INTRODUCTION TO PARTICLE PHYSICS

Kari Rummukainen University of Oulu

- What is particle physics? It studies (or attempts to) properties of Nature at fundamental level, whatever it is.

- Prerequisites:
  - special theory of relativity
  - Quantum mechanics I

- Material:
  - lecture notes

  Books:
  - David Griffiths: "Introduction to elementary Particles"
  - Halzen & Martin: "Quarks and Leptons"

  Both are quite good introductory texts; we shall mostly follow Griffiths.
  $\exists$ in Oulu textbook library. (oldish, both ~1984)

- Lectures: MO 10–12, THU 12–14 TE 320
- Exercises: TUE 12–14 Janne Kuokkanen
- WEB: http://cc.oulu.fi/~tf/tiedostot

Contents (roughly)

These correspond (fairly well) to sections in Griffiths

Units

- Standard unit of energy: eV, electron volt
  Energy of a particle of 1 unit of charge (electron, proton) when accelerated with a 1 V potential

  $1\ \text{eV} = 1.602\times10^{-19}\ \text{CV} = 1.602\times10^{-19}\ \text{J}$

  $\text{MeV} = 10^{6}\ \text{eV}$; $\text{GeV} = 10^{9}\ \text{eV} = 1.602\times10^{-10}\ \text{J}$

- Usually "natural units" in use:

  $$\boxed{c = \hbar = k_B = 1}$$

  - $c=1 \Rightarrow [\text{time}] = [\text{distance}]$ $\quad$ ([ ] : unit of)

    1 fm of time = time in which light travels 1 fm

    $c_{SI} = 2.9979\times10^{8}\ \text{m/s}$

  - $\hbar \equiv h/2\pi = 1 \Rightarrow$

    $\hbar_{SI} = 1.0546\times10^{-34}\ \text{Js} \Rightarrow [\text{energy}] = [\text{time}]^{-1} = (\text{length})^{-1}$

  - $k_B = 1 \Rightarrow [\text{temperature}] = [\text{energy}]$

    - not used in these lectures

- In particle physics quantities usually given in units of $\text{GeV}^{\text{power}}$, convert to SI by multiplying with appropriate c, $\hbar$, k_B

- Sometimes also use

  $\text{fm} = 10^{-15}\ \text{m} = \text{fermi}$

- mass : $\underline{m_{new} = m_{SI}\, c^2}$, $\underline{[m] = \text{GeV}}$

- speed : $[v_{SI}] = \frac{m}{s} \Rightarrow v_{new} = v_{SI}/c$; dimensionless

- impulse: $[p_{SI}] = kg\,\frac{m}{s}$; $p_{new} = p_{SI} \cdot c$; $\underline{[p] = \text{GeV}}$

Relativistic energy $E = \sqrt{(mc^2)^2 + |\bar{p}c|^2} \longrightarrow$

$$E = \sqrt{m^2 + \bar{p}^2} \quad , \quad E = m \quad \text{if } \bar{p} = 0$$

- length : $\hbar = 1$ relates length $\Leftrightarrow$ energy.

Motivation: in QM,

$$\underline{\bar{p} = \hbar \bar{k}} = \hbar \, \frac{2\pi}{\lambda} \leftarrow \text{de Broglie} \longrightarrow \underline{\bar{p} = \bar{k}}$$

Convert $1\,\text{fm} = 10^{-15}\,\text{m}$ to energy:

$$\underbrace{1\,\text{fm} \times \frac{1}{\hbar c}}_{\text{unit} = \text{energy}^{-1}} = 10^{-15}\,\text{m} \Big/ 2.9979 \times 10^{8}\,\frac{m}{s} \times 1.0546 \times 10^{-34}\,\text{Js}$$

$$= 3.1630 \times 10^{11}\,\frac{1}{J} = \underline{\underline{\frac{1}{0.197\,\text{GeV}}}}$$

Thus, correspondence

$$\boxed{1\,\text{fm} = \frac{1}{197\,\text{MeV}}}$$

Note: Griffiths unfortunately does not use this, but it is straightforward to convert.

- Charge :

Use convention where Coulomb force

$$\bar{F} = \frac{Q_1 Q_2}{4\pi \underset{\uparrow \text{ set to } = 1}{\epsilon_0} r^2} \hat{e}_r \qquad \text{Lorentz-Heaviside}$$

Now $[F] = [r]^{-2}$, thus charge dimensionless.

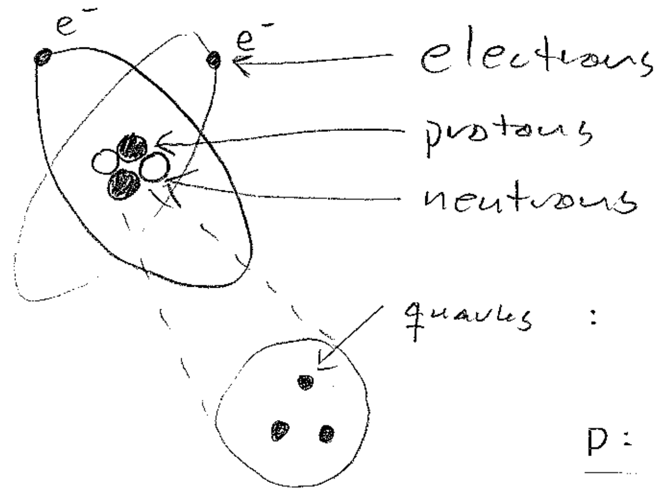
Dimensionless fine structure constant

$$\alpha \equiv \frac{E_{pot} \text{ for } 2e^- \text{ distance } \frac{\hbar}{mc} \text{ apart}}{\text{Rest mass of } e^-}$$

$$= \frac{e^2}{4\pi \hbar c} = \frac{e^2}{4\pi} \cong \frac{1}{137}$$ ← independent of dim. system!

1. Overview

1.1. Structure of Standard Model



quarks : protons & neutrons consist of 3 quarks each; p: uud ; n: udd

In addition, there is a number of unstable and/or (almost) invisible particles.
All known particles & interactions (except gravity) are contained in the **Standard Model**

		mass		mass		mass	el. charge
QUARKS	u (up)	1.5–3 MeV	c (charm)	~1.25 GeV	t (top)	174 GeV	+2/3
	d (down)	3–7 MeV	s (strange)	~95 MeV	b (bottom)	4.2 GeV	−1/3
LEPTONS	ν_e (el. neutrino)	<3 eV	ν_μ (myon neutrino)	<0.19 MeV	ν_τ (tau neutrino)	<18.2 MeV	0
	e (electron)	0.511 MeV	μ (myon)	105.7 MeV	τ (tau)	1.78 GeV	−1

Interactions are mediated by gauge bosons

- Electromagnetism: photon γ ; $m_\gamma = 0$
- Strong interaction: gluon g , $m_g = 0$
- Weak interaction: W^+, W^- , $m_W = 80$ GeV
  Z^0 , $m_Z = 91$ GeV

Higgs boson : not yet found! $114\ \text{GeV} < m_H \overset{?}{\lesssim} 200\text{–}300\ \text{GeV}$

- Quarks & leptons are fermions (spin $\frac{1}{2}\hbar$), gauge bosons vector bosons ($s = 1\,\hbar$) and Higgs particle is a scalar boson ($s = 0$)

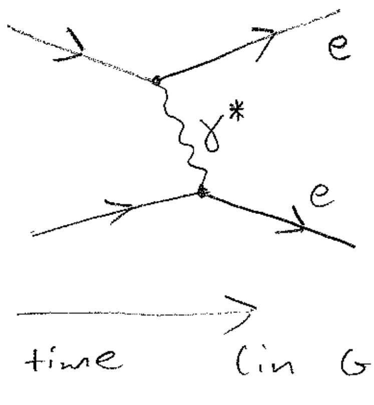
- All fermions have antiparticles with opposite charge (and other quantum numbers).

  e.g. $\bar{e} = e^+$ positron

- bosons are own antiparticles

1.2. Interactions

- Shown pictorally with Feynman diagrams
  e.g. $ee \to ee$ scattering:



electrons exchange a virtual photon (usually $*$ is not written)

(in Griffiths, time $\uparrow$.. $\to$ is more standard)

- EM interaction: charged particles
  all quarks, e, μ, τ, $W^\pm$

- Strong interaction: only quarks & gluons!

- Weak: all

Neutrinos see only weak interactions!

1.3. Hadrons

- Strong interaction binds quarks (and gluons) into bound states, **hadrons**:

  qqq 3 quarks : **baryons**

  p : uud
  n : udd
  Λ : uds ... +

  $q\bar{q}$ quark + antiquark : **mesons**

  π^+ : $u\bar{d}$
  π^- : $d\bar{u}$
  π^0 : $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ .... +

Why?

- Quarks (and actually gluons) have a "strong color charge" which has 3 values: R, G, B
- Antiquarks have $\bar{R}, \bar{G}, \bar{B}$ ($\bar{R} = -R$)

- QCD: only color neutral states exist!

  Simplest:
  - $R\bar{R}$, $G\bar{G}$, $B\bar{B}$ — mesons
  - RGB (sums to neutral, like color!) — baryons
  - $\bar{R}\bar{G}\bar{B}$ — antibaryons

History: color was invented as a quantum number in 60's to explain baryons:

Δ^{++} : uuu
$$\begin{cases} \text{el. charge } +2 \\ \text{spin } +\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{3}{2} \\ \text{all quarks in the orbital ground state} \end{cases}$$

It is not possible to have identical fermions

→

$\Rightarrow$ in the same state $\Rightarrow$ need new quantum number with (at least) 3 values:

Δ^{++} : $u_R u_G u_B$ antisymmetrised

- In 70's it was understood that the color has a dynamical role, it is the "charge" of strong interactions (QCD)

- No colorful states ever seen! Forbidden by QCD (single quarks, gluons) - Color confinement, Quark confinement

- Exotic combinations:

  not probably seen

  pentaquarks: Θ^+ $udud\bar{s}$ 1,54 GeV

  glueballs: only gluons! ~ 1.6 GeV

  some candidates

- $\exists$ hundreds of hadrons, but only proton is stable (Baryon number conservation)

- Hadronic structure is very complicated

  - quarks + gluon fields
  - don't know how to compute analytically / perturbatively
  - lattice QCD, computer simulations

86

BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N p	uud	$+1$	938.280	∞	—
N n	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	$+1$	1189.4	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	-1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	-1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	$+1$	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	$+2, +1, 0, -1$	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	$+1, 0, -1$	1385	2×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	$0, -1$	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	-1	1672	0.82×10^{-10}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

PSEUDOSCALAR MESONS (Spin 0)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	$+1, -1$	139.569	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	$+1, -1$	493.67	1.24×10^{-8}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^\pm\pi^\mp$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	$0, 0$	497.72	K_S^0 0.892×10^{-10}	$\pi^+\pi^-$, $\pi^0\pi^0$
				K_L^0 5.18×10^{-8}	$\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$
η'	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi$, $\rho^0\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	$+1, -1$	1869	9×10^{-13}	$K\pi\pi$
D^0, $\bar{D}^0$	$c\bar{u}$, $u\bar{c}$	$0, 0$	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}$, $s\bar{c}$	$+1, -1$	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}$, $b\bar{u}$	$+1, -1$	5271	14×10^{-13}	$D + ?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	$0, 0$	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

"Strange" $S \neq 0$

"Charmed" $C \neq 0$

Charmed and strange

VECTOR MESONS (Spin 1)

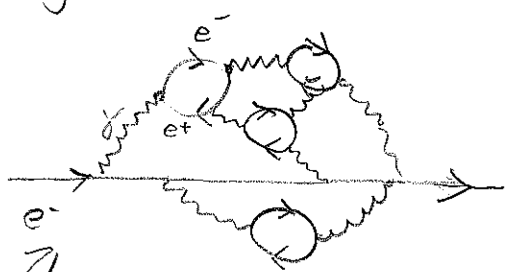
Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}$, $d\bar{u}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$	$+1, -1, 0$	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$	$+1, -1, 0, 0$	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0$, $\pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	K^+K^-, $K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $d\bar{c}$, $c\bar{u}$, $u\bar{c}$	$+1, -1, 0, 0$	2010	$>1 \times 10^{-22}$	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-

1.5 QCD and asymptotic freedom

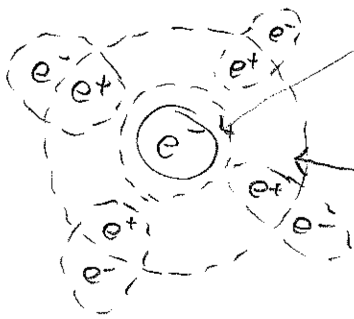
- Quark confinement

- (Pictorial explanation in Halzen, Martin pg. 9)

- Consider e^- in QED: e^- is surrounded by a cloud of virtual e^+e^--pairs:



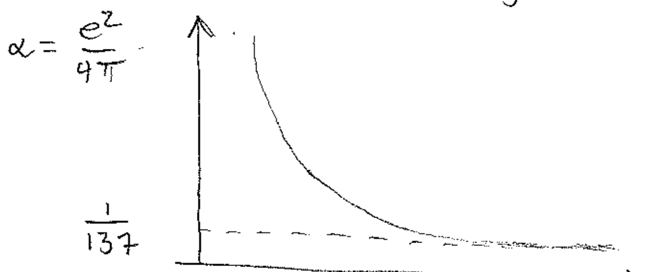
only 1 vertex:



more charge here

than here

"Vacuum polarization" → e^- charge effectively reduced at long distances!

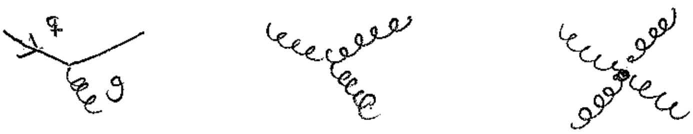


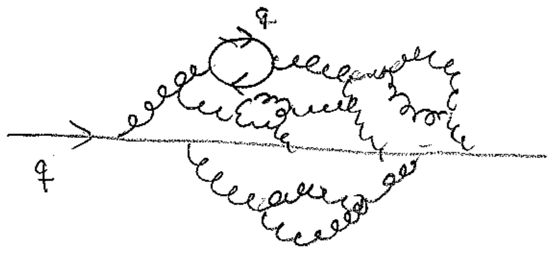
"shadowing", "screening"

⇒ Normal e is the charge seen at dist $= \infty$

- In QCD the crucial difference is that gluons interact:

vertices

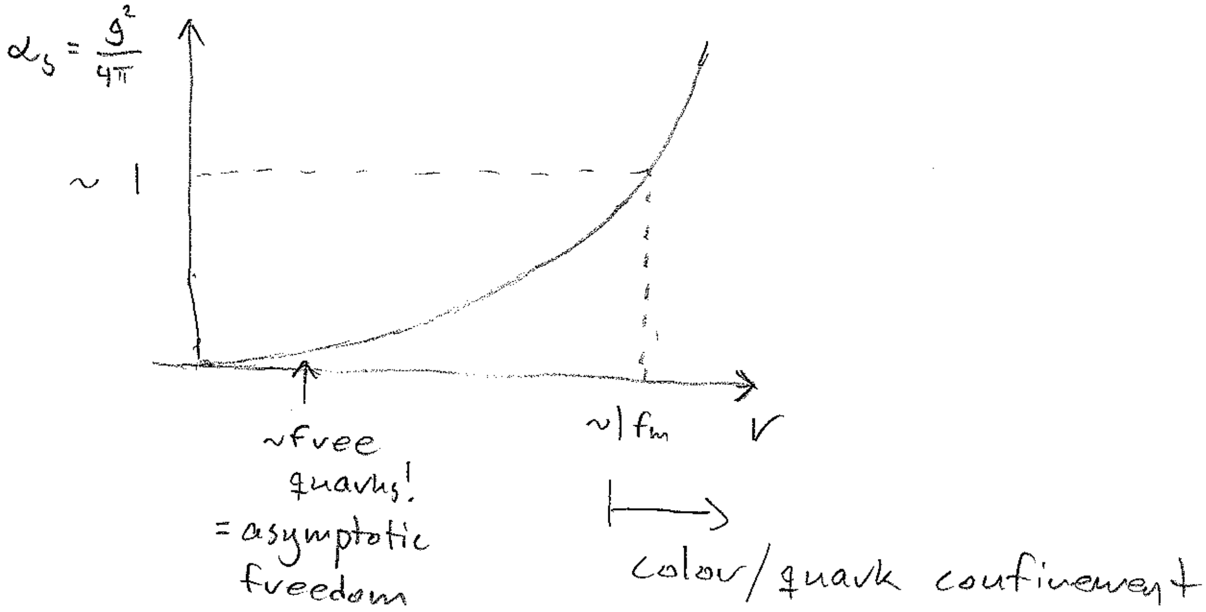




screening by q-loops canceled by gluons

Gluons <u>antishadow</u> (calculated in QCD 1974, Nobel 2004)

$\Rightarrow$ <u>asymptotic freedom</u> (for quarks)

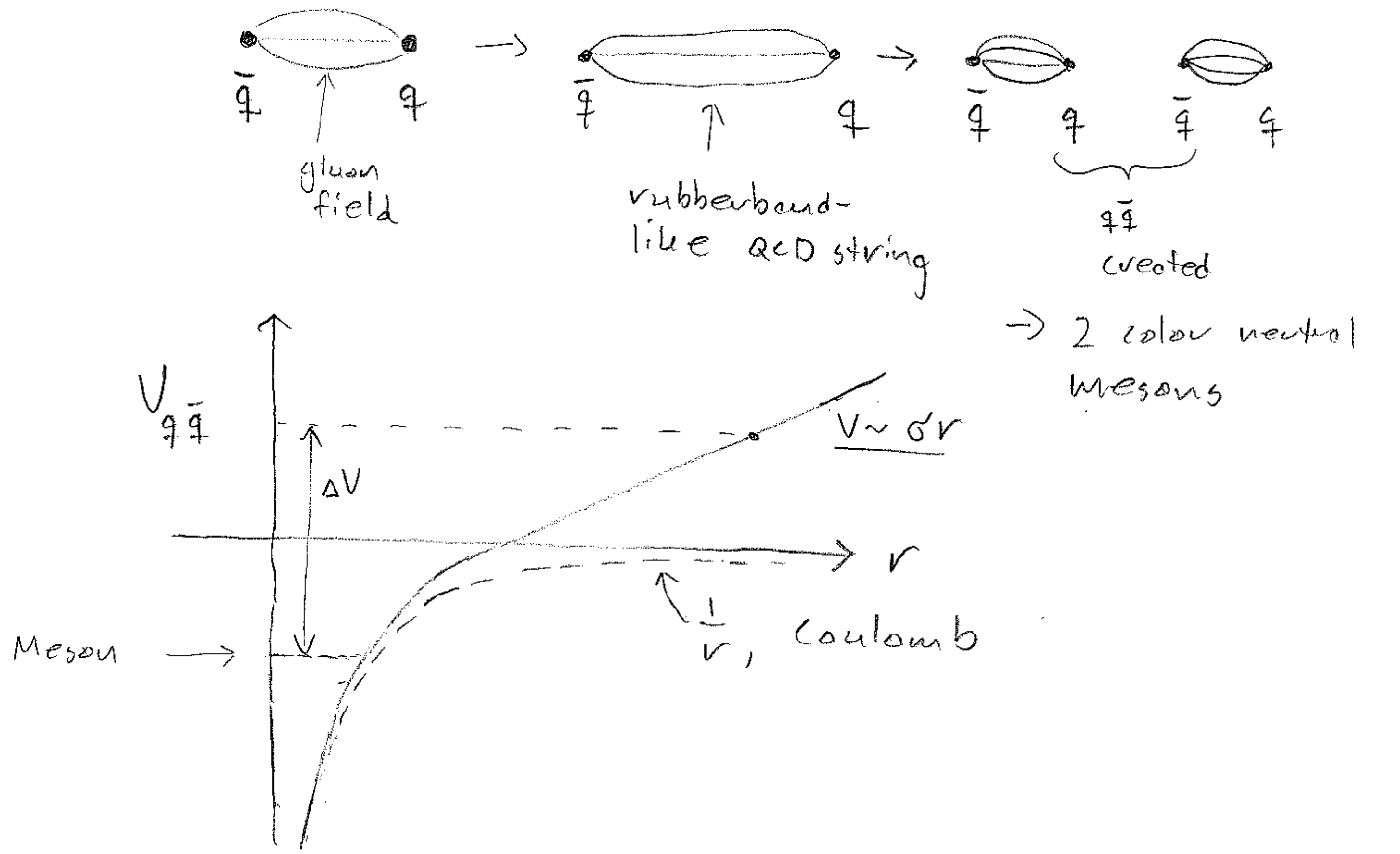


Small distance $\rightarrow$ large energy ($\Delta p \Delta x \sim 1$)

$\Rightarrow$ at very large energies we can "see" $\sim$free quarks inside hadrons

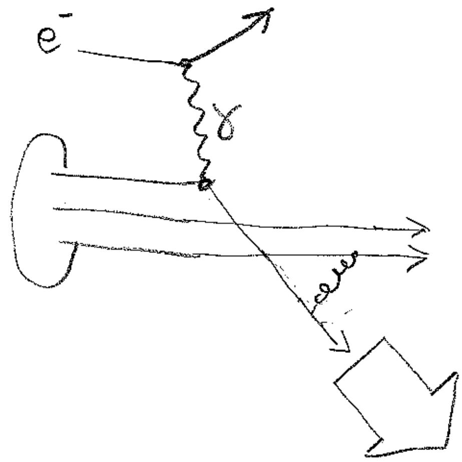
- Quarks (proton substructure) observed in 1969: large angle scattering in e^-p -collisions: <u>pointlike</u> charges within proton

- What happens if we try to pull quark away from proton (meson, for simplicity)



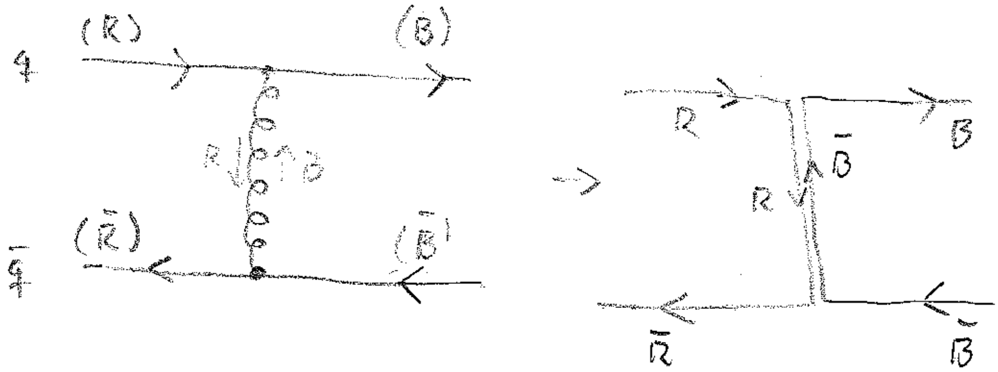
- Potential between q and $\bar{q}$ linearly increasing at large r : $V \sim \sigma r$, $\underline{\sigma \text{ string tension}}$.
- When $\Delta V = m_{meson}$, it becomes energetically favourable to create $q, \bar{q}$-pair and to form a new meson $\Rightarrow$ string "breaks"
- Seen in numerical simulations!

In real experiments: p-e⁻ scattering at high energy

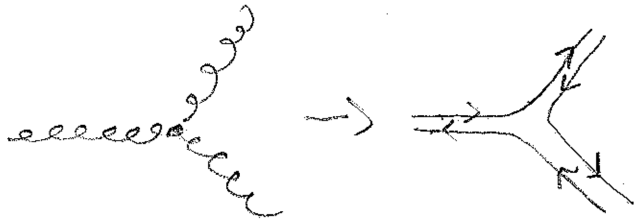


hadron jet with a large number of hadrons!

- Color flow in QCD interactions:



- gluon carries color and anticolor
- in gluon-gluon vertices



1.6. Particle properties

- Particles characterised by a few properties. "Official" list: Particle Data Group (PDG) Book & booklet

- mass
- lifetime, decay rate $= \frac{1}{\text{lifetime}}$ $\quad \Gamma = \frac{1}{\tau}$
- decay channels (determined by interactions)
- Quantum numbers:
  - spin J (fermions/bosons)
  - electric charge Q (in units of e)
  - baryon number $B = \frac{1}{3}$ (quarks), $-\frac{1}{3}$ (antiquarks)
    $B = 0$ others
  - lepton number $L = 1$ $(e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau)$, -1 (anti)
    $L = 0$ others

In classic standard model where $m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$ there are 3 absolutely conserved lepton numbers:

$L_e = 1$ (e, ν_e) ; $L_\mu = 1$ (μ, ν_μ) ; $L_\tau = 1$ (τ, ν_τ)

$= 0$ otherwise.

However, ν-oscillations infer $m_\nu \neq 0$, and these are not completely conserved, but

$$L = L_e + L_\mu + L_\tau$$

is. However, L_e etc. are conserved to a very good accuracy in normal processes

- Parity $P = \pm 1$, Charge conjugation $C = \pm 1$

  (note: in general particles not eigenstates of C)

- Flavor quantum numbers

  - Isospin $I_3 = +\frac{1}{2}$ (u), $-\frac{1}{2}$ (d)
  - Strangeness $S = -1$ (s), 0 others
  - Charmness $C = +1$ (c), 0 others
  - Bottomness, Topness $B = -1$ (b), $T = +1$ (t)

Some quantum numbers are fully conserved in Standard Model (Q, B, L); others only approximately (conserved only in strong interactions)

Decays:

e^- : $J = \frac{1}{2}$, $Q = -1$, $L = 1$, $m_e = 0.511$ MeV

μ^- : ″ $m_\mu = 105.7$ MeV

lifetime τ: $\tau = \infty$ SM, $\tau > 4.6 \times 10^{26}$ y (measured)

Myon lifetime $\tau = 2.2 \times 10^{-6}$ s

Decays through channel

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

(J, Q, L equal on both sides!)

On the other hand, lifetime of τ-lepton 2.9×10^{-13} s

$m_\tau = 1.78$ GeV

Decay channels: probability, branching ratio

$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$	17%
$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$	18%
$\tau^- \to \pi^- + \pi^0 + \nu_\tau$	25%
$\tau^- \to \pi^- + 2\pi^0 + \nu_\tau$	9%

... others

($m_{\pi_0} = 135$ MeV, $m_{\pi^-} = 140$)

(Here μ^-, π decay further)

Note about decays:

- Quantum mechanical decay probability is constant in time. Thus, if we have n myons, say,

$$\partial_t n = -\Gamma n \quad \Rightarrow \quad \underline{n(t) = n_0 e^{-\Gamma t}}$$

and mean lifetime

$$\underline{\tau} = \frac{\int_0^\infty dt\, t\, e^{-\Gamma t}}{\int_0^\infty dt\, e^{-\Gamma t}} = \underline{\frac{1}{\Gamma}}$$

- Mean lifetime $\neq$ half-life $\equiv$ time in which ½ of particles is gone

$$\frac{\int_0^{\tau_{1/2}} e^{-\Gamma t}}{\int_0^\infty e^{-\Gamma t}} = 1 - e^{-\Gamma \tau_{1/2}} = \frac{1}{2} \Rightarrow \tau_{1/2} = \frac{1}{\Gamma} \ln 2$$

Conservation laws (at each vertex $\Rightarrow$ total process)

- B, L (L_e, L_μ, L_τ), Q conserved
- $E, \bar{p}$ (or 4-momentum p) conserved
- Flavour quantum numbers:

  I_3, S, C, B, T $\begin{cases} \text{- conserved in QCD, EM} \\ \text{- violated by weak!} \end{cases}$

  ← Still usable, because weak interactions slow!
- Parity P, charge conjugation C
  - Conserved QCD, EM; violated in weak

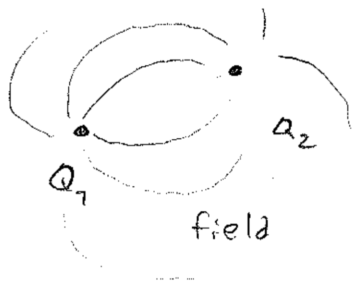
1.7. More about interactions

- In classical physics interactions are mediated through <u>continuous fields</u>

  E.g. Coulomb force

  $$\vec{F} = \frac{Q_1 Q_2}{4\pi r^2}\,\hat{e}_r$$

  is due to electric field between Q_1 and Q_2.

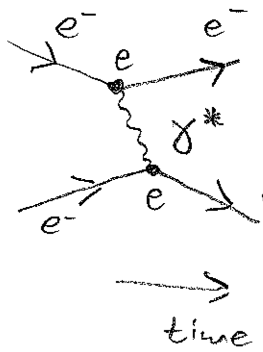


- In Quantum Field Theories (QFT), which underlie all particle physics, interaction is an exchange of <u>quanta</u>. Many quanta $\rightarrow$ continuous fields.

1.7.1 Electromagnetic interaction QED

$e^- e^- \rightarrow e^- e^-$

Feynman diagram



γ^* <u>virtual</u> photon

"Real" particles:

$$\underline{E^2 = m^2 + p^2} \qquad (\hbar = c = 1)$$

Virtual particles do not need to obey this!

<u>Virtuality</u> $(\Delta E)^2 = |E^2 - (m^2 + p^2)| = |E^2 - p^2|$ for photon.

Sometimes it is said that $m_{\gamma^*} \neq 0$ (or, more generally, $m_{virt} \neq m_{Real}$)

Virtual particles called <u>off-shell</u> (off mass-shell).
"Real" <u>on-shell</u> (on mass-shell)

- External particles <u>always on-shell</u>, internal lines more or less off-shell

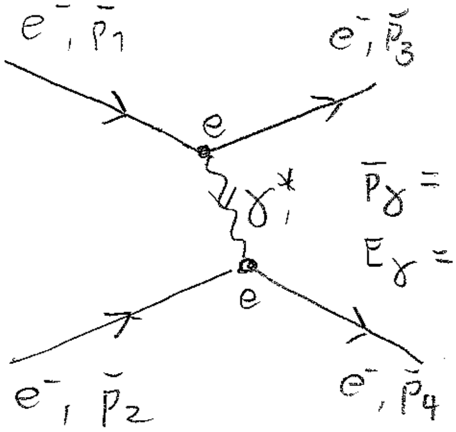
- Uncertainty principle: $\Delta t \Delta E = \hbar = 1$; $\Delta x \Delta p = 1$
  - lifetime: $\underline{\Delta t_{\gamma^*} \simeq 1/\Delta E_{\gamma^*}} \sim 1/E_{\gamma^*}$ ← typically
  - Range: $\underline{\Delta r_{\gamma^*} \simeq 1/\Delta E_{\gamma^*}}$

- E and $\bar{p}$ conserved in each vertex!

- <u>Note</u>: repulsion of particles is easy to imagine with the above diagram. However, because of virtuality of γ^* the interaction can be attractive or repulsive!

- Roughly: $\begin{cases} \text{on-shell} \rightarrow \text{propagating "classical" particles} \\ \text{off-shell} \rightarrow \text{"classical" fields} \end{cases}$

Momentum and energy are completely conserved at each vertex:



$$\bar{p}_\gamma = \bar{p}_1 - \bar{p}_3 = \bar{p}_4 - \bar{p}_2$$
$$E_\gamma = E_1 - E_3 = E_4 - E_2$$
$$(\Delta E)^2 =$$

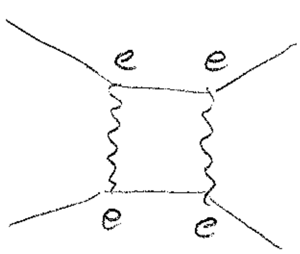
This diagram corresponds to probability amplitude

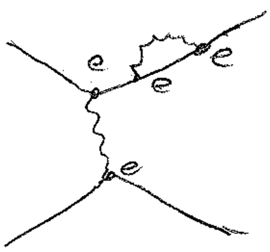
$$T^{(0)}_{if} = {}_{out}\langle e^-_3\, e^-_4 \,|\, \hat{T} \,|\, e^-_1\, e^-_2 \rangle_{in} =$$  $$\sim \frac{e^2}{\Delta E^2_{\gamma^*}}$$ quite general

and the probability or cross-section is

$$\boxed{\sigma^{(0)} \sim |T|^2 = \Big|}$$  $$\boxed{\Big|^2 \sim \frac{e^4}{(\Delta E)^4}}$$

At higher order corrections





These are clearly higher order in e^2 (suppressed by α → QED converges well!)

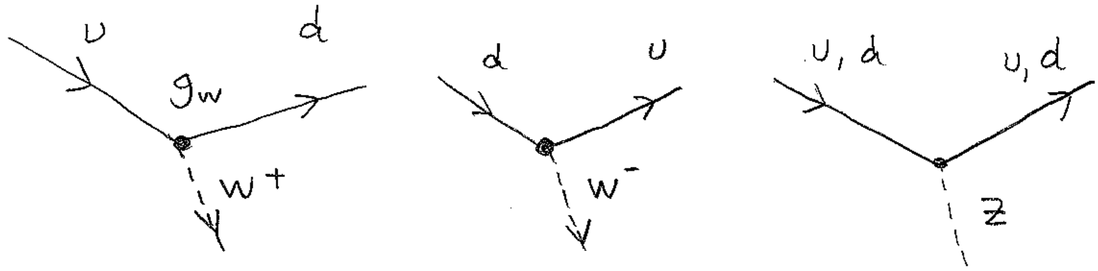
$$\sigma = \sigma^0 (1 + O(\alpha))$$

1.7.2 Weak interaction

- W^+, W^-, Z^0 , $m_{W^\pm} = 80{,}3$ GeV ($\sim 80\, m_p$)

  $m_Z = 91{,}2$ GeV

- Important vertices:

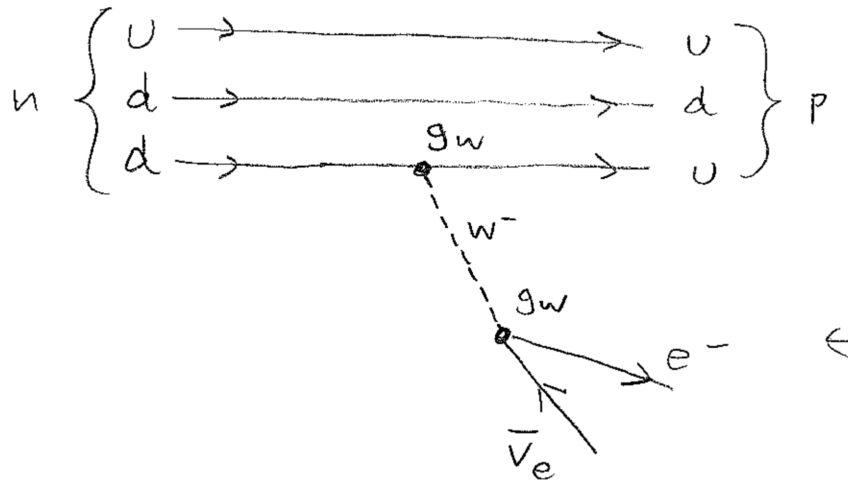


where u is any of u, c, t and d d, s, b.

- Likewise for leptons, substituting $\begin{cases} u \to \nu \\ d \to e \end{cases}$

- Antiparticles : $\begin{cases} u \to \bar{u} \\ d \to \bar{d} \\ W^\pm \to W^\mp \\ Z \to Z \end{cases}$

- For example, decay of neutron: (β-decay)



(Q, B, L_e conserved)

Switching to

describes $\nu_e n \to e^- p$ scattering

lifetime 869 s (free n) !

$^{10}C \to {}^{10}B + e^+ + \nu_e$, $\tau = 20\,s$

Virtuality of W: n at rest,

$E_d \sim |\vec{p}_d| \sim E_u \sim |\vec{p}_u| \lesssim 1\,\text{GeV} \ll m_W$

$\Rightarrow E_W \sim |\vec{p}_W| \ll m_W$

$\Rightarrow$ virtuality $\underline{\Delta E^2} = |E^2 - (m^2+p^2)| \simeq \underline{m_W^2}$ $\Rightarrow$ Range $\sim 2\cdot 10^{-3}$ fm

Thus, we can guesstimate the amplitude (typical for weak)

$$\underline{T \sim \frac{g_W^2}{M_W^2}} \sim G_F = \sqrt{2}\,\frac{g_W^2}{8M_W^2}$$

Fermi constant, used to parametrise weak interactions.

The <u>smallness</u> of weak interactions is due to the <u>large mass of W, Z !</u>

Coupling constant g_W is actually of order e: $\underline{g_W \simeq 2e}$ (electron charge = QED coupling constant)

- Decay rate $\underline{\Gamma = \frac{1}{\tau} \sim G_F^2 m_n^5}$
- This is universal and depends only of the mass of the decaying particle:

$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad \Gamma \sim G_F^2 m_\mu^5$

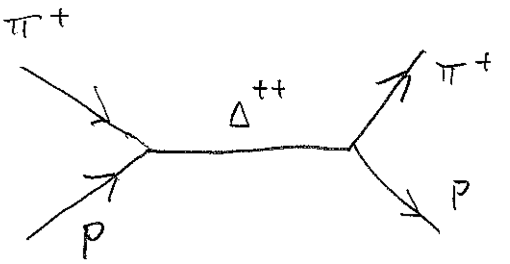
$\tau^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad \Gamma \sim G_F^2 m_\tau^5$

Thus, $\dfrac{\tau_\tau}{\tau_\mu} \simeq \dfrac{0{,}18}{1}\left(\dfrac{m_\mu}{m_\tau}\right)^5 \simeq 1.3\cdot 10^{-7}$

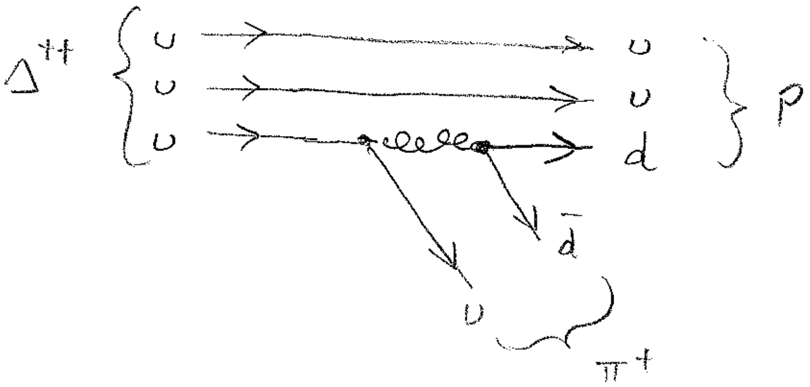
branching ratios, page 14

1.7.3 Strong interactions

- Consider process $\pi^+ p \to \Delta^{++} \to \pi^+ p$



- At quark level, $\Delta^{++} \to \pi^+ p$:



- Very fast, $\tau_{\Delta^{++}} \sim 10^{-23}$ sec (typical for strong)

1.8 Relative strength of interactions

Typical lifetimes :

Strong : $\tau \sim 10^{-24} - 10^{-22}$ s (above)

EM : $\tau \sim 10^{-16}$ s ($\pi^0 \to \gamma\gamma$)

Weak : $\tau \sim \underset{\uparrow \tau}{10^{-13}\,\text{s}} - \underset{\uparrow \mu}{10^{-6}\,\text{s}}$, up to 15 min (n)

→

Crude measure!

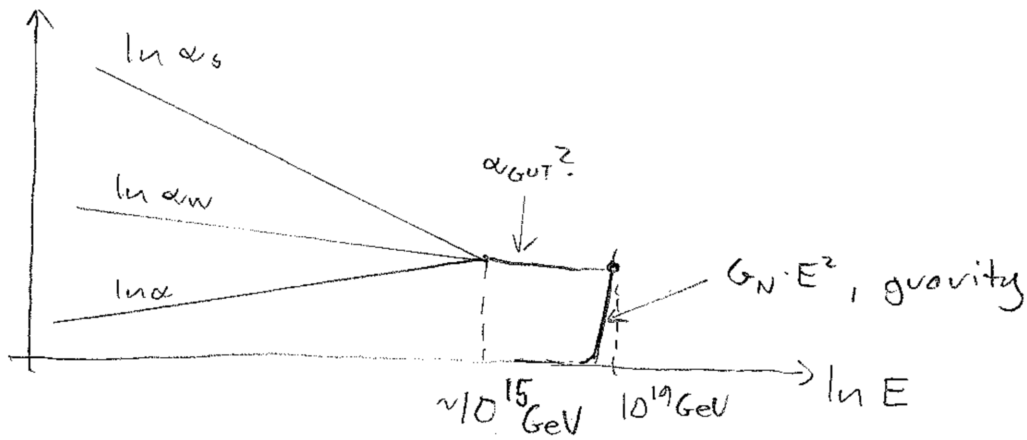
	strength	at particle physics scale
strong	1	α_s
EW	10^{-2}	α
Weak	10^{-6}	$\tau \propto \alpha^2 \Rightarrow \alpha_w^{eff} \sim \left[\frac{10^{-24}}{10^{-12}}\right]^{1/2} \alpha_s$
Gravity	10^{-39}	G_N/m_p^2

These are very observable-dependent!

- Note: if energy in a particle physics experiment is $> m_W$, weak interaction is not weak any more! (stronger than EM, $g_W \sim 2e$)
  $\rightarrow$ can produce W, Z at high energies

1.9. What happens at much higher energies than m_W ?

- We don't know if S.M. remains valid!
- Higgs ? assume Higgs is found and S.M. valid: evolution of α's can be calculated:



- Roughly unify at $\sim 10^{15}$ GeV !
  $\Rightarrow$ New theory which unifies all interactions ?

Grand Unified Theory, GUT ?

Gravity kicks in when $E \sim M_{PLANCK} = \frac{1}{\sqrt{G_N}}$

$\Rightarrow$ need quantum gravity, not known!

- Superstrings?

- However S.M. itself has problems:

  Higgs mass requires precise fine-tuning for the theory to remain physical to relative accuracy $\frac{\delta m_H^2}{m_H^2} \simeq \frac{m_W^2}{E^2}$

- Unnatural at large E! "Hierarchy problem"

$\Rightarrow$ New theory already visible at $E \gtrsim 1$ TeV?

- Supersymmetry, extra dimensions, ...
- Possibly visible at LHC?
- Theoretical favourite (?): Supersymmetry (SUSY)
  - More than doubles the number of particles!
  - does not ruin unification

- No completely convincing candidates known
  $\rightarrow$ nature can surprise us (again)?

(LHC starts 2007, results 2009 $\rightarrow$)

- Open questions in S.M.:
  - Higgs? m_H, or is it elementary at all?
  - m_ν? Currently under active study

  } LHC + other exp.

  - theoretical problems: why 3 families? why such a variety of masses?

1.10 Cosmology

In the Big Bang model the temperature of the Universe evolves as (expansion)

$$\frac{T}{10^{10}K} \sim \frac{T}{1\,MeV} \sim \frac{1}{\sqrt{t/sec.}}$$, where t is the age of the Universe

- Energy of particles $E \sim T$, distance $\sim \frac{1}{T}$

$\Rightarrow$ when $t \lesssim 10^{-12}s$, $E \gtrsim 1\,TeV \sim$ highest energy of present accelerators! (LHC $\sim$ 7 TeV)