1. Overview of Particle Physics

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1.1 Elementary Particles and Interactions

Key questions:

- Which are the elementary building blocks of nature?
- Which are the interactions among them?

Answers are space-time dependent:

- Ancient Greeks: earth, water, air and fire
- . . .
- Current pragmatical view: it depends on the energy scale we probe nature

Energy	Elementary Particles	Interactions	Range	Mediator
$\lesssim$ eV	atoms	complicated potentials	long (Van der Waals)	??
$\sim$ keV	e^-, nuclei	e.m. potentials	long (Coulomb)	??
$\sim$ MeV	e^-,e^+, p, n, ν_e, $\bar{\nu}_e$	e.m. strong weak	long short zero	photon ? ?
$\sim$ GeV	plus μ^-, ν_μ, light hadrons, and their antiparticles	e.m. strong weak	long short zero	photon pion?mesons? ?
$\sim$ 10 GeV	plus τ, ν_τ, quarks (u,d,s,c,b) and their antiparticles	e.m. strong weak	long short (?) zero	photon gluon (?) ?
$\sim$ TeV	plus $W^\pm$, Z^0, t, H^0	e.m. strong weak	long long short	photon gluon $W^\pm$, Z^0

Natural Units

- At subatomic scales, we need Quantum Mechanics $\Longrightarrow$ there will be $\hbar$ in all formulas
- At high speeds, we need Special Relativity $\Longrightarrow$ there will be c in all formulas

A clever way to avoid the proliferation of $\hbar$ and c is just not writting them, namely taking $\hbar = c = 1$. Then

- Any dimensionful magnitude reduces to some power of energy (eV).
- SI units are recovered by plugging in the appropriated powers of $\hbar$ and c, and using 1 eV $\simeq 1.6\, 10^{-19}$ J
- It is more convenient to develope intuition in natural units:

$$E_{\rm Rydberg} = 13.6 \text{ eV},\ m_e \simeq 0.5 \text{ MeV},\ m_p \simeq 940 \text{ MeV}$$

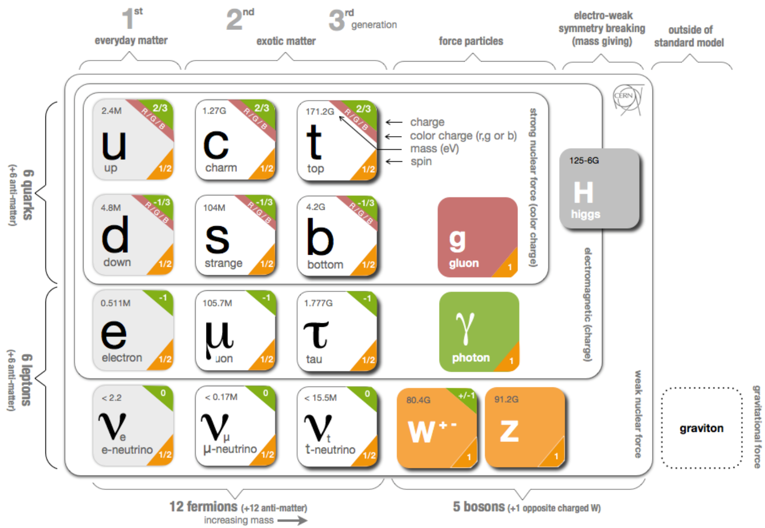
However, for distances (L) and cross sections (L^2) traditional units are still used:

- Fermis (fm) for distances (1 fm $= 10^{-15}$ m, $\hbar c \simeq 197$ MeV fm, $r_p \sim 0.84$ fm)
- Barns (b) for cross sections (1 b$=$ 100 fm^2, $\sigma_{np\to np}^{\rm thermal} \simeq 82$ b, $\sigma_{pp}^{\rm total}(13\,{\rm TeV}) \sim 110$ mb, $\sigma_{pp\to Z^0}^{\rm total}(13\,{\rm TeV}) \simeq 2$ nb)

The most relevant physical magnitudes and conversion factors can be found here

The Standard Model

Elementary Particles and Interactions at energies $\lesssim 10$ TeV



Apparent puzzles:

- Quarks and gluons are not observed as free particles, why?
- Gluons are massless but strong interactions short range, why?

Is that all? Definitely not:

- Gravity
  - Extremelly weak, neglegible at subatomic distances
  - Long range $\Longrightarrow$ massless mediator
  - Gravitational wave detection, indirect (1974) and direct (2015) suggests that an additional elementary particle exists, the graviton.
- Dark Matter
  - Gravitational effects detected at galactic and cosmological level
  - No e.m. signals observed
  - Suggests that at least one new kind of particle must exist

The highest energies in nature

- Collider
  - Present: LHC ~ 13 TeV
  - Future: FCC(hh) ~ 100 TeV, FCC(he) ~ 50 TeV, FCC(ee) ~ 30 TeV
- Cosmic rays
  - Ultrahigh Energy Cosmic Rays (UHECR), $E > 10^4$ TeV
  - World record $E \sim 3.10^8$ TeV (Utah, 1991)

Tools

- At subatomic scales, we need Quantum Mechanics
- At high speeds, we need Special Relativity

The combination of these two theories leads to Quantum Field Theory:

- The states contain an arbitrary number of particles
- The states correspond to unitary representations of the Poincaré group ($ISO(3,1)$)
  - The irreducibe unitary representations of $ISO(3,1)$ are characterized by

$$m^2 \in \mathbb{R}^+ \quad , \quad \mathbf{p} \in \mathbb{R}^3 \quad , \quad J \in \mathbb{Z}^+/2 \quad , \quad J_3$$

    - ★ If $m \neq 0$, $J_3 = -J, -J+1, \ldots, J-1, J$
    - ★ If $m = 0$, $J_3 = -J, J$
  - Elementary particles are expected to follow this pattern, even beyond the Standard Model (SM)
  - No hint of Poincaré invariance violation has been observed so far

In the SM:

- Matter Fields: $J = \frac{1}{2}$
  - Quarks and charged leptons: $m \neq 0$
  - Neutrinos: $m \sim 0$
- Mediators: $J = 1$
  - Photons and gluons: $m = 0$
  - $W^{\pm}$, Z^0: $m \neq 0$
- Higgs: $J = 0$, $m \neq 0$

Beyond the SM (expected):

- Graviton: $J = 2$, $m = 0$
- Dark Matter $J =?$, $m =?$
- ...

Strength of the Interactions

	$E \sim m_p \sim 1$ GeV (low energy physics)	$E \sim m_Z \sim 100$ GeV (high energy physics)
Strong	$\alpha_s(m_p) \sim 1$	$\alpha_s(m_Z) \sim 0.1$
Electromagnetic	$\alpha(m_p) \sim \frac{1}{137} \sim 10^{-2}$	$\alpha(m_Z) \sim \frac{1}{129} \sim 10^{-2}$
Weak	$G_F m_p^2 \sim 10^{-5}$	$\alpha_W(m_Z) = \frac{m_W^2 G_F}{4\pi}$ $\sim 0.58\,\alpha \sim 10^{-2}$
Gravity	$G m_p^2 \sim 10^{-39}$	$G m_Z^2 \sim 10^{-35}$

$G_F \sim 1.66\,10^{-5}$ GeV^{-2}, $G \sim 6.7\,10^{-39}$ GeV^{-2}, $m_p \sim 0.94$ GeV, $m_W \sim 80$ GeV, $m_Z \sim 91$ GeV.

- At $E \sim m_Z$ weak and electromagnetic interactions have the same strength $\Longrightarrow$ Electroweak unification
- Is there a scale where strong and electroweak interactions have the same strength?
  - Yes, $E \sim 10^{16}$ GeV, Grand Unification scale
- Is there a scale where gravity becomes as important as the other interactions?
  - Yes, $E \sim G^{-\frac{1}{2}} \sim 10^{19}$ GeV, Planck scale

Conservation laws

- Related to space-time symmetries:
  - Energy and momentum conservation
  - Angular momentum conservation
- Related to internal symmetries:
  - Electric charge
  - Baryonic number (B)
  - Leptonic number (L)
    - ★ Electronic, muonic and tauonic numbers are conserved in the SM, but not in nature (neutrino oscillations)
    - ★ Subtle quantum effects violate both B and L at (nowadays) unobservable level in the SM so that only B+L is actually conserved
- Strong and electromagnetic interactions also conserve
  - Parity
  - Charge conjugation
  - Time reversal
  - Flavor

1.2 Baryons and Mesons

In the SM quarks and gluons are the building blocks of the strong interactions, but in nature only hadrons, particular combinations of quarks and antiquarks, mostly mesons and baryons, are observed.

- Why free quarks and gluons are not observed?
- Why the strong interactions are short range if the gluon is massless?
- Why only particular combinations of quarks and antiquarks are observed?

Mesons and baryons can be organized in representations of $SU(2)$, Isospin

- Lighter Mesons

Meson	Mass (MeV)	Decay width (MeV)	J^{PC}	Isospin
(π^+, π^0, π^-) $(u\bar{d}, [u\bar{u}, d\bar{d}], d\bar{u})$	140	$\Gamma_{\pi^+\to\mu^+\nu_\mu} = 2.5\,10^{-14}$ $\Gamma_{\pi^0\to\gamma\gamma} = 7.7\,10^{-6}$	0^{-+}	1
$f_0(500)$ or σ	$400-550$	$400-700$	0^{++}	0
η $([u\bar{u}, d\bar{d}])$	548	$1.3\,10^{-3}$	0^{-+}	0
(ρ^+, ρ^0, ρ^-) $(u\bar{d}, [u\bar{u}, d\bar{d}], d\bar{u})$	770	148	1^{--}	1
ω $([u\bar{u}, d\bar{d}])$	782	8.5	1^{--}	0

- Except for the σ, the remaining particles can be understood as composed of a quark and an antiquark with spin $J = 1/2$ and isospin $I = 1/2$ in a state of $L = 0$ orbital angular momentum. The up (u) and down (d) components of the isospin doublet must have electric charges $Q_u = 2/3e$ and $Q_d = -1/3e$.

$$J = \frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1 \quad , \quad I = \frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1$$

- Lighter Baryons

Baryon	Mass (MeV)	Decay width (MeV)	J^P	Isospin
$(p\,,n)$ $(uud\,,udd)$	940	$\Gamma_p < 4.9\,10^{-49}$ $\Gamma_{n\to p\,e^-\,\bar{\nu}_e} = 6.3\,10^{-25}$	$\frac{1}{2}^+$	$\frac{1}{2}$
$(\Delta^{++}\,,\Delta^{+}\,,\Delta^{0}\,,\Delta^{-})$ $(uuu\,,uud\,,udd\,,ddd)$	1.232	117	$\frac{3}{2}^+$	$\frac{3}{2}$

- Can be understood as composed of three quarks in a state where all orbital angular momentum are zero.

$$J=\frac{1}{2}\otimes\frac{1}{2}\otimes\frac{1}{2}=\frac{1}{2}\oplus\frac{1}{2}\oplus\frac{3}{2}\quad,\quad I=\frac{1}{2}\otimes\frac{1}{2}\otimes\frac{1}{2}=\frac{1}{2}\oplus\frac{1}{2}\oplus\frac{3}{2}$$

But:

- ⋆ The 3/2 representation is totally symmetric under the exchange of any of the two quarks $\Longrightarrow$ Δs violate Pauli principle

Color

- We need a new quantum number such that the product of the three fundamental representations gives a totally antisymmetric representation
- This is achieved assuming that quarks are in the fundamental representation of $SU(3)$

However:

- Color multiplets are not observed
    - The dynamics must only allow color singlet states as observable states
    - The product of three fundamental representations must contain a color singlet one
- This is achieved in QCD, which has the gluons (8) as mediators

Quarks (3), antiquarks (3^*) and gluons (8) must be combined to form color singlet states (1). We shall see by studying the products of $SU(3)$ representations that:

$$3 \otimes 3^* = 1 \oplus 8 \quad , \quad 3 \otimes 3 = 3^* \oplus 6 \quad , \quad 3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

Hence, quark-antiquark and three quark states can exist as physical states but quarks, gluons or quark-quark states cannot.

- Are there hadrons beyond mesons and baryons?
  - QCD allows it
  - σ and κ are most likely two-quark two-antiquark states
  - Unambiguous identification requires heavy quarks:
    - Tetraquarks: $Z_c(3900)$ $(uc\bar{d}\bar{c}\,,[uc\bar{u}\bar{c}\,,dc\bar{d}\bar{c}]\,,dc\bar{u}\bar{c})$, $Z_b(10610)$ $(ub\bar{d}\bar{b}\,,[ub\bar{u}\bar{b}\,,db\bar{d}\bar{b}]\,,db\bar{u}\bar{b})$, $Z_{cs}(3985)$ $(cs\bar{c}\bar{u}\,,cs\bar{c}\bar{d})$, $X(6900)$ $(cc\bar{c}\bar{c})$, $T_{cc}(3875)$ $(cc\bar{d}\bar{d}\,,[cc\bar{u}\bar{d}\,,cc\bar{d}\bar{u}]\,,cc\bar{u}\bar{u})$, ...
    - Pentaquarks: $P_c(4312)^+(uudc\bar{c})$, ...
- At low energies, the strong interactions are short range, because the lightest physical states are the pions ($m_\pi \sim 140$ MeV)

1.3 Weak interactions

- Typical decay width of hadron resonances (ρ,ω,Δ) $\sim$ 1-100 MeV
- But the hadrons in the lightest isospin multiplets ($\pi^{\pm}$,π^0,p,n) have much smaller decay widths
  - Isospin is (approximately) conserved in the strong interactions
  - The hadrons in the lightest isospin multiplets must decay through a different interaction
    - ★ Electromagnetic (π^0). Decay width $\sim 10^{-5}$ MeV
    - ★ Weak ($\pi^{\pm}$,n). Decay widths $\sim 10^{-14}$-10^{-24} MeV

Weak interactions are also necessary to explain:

- Muon decay $\Gamma_{\mu^- \to e^- \bar{\nu}_e \nu_\mu} = 2.6\,10^{-16}$ MeV
- Decays of the lightest strange hadrons: $\Gamma_{K^\pm} = 4.6\,10^{-16}$ MeV, $\Gamma_{K^0_S} = 6.3\,10^{-12}$ MeV, $\Gamma_{K^0_L} = 1.1\,10^{-14}$ MeV, $\Gamma_{\Lambda^0} = 2.1\,10^{-12}$ MeV

Strangeness

- Produced as particle-antiparticle pairs at the rate of strong interactions
- Organized in isospin multiplets
- The hadrons in the lightest multiplet decay through the weak interactions

$\Longrightarrow$ Strangeness is conserved by the strong interactions

- Strange mesons

Meson	Mass (MeV)	Decay width (MeV)	J^{PC}	I	S
(K^+, K^0) $(u\bar{s}, d\bar{s})$	495	$\Gamma_{K^+} = 4.6\,10^{-16}$ $\Gamma_{K^0} = 6.3\,10^{-12}$-$1.1\,10^{-14}$	0^-	$\frac{1}{2}$	1
$(\bar{K}^0, K^-)$ $(s\bar{d}, s\bar{u})$	495	$\Gamma_{K^-} = 4.6\,10^{-16}$ $\Gamma_{\bar{K}^0} = 6.3\,10^{-12}$-$1.1\,10^{-14}$	0^-	$\frac{1}{2}$	-1
$K_0^*(700)$ or κ	824	478	0^+	$\frac{1}{2}$	1
(K^{*+}, K^{*0}) $(u\bar{s}, d\bar{s})$	892	48	1^-	$\frac{1}{2}$	1
$(\bar{K}^{*0}, K^{*-})$ $(s\bar{d}, s\bar{u})$	892	48	1^-	$\frac{1}{2}$	-1
η' $([u\bar{u}, d\bar{d}, s\bar{s}])$	958	0.19	0^{-+}	0	0
ϕ $(s\bar{s})$	1020	4.2	1^{--}	0	0

- Except for the κ, the remaining particles can be understood as composed of a quark and an antiquark with spin $J = 1/2$ and isospin $I = 1/2$, and an extra quark, the strange one, with $J = 1/2$ and $I = 0$ in a state of $L = 0$ orbital angular momentum. The electric charge of the strange quark must be $Q_s = -1/3e$.
- Strange baryons

Baryon	Mass (MeV)	Decay width (MeV)	J^{PC}	I	S
Λ (uds)	1116	$2.1\,10^{-12}$	$\frac{1}{2}^+$	0	-1
$(\Sigma^+, \Sigma^0, \Sigma^-)$ (uus, uds, dds)	1190	$\Gamma_{\Sigma^+} = 7.0\,10^{-12}$ $\Gamma_{\Sigma^0} = 7.5\,10^{-3}$ $\Gamma_{\Sigma^-} = 3.7\,10^{-12}$	$\frac{1}{2}^+$	1	-1
(Ξ^0, Ξ^-) (uss, dss)	1318	$\Gamma_{\Xi^0} = 1.9\,10^{-12}$ $\Gamma_{\Xi^-} = 3.4\,10^{-12}$	$\frac{1}{2}^+$	$\frac{1}{2}$	-2
$(\Sigma^{*+}, \Sigma^{*0}, \Sigma^{*-})$ (uus, uds, dds)	1385	37	$\frac{3}{2}^+$	1	-1
(Ξ^{*0}, Ξ^{*-}) (uss, dss)	1530	9.5	$\frac{3}{2}^+$	$\frac{1}{2}$	-2
Ω^- (sss)	1672	$6.8\,10^{-12}$	$\frac{3}{2}^+$	0	-3

Discret Symmetries

- Parity (P) and Charge conjugation (C) are violated in a maximal way
- Additional small violations of CP in neutral kaon decays

1.4 More generations

Charm

- The existence of an extra quark beyond up, down and strange ones was predicted on basis that weak decays that change the quark flavor but not the electric charge (flavor changing neutral currents) were not observed ($\sim$ 1970). It was called charm (c)($Q_c = 2/3e$, $I = 0$) .
- The existence of charm was necessary in the electroweak theory ($\sim$ 1967)
- It was discovered in $e^+ e^- \to \gamma^* \to J/\psi$ in 1974, interpreting J/ψ as a $(c\bar{c})$ bound state

$$m_{J/\psi} = 3097\mathrm{MeV} \quad , \quad \Gamma_{J/\psi} = 0.093\mathrm{MeV} \quad , \quad J^{PC} = 1^{--}$$

- Charm mesons

Meson	Mass (MeV)	Decay width (MeV)	J^{PC}	I	C
(D^+, D^0) $(c\bar{d}, c\bar{u})$	1870	$\Gamma_{D^+} = 5.6\,10^{-10}$ $\Gamma_{D^0} = 1.4\,10^{-9}$	0^-	$\frac{1}{2}$	1
(D^{*+}, D^{*0}) $(c\bar{d}, c\bar{u})$	2010	0.083	1^-	$\frac{1}{2}$	1
η_c $(c\bar{c})$	2980	30	0^{-+}	0	0
J/ψ $(c\bar{c})$	3100	0.093	1^{--}	0	0

Bottom

- It was also discovered in $e^+ e^- \to \gamma^* \to \Upsilon$ in 1977, interpreting Υ as a $(b\bar{b})$ bound state ($Q_b = -1/3\, e$, I=0)

$$m_\Upsilon = 9460\,\mathrm{MeV} \quad , \quad \Gamma_\Upsilon = 0.054\,\mathrm{MeV} \quad , \quad J^{PC} = 1^{--}$$

- The electroweak theory implied then the existence of another quark, the top (t)
- Bottom and top were necessary to explain the *CP*-violation observed in the decays of the neutral kaons
- Bottom mesons

Meson	Mass (MeV)	Decay width (MeV)	J^{PC}	I	B
(B^+, B^0) $(u\bar{b}, d\bar{b})$	5280	$\Gamma_{B^+} = 3.4\,10^{-10}$ $\Gamma_{B^0} = 3.7\,10^{-10}$	0^-	$\frac{1}{2}$	1
(B^{*+}, B^{*0}) $(u\bar{b}, d\bar{b})$	5325	?	1^-	$\frac{1}{2}$	1
η_b $(b\bar{b})$	9400	10	0^{-+}	0	0
Υ $(b\bar{b})$	9460	0.054	1^{--}	0	0

QCD behaves very differently at the scale of the light quarks $(u\,,d\,,s)$ than at the scale of the heavy quarks $(c\,,b)$

$q=u,d$	$b\bar{b}$	$b\bar{q}$	$c\bar{c}$	$c\bar{q}$	$s\bar{s}$	$s\bar{q}$	$q\bar{q}(I=0)$	$q\bar{q}(I=1)$
$\frac{m_{1^{-}}-m_{0^{-}}}{m_{1^{-}}+m_{0^{-}}}$	0.003	0.004	0.020	0.036	0.031	0.28	0.17	0.69

- There is an approximate spin symmetry for hadrons containing one or two heavy quarks
- This is similar to the hydrogen atom and positronium
- The decay width of $Q\bar{Q}$, $Q=c\,,b$ are larger for the 0^{-+} state than for the 1^{--} state, like in positronium
- Suggests that QCD at high energies has similarities with QED

Top

- The last of the known quarks, the top $(Q_t=2/3\,e)$, was discovered in 1995 at the Tevatron, a $p\bar{p}$ collider

$$m_t=172\,\mathrm{GeV} \quad , \quad \Gamma_t=1.4\,\mathrm{GeV}$$

- It decays due to the weak interactions before forming hadrons $(G_F m_t^2 \sim 0.34)$