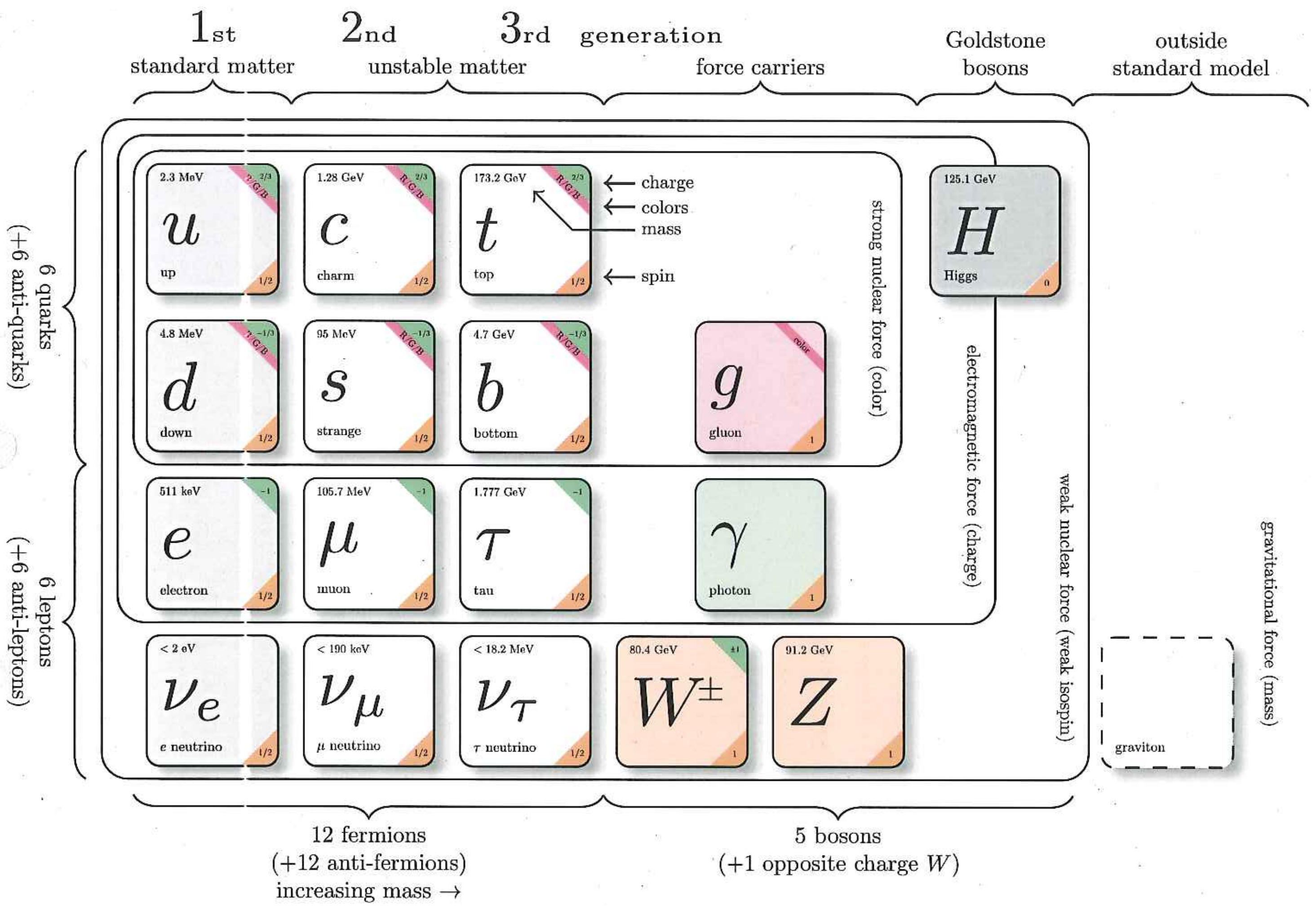
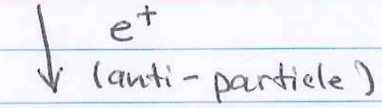

1st
2nd
3rd
generation
standard matter
unstable matter
force carriers
Goldstone bosons
outside standard model
6 quarks (+6 anti-quarks)
6 leptons (+6 anti-leptons)
2.3 MeV
2/3
R/G/B
u
up
1/2
1.28 GeV
2/3
R/G/B
c
charm
1/2
173.2 GeV
2/3
R/G/B
t
top
1/2
charge
colors
mass
spin
strong nuclear force (color)
125.1 GeV
H
Higgs
0
4.8 MeV
−1/3
R/G/B
d
down
1/2
95 MeV
−1/3
R/G/B
s
strange
1/2
4.7 GeV
−1/3
R/G/B
b
bottom
1/2
color
g
gluon
1
electromagnetic force (charge)
511 keV
−1
e
electron
1/2
105.7 MeV
−1
μ
muon
1/2
1.777 GeV
−1
τ
tau
1/2
γ
photon
1
weak nuclear force (weak isospin)
gravitational force (mass)
< 2 eV
ν_e
e neutrino
1/2
< 190 keV
ν_μ
μ neutrino
1/2
< 18.2 MeV
ν_τ
τ neutrino
1/2
80.4 GeV
±1
$W^\pm$
1
91.2 GeV
Z
1
graviton
12 fermions (+12 anti-fermions) increasing mass →
5 bosons (+1 opposite charge W)

Electro-magnetic force → quantum electrodynamics (QED)

Charged particles — solid line with arrows



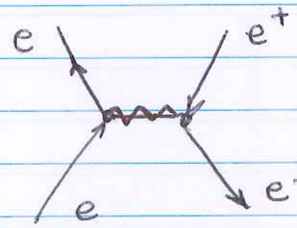
Photons — wavy lines. When attached to a vertex they designate absorption or emission

Region below the vertex — initial state
— " — above — " — — final state

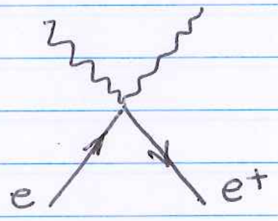
Any line b/w two vertexes represent a virtual particle

Any process that follow these rules, and whose final state and initial state obey conservation laws is a possible physical process!

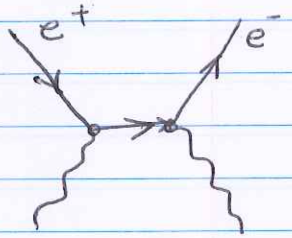
Possible electron-positron interaction



Coulumb interaction



electron-positron annihilation

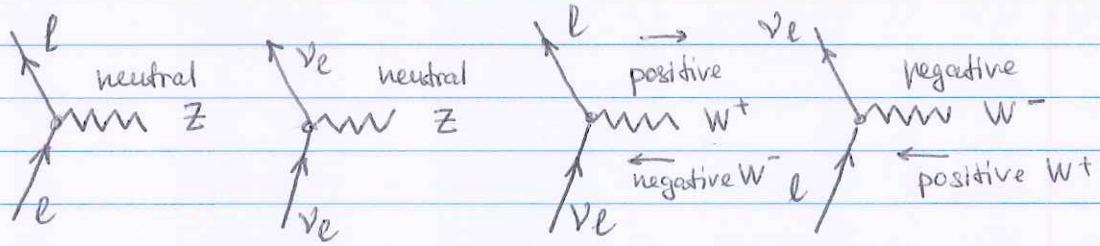


electron-positron pair production

Feynman diagrams are more than funny pictures, they are prescriptions for very precise calculations.

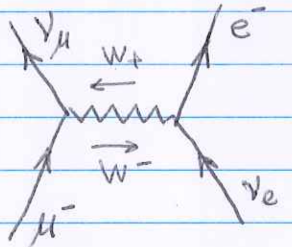
It turned out that weak interaction can be described in a similar fashion

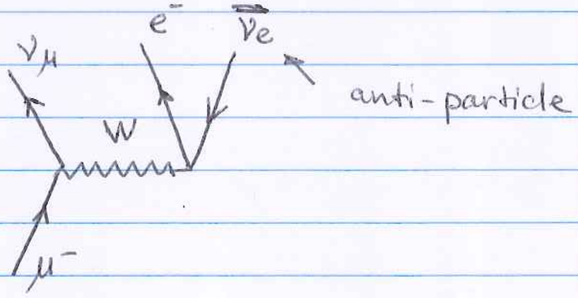
Possible vertices



where $\begin{pmatrix}\nu_l \\ l\end{pmatrix} = \begin{pmatrix}\nu_e \\ e\end{pmatrix}$ or $\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$ or $\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$

Possible processes





$\mu^- + \nu_e \rightarrow e^- + \nu_\mu$ $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

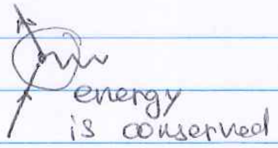
~~It is now established~~

~~We~~ It is now established that at very high energies electromagnetic and weak force become indistinguishable → same electroweak interaction.

Why they look so different at "regular" energies?

because W and Z bosons are massive

$M_W c^2 = 80\ \text{GeV}, \ M_Z c^2 = 91\ \text{GeV}$



→ QM allows energy-conservation breaking for a short period of time!

$\Delta E \, \Delta t \sim \hbar$

Exchange "duration" $\Delta t \sim \frac{\hbar}{\Delta E}$

since ~~electr~~ photons are massless, they can travel
distance $d \sim c\Delta t = \frac{c\hbar}{\Delta E} = \frac{200 eV \cdot nm}{1 eV} = \underline{200 nm}$

huge distance!
for nuclear
standards

Contrary, for a massive particle, however
$\Delta E \sim M_W c^2$ (energy is required to create
an interaction carrier particle)
$d \lesssim c \cdot \Delta t = \frac{c\hbar}{\Delta E} = \frac{200 eV \cdot nm}{80 \cdot 10^9 eV} \simeq 2.5 \cdot 10^{-9} nm = 2.5 \cdot 10^{-18} m$

Once released

Quantum Chromodynamics (QCD)

How do quarks interact?

Δ^{++} particle $\enclose{circle}{uuu}$ all three quarks have
spin $3/2$ the same ~~char~~ spin!
(three particles in the same state?!)

Thus, the quarks need to have some other way to distinguish themselves → another charge

three quarks (in barions) → three color charges (red, green, blue)

Turned out, any hadron have to be <u>colorless</u>

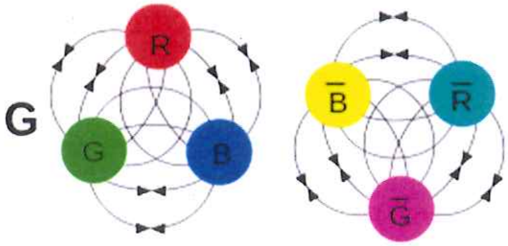
barions: red + green + blue = white ↘ no
meson: red + antired = black ↗ color!

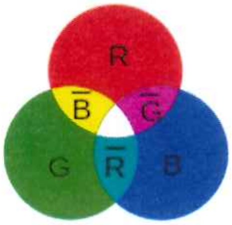
Force carriers b/w quarks: gluons (8 overall)
each gluon is "marked" with two colors
Characteristic of quark-gluon model: confinements
the interaction b/w quarks at a short distance is weak (assimptotic freedom). But it grows with distance → until the bond "snaps" by producing a pair of a quark + antiquark

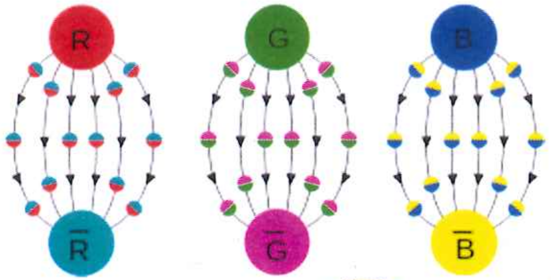
$$q_g q_b \enclose{circle}{q_r} \longrightarrow q_g \, q_b \overset{\text{strong bond}}{\cdots} q_r \longrightarrow q_g q_b \leftarrow q_r \bar{q}_r \rightarrow q_r$$

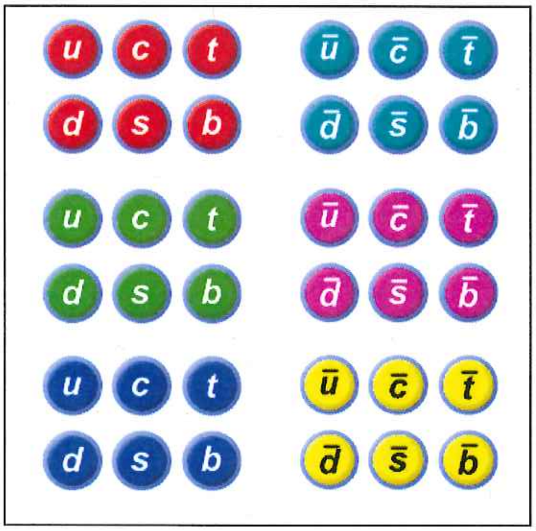
quarks are
more or less free

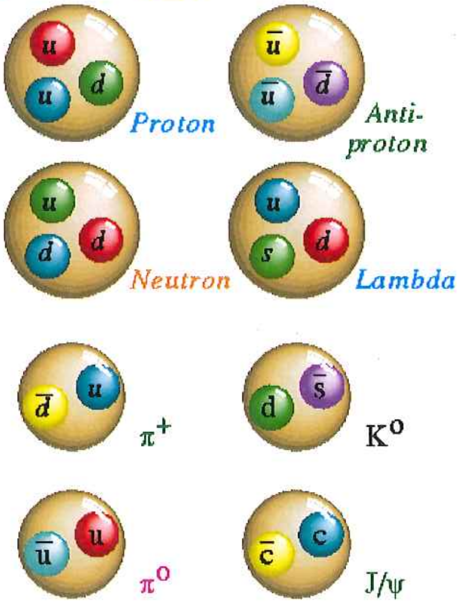
$$\rightarrow q_g q_b q_r + \bar{q}_r q_r$$


G
R
G
B
B̄
R̄
Ḡ

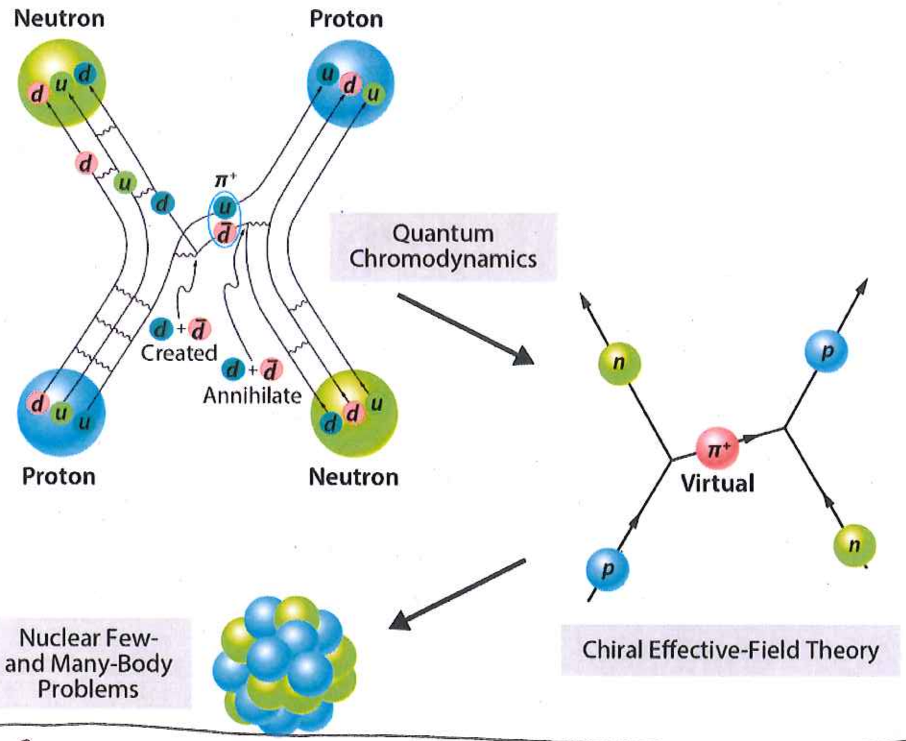

R
B̄
Ḡ
G
R̄
B


R
R̄
G
Ḡ
B
B̄

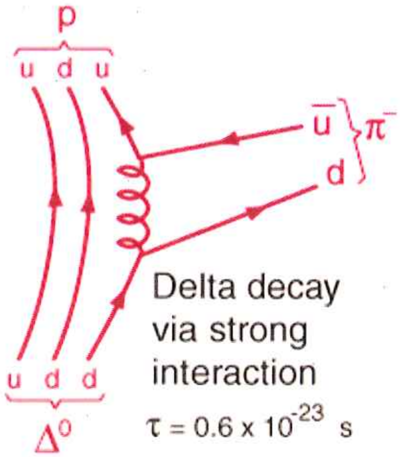

u c t
ū c̄ t̄
d s b
d̄ s̄ b̄
u c t
ū c̄ t̄
d s b
d̄ s̄ b̄
u c t
ū c̄ t̄
d s b
d̄ s̄ b̄


u u d
Proton
ū ū d̄
Anti-proton
u d d
Neutron
u s d
Lambda
d̄ u
π^+
d s̄
K^0
ū u
π^0
c̄ c
J/ψ

Proton-neutron attraction via strong force



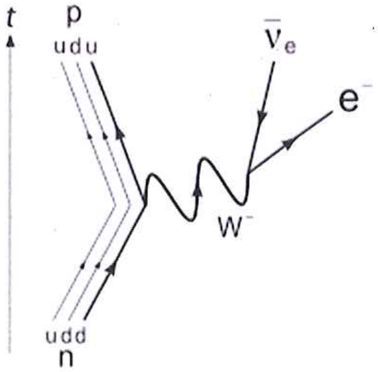
$\Delta^0 \rightarrow p + \pi^-$



Delta decay via strong interaction

$\tau = 0.6 \times 10^{-23}$ s

Neutron decay via weak force



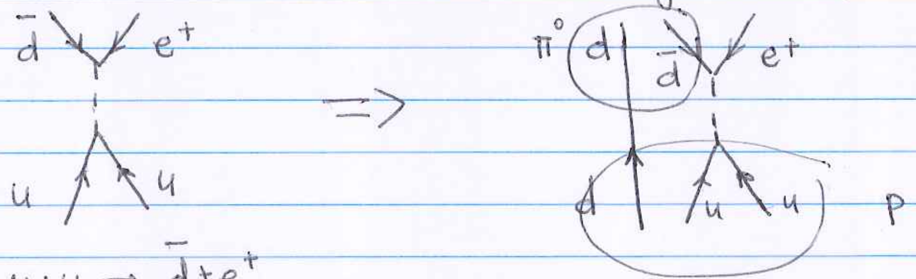
Grand unification theory
EM + weak + strong interactions

quarks $\begin{pmatrix} u \\ d \end{pmatrix}_{r,g,b}$ $\begin{pmatrix} s \\ c \end{pmatrix}_{r,g,b}$ $\begin{pmatrix} t \\ b \end{pmatrix}_{r,g,b}$

leptons $\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$ $\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$ $\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$

Some calculations suggest that these particles can be represented as 5 fundamental particles + 24 interaction-carrying bosons!

~~an example~~ Some interaction bosons are the same as 4 in electroweak interaction (γ, $W^\pm$, Z) and 8 gluons
Other 12 are called X (for electric charge $\pm 4/3$) or Y (for electric charge $\pm 1/3$)



$u + u \rightarrow \bar{d} + e^+$

Proton decay $p \rightarrow \pi^0 + e^+$

GUT problem — proton is stable!

Conclusion: GUT seems an elegant idea, but it clearly has proplems for now