virtual γ exchange. γ takes on momentum required for conservation.

- Higher-order diagrams:
  - $\mathcal{O}(g^3)$ in wick expansion, often contain "loops" where an undefined momentum parameter exists.
  - $\mathcal{O}(g^1) \Rightarrow$ no scattering
  - $\mathcal{O}(g^2) \Rightarrow$ leading order / second order diagrams.
  - Diagrams superpose to determine the probability of scattering (amplitude). $\mathcal{O}(g^n)$, n^{th} diagrammatic probability has amplitude $A \propto \frac{1}{\alpha^n}$.

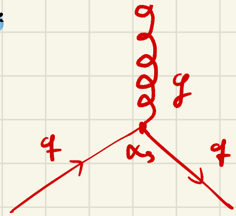
each vertex adds value of $\alpha = (137)^{-1}$ to amplitude.

 ,  ,  , . . .

"Neglect higher-order contributions"

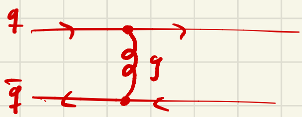
• Processes in QCD:

Basis vertex:



Fundamental Colour charge α_s

Gluon exchange: attractive forces between q, $\bar{q}$ pair:



• Mesons: nine $q\bar{q}$ combinations:

$u\bar{u}$	$u\bar{d}$	$u\bar{s}$
$d\bar{u}$	$d\bar{d}$	$d\bar{s}$
$s\bar{u}$	$s\bar{d}$	$s\bar{s}$

} are all bosons (have spin +1)

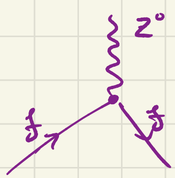
• Baryons: 10 qqq combinations:

uuu	uud	udd
ddd	uds	dds
uss	dss	sss
	uus	

} are all fermions (spin $\frac{3}{2}$, $\frac{1}{2}$)

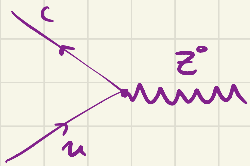
HADRONS.

• "Neutral Current" Weak Interactions:



- f is any fermion
- Z^0 is similar to "massive" photon but couples to a ("weak") charge.

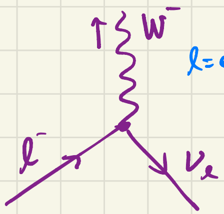
- For quarks and charged leptons, intergenerational flavour mixing is not allowed. ie,



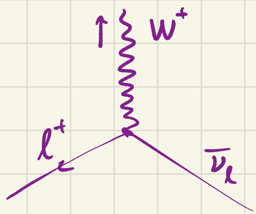
is forbidden.

Flavour Changing Neutral Currents Don't exist in SM.

- "Charged Current" weak interactions:



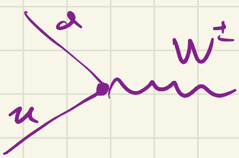
$\ell = e, \mu, \tau$

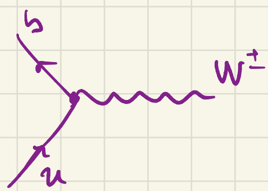


Emitting a W^+ changes a charged lepton into a neutrino & vice versa.

- Quark flavour mixing: still not allowed!

Forbidden:





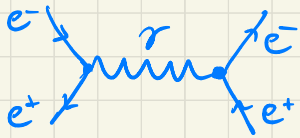
Strongest coupling: between up, down type quarks in the same generation

Next Strongest : between neighbouring generations

Weakest coupling: between first and third generations.

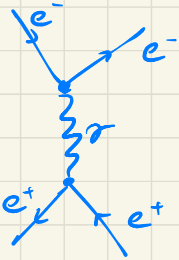
- **Bhabha Scattering:** $e^+e^- \to e^+e^-$:

s-channel:



(electron-positron)

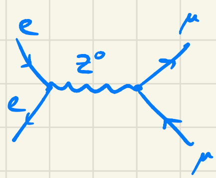
t-channel:



Furthermore: $e^+e^- \to \mu^+\mu^-$:

(electron-muon)

,



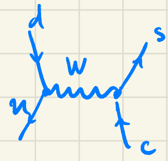
$e\bar{\nu}_e \to e\bar{\nu}_e$:

(electron-neutrino)

Other diagrams:

* note that it is very difficult to scatter quarks at "lower" energies.

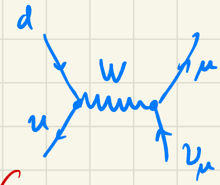
$e\bar{\nu}_e \to \mu\bar{\nu}_\mu$



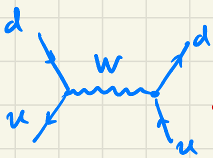
$d\bar{u} \to s\bar{c}$

$e\bar{\nu}_e \to d\bar{u}$

or $\to s\bar{u}$



$d\bar{u} \to \mu\bar{\nu}_\mu$



$d\bar{u} \to d\bar{u}$

Very difficult to do.

- **Conservation Laws and Considerations:**

We must first consider:

- Relativistic Kinematics
- Dynamics (spin/addition of $\vec{L}$, "internal" symmetries such as Baryon/Lepton number, Isospin, Parity + Helicity, Charge, and G-parity)

Conservation: Energy, momentum, charge, parity, time reversal, colour, etc.

[1] Charge Conservation: q must be conserved at each moment in time.

Similarly, colour must be conserved throughout

Strong interactions.

[2] Baryon Number: $B = +1$ for all baryons

$B = -1$ for all anti-baryons

$B = 0$ for other particles (and mesons)

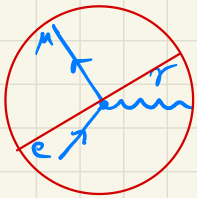
Quarks: i.e. $+\frac{1}{3}$ for all q, $-\frac{1}{3}$ for all $\bar{q}$

[3] Lepton Number:

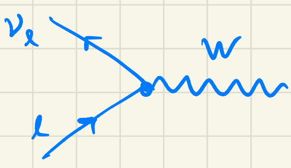
$$L_e = \begin{cases} +1 & e^-, \nu_e \\ -1 & e^+, \bar{\nu}_e \end{cases} \qquad L_\mu = \begin{cases} +1 & \mu^-, \nu_\mu \\ -1 & \mu^+, \bar{\nu}_\mu \end{cases} \qquad L_\tau = \begin{cases} +1 & \tau^-, \nu_\tau \\ -1 & \tau^+, \bar{\nu}_\tau \end{cases}$$

which are "slightly" violated by neutrino oscillations.

For photons, there is no coupling between two different types of leptons although charge is conserved:



Charged leptonic weak interactions has the allowed vertices



Sometimes during neutrino flavour oscillations, the vertex

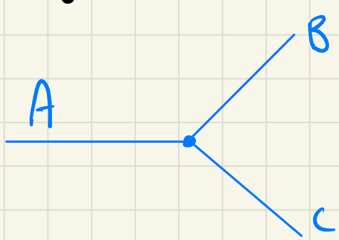
can exist.

In neutral weak interactions, the vertices

are allowed.

- **Particle Decays**:

The decay



$A \to B + C$

is forbidden kinematically if $M_A < M_B + M_C$.

Each fundamental interaction has an associated timescale (lifetime) denoted by τ.

Strong interaction: $\sim 10^{-23}$ s

Electromagnetic Interaction: $\sim 10^{-16}$ s

Weak Interaction: $\sim 10^{-13}$ s up to 15 minutes.

decay of free neutron

Strong decays: always hadrons $\rightarrow$ hadrons

EM: photons always involved

Weak: neutrinos always involved.

For multiple available final states, the most probable decay will often be the one where there is the largest mass difference between initial and final states. For two-body decays, $1 \rightarrow 2+3$,

$$\underbrace{\frac{1}{\tau} = \Gamma}_{\text{decay rate}} = \underbrace{\frac{|\vec{p}|}{8\pi\, m_1^2\, \hbar c}}_{\text{Kinematics}} \overset{\text{Statistical factor}}{S} \, \overset{}{\underset{\text{dynamics}}{|M|^2}}$$

This is just a rule of thumb, however. $\pi^+ \rightarrow \mu^+ \nu_\mu$ occurs 99.988% of the time although $\pi^+ \rightarrow e^+ \nu_e$ is kinematically favored.

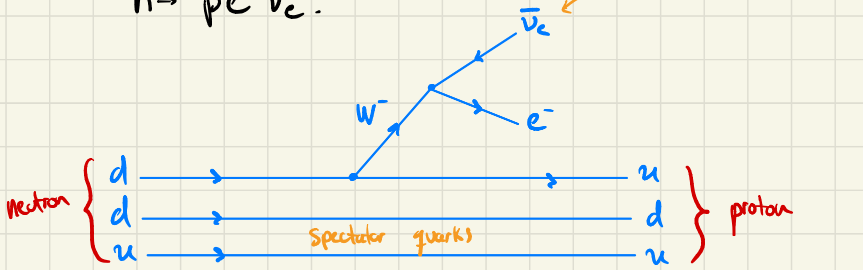
- Hadron interactions:

Particle decay rate depends on mass. Heavier particles are more likely to decay faster.

In hadron decay containing a heavy quark (not u or d), if the decay involves a quark flavor change (via weak interaction), the decay is always due to the heaviest quark decaying into a lighter one.

- **Example: Neutron β-decay:**

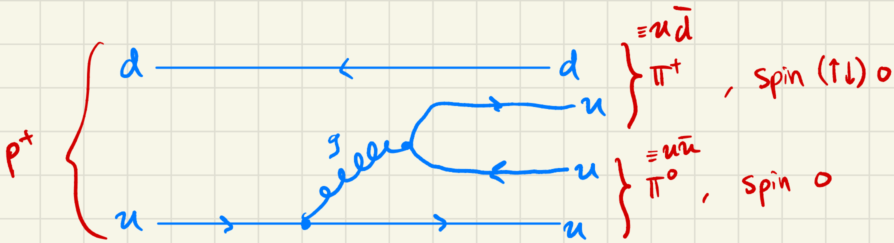
$n \to p e^- \nu_e$:



- Decays of light $u\bar{d}$ mesons:

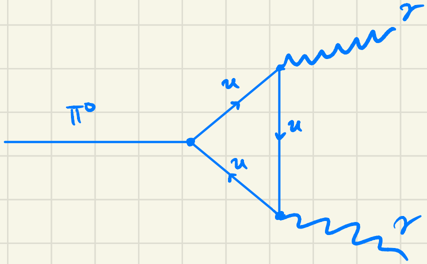
$\rho^+(770) = u\bar{d}$ (spin 1 / vector meson)

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



- Decays of neutral pion π^0: only EM- interaction

$\pi^0 \to \gamma\gamma$



$\tau \sim 10^{-16}$ s.

- Decay of charged pion π^+: only weak interaction

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

$\tau \sim 10^{-8}$ s

- Discovery of anti-proton: $p + p \to p + p + p + \bar{p}$
  - Minimum kinetic energy in initial state was the same as that required for the production of 2 addition baryons (B # conserved).

In meson decay, in constrast, can have n particles in the final state (as many allowed by kinematics).