FYSH300, fall 2011

Tuomas Lappi
tuomas.v.v.lappi@jyu.fi

Office: FL249. No fixed reception hours.

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Part 1: Introduction

Dates, times

- Lectures: Mon, Wed at 14h15, FYS3
- Exercises: Mon, at 12h15, FYS5
  - Problems available online Friday, distributed on Monday's lecture **Return Monday by 9 o'clock to box in lobby**
- Teachers:
  - Tuomas Lappi, first 6 weeks lectures 12.9.–19.10, first midterm exam. Room FL249 (next to copy machine)
  - Thorsten Renk, second 6 weeks lectures 24.10.–30.11, second midterm exam. Also room FL249.
  - Heikki Mäntysaari, room FL347, exercises

Passing the course:

- Option 1: midterms + exercises $2 \times 24 + 12 = 60$
- Option 2: final exam + exercises $48 + 12 = 60$ points, available only on first final exam after lectures
- Option 3: final exam, max 60 points.
- Min 30 points to pass, **and** min 7 points for each midterm for option 1

Language and literature

The language of physics research is English, you should practice it.
Language of this course is mixed Finnish/English:

- Written material distributed in English
- You can always ask questions, answer exercises and exam questions in Finnish (2nd midterm: check with Thorsten)
- Language of lectures varies: TL, HM: Finnish/English as needed, TR: English

Course material

KJE Handwritten notes in Finnish by Kari J. Eskola. Lectures closely follow these detailed notes, recommended reading. URL, passwd by email.

TL These slides for first half available online and distributed as handout: mostly condensed version of KJE's notes

Useful reading:

- Particle Physics, B.R. Martin and G. Shaw, Wiley (1997); in FYS4
- Quarks and Leptons: An Introductory Course in Modern Particle Physics, F. Halzen and A.D. Martin, Wiley (1984).

Particle physics at JYFL

BSc, MSc thesis subjects . . .
Theory:

- URHIC (strong interactions)
  - K.J. Eskola
  - T. Renk
  - T. Lappi
- bSM: K. Tuominen
- cosmology: K. Kainulainen (away at CERN until summer -12)
- neutrinos: J. Maalampi.

Experiment:

- ALICE: J. Rak, D. Kim, S. Räsänen
- LAGUNA project (neutrinos), W. Trzaska, J. Maalampi

Contents 1, outline

Part 1: Phenomenology, symmetries, tools

1. Introduction — units — structure of matter, terminology — fundamental interactions — Feynman diagrams (much more later on) — hadrons
2. Special relativity — Minkowski space — Lorentz transformations — particle kinematics
3. Scattering theory — cross sections — decay widths
4. Particle content of the standard model — leptons — quarks — gauge bosons — quantum numbers and conservation laws
5. Spacetime symmetries — translation — rotation — parity — charge and time conjugation
6. Hadrons — isospin — resonances — quark diagrams
7. Hadronic states and color — quark-antiquark states — mesons, baryons in quark model — confinement

Contents 2, outline

Part 2: Standard model

- Classical field theory
- Group theory
- Relativistic wave equations, antiparticles
- Quantization
- QED
- QCD
- Electroweak theory

Thought experiment

An archaic people living across a great ocean measures

- **Height** in a unit called “feet”
- **Distance** in unit called “mile”

Original definitions:

- mile = 1000 steps
- foot: anatomical

With new technology need more precise ones:

- mile = distance traveled by light in 1/186282 second
- foot: standard platinum stick

Great physics discovery! Can measure distances with standard 1 foot ruler, and result is **always** 1 mi = 5280 ft ▶ symmetry.
Define new physical constant, “ruler constant” as $c_r = 5280$ft/mi. Now can measure distances in feet or height in miles!
Formal conversion: $c_r = 1$

Natural system of units

Analogous discoveries in real world:

- Relativity: speed of light c is constant: relates time and distance
- Quantum mechanics: energy is related to frequency (1/time) and momentum to wavenumber (1/distance) by Planck $\hbar$
- Temperature related to energy of microscopic degrees of freedom by Boltzmann k_B

In particle physics it is convenient to use **natural units** which are obtained from

$$\hbar = \frac{h}{2\pi} = 6.58211915 \cdot 10^{-25}\text{GeV } s = 1$$

$$c = 2.99792458 \cdot 10^{8}\text{m/s} = 1$$

Also $k_B = 1$ (less important in this course).

Sizes of things

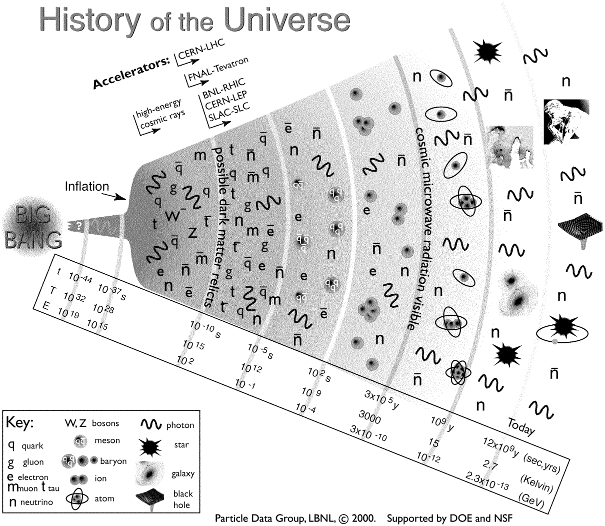
The particle physics scales are GeV (proton mass) and **fermi** 1fm $= 10^{-15}$m
From $\hbar c = 1$ follows

$\hbar c = 0.197326968\text{GeV fm} = 1$ ▶ GeV fm ≈ 5 (remember by heart)

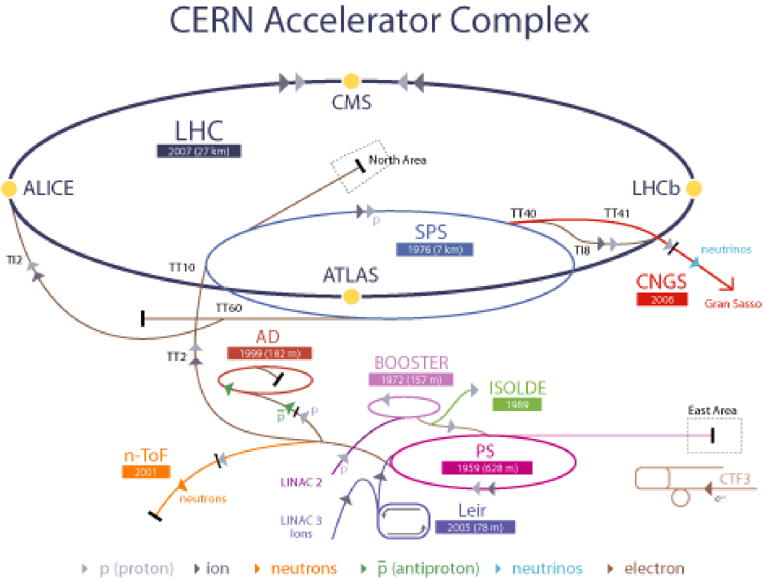
Units of different quantities

- Energy $[E] =$ GeV (or keV, MeV, TeV ...)
- Velocity $[v] = [c] = 1$ $(0 \leq v \leq 1 = c)$
- Momentum: $[p] = [E/c] =$ GeV (liikemäärä)
- Mass: $[m] = [mc^2] = [E] =$ GeV (Einstein!)
- Length $[l] =$ fm (easier than $[l] = 1/\text{GeV}$)
- Time $[t] =$ fm (or $[t] = 1/\text{GeV}$)

Small distances, high temperatures, early universe

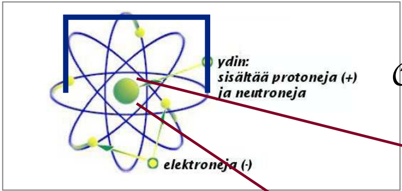


Small distances, high energies, big experiments

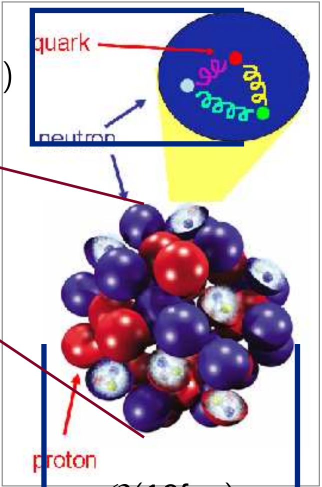


Stable matter

$\mathcal{O}(10^{-10}\mathrm{m})$



$\mathcal{O}(1\mathrm{fm})$



$\mathcal{O}(10\mathrm{fm})$

- **Atom:** electrons and nucleus, bound by electromagnetism $\Longrightarrow$ photon
- **Nucleus:** protons and neutrons, bound by strong interaction $\Longrightarrow$ gluon

Unstable matter

Some nuclei are unstable, e.g. to $\beta^{\pm}$-decay

$$
\begin{aligned}
(Z, A) &\rightarrow (Z+1, A) + e^- + \bar{\nu}_e \\
(Z, A) &\rightarrow (Z-1, A) + e^+ + \nu_e
\end{aligned}
$$

(Z charge, A mass)

- e^+ **positron**, antiparticle of electron
- $\bar{\nu}_e$ electron antineutrino
- ν_e electron **neutrino**

These are weak interaction processes

- Change p to n, not possible in e.m. or strong interaction
- Mediated by $W^{\pm}$ gauge boson (above, there is also Z boson)
- Weak $\implies$ reaction happens very slowly (Because $W^{\pm}$ are very heavy, will see later how this makes the process slow.)

Some terminology

Elementary particle: indivisible, does not consist of smaller parts (alkeishiukkanen)

Composite particle: consists of elementary particles

Fermion particle with spin $1/2$, $3/2$, ... Pauli principle (kieltosääntö)

Boson spin $0, 1, 2 \ldots$, no Pauli principle

lepton elementary particles, electron, neutrino and similar, e.m. and weak interaction

quark elementary particles, e.m., weak and strong interaction

hadron Composite particle of quarks

(Joissain lukiokirjoissa “perushiukkanen” = elementary, termiä “alkeishiukkanen” käytetään ihmeellisellä tavalla)

Fundamental interactions

Four fundamental interactions $\Longrightarrow$ really just three

- Gravity
  $\Longrightarrow$ no quantum theory yet
- Electromagnetism
- Weak nuclear interaction
- Strong nuclear interaction

Electroweak theory (1960's) $\Longrightarrow$ Higgs

Standard model of particle physics

bSM = beyond SM: More unification? Speculative ideas:

- **GUT** Grand unified theory: combine EW and strong
- String theory: unify all four, provide quantum theory of gravity?

Gravity neglected on this course (HT):

- Weak on GeV, TeV scales, where particle physics experiments are done
- Strongest force for much larger energies, Planck scale

SM interactions, gauge bosons

Recall what you know about electromagnetism and quantum mechanics:

- Interaction mediated by **field** A_μ ($\rightarrow E, B$) (classical)
- Field can always be Fourier-transformed into superposition of **waves** (classical)
- Wave-particle **duality**: waves are particles, particles are waves (quantum)

This is what we mean when we say that

"interactions are mediated by particles" (välittäjähiukkanen)

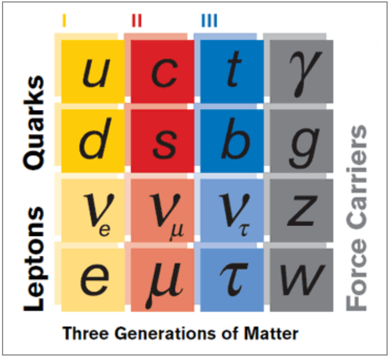
Quantum **F**ield **T**heory provides the mathematical machinery to do this consistently (on this course we skip the machinery)

- Gravity $\Longrightarrow$ graviton
- Electromagnetism $\Longrightarrow$ photon
- Weak force $\Longrightarrow$ W and Z bosons
- Strong force $\Longrightarrow$ gluon

Structure follows from **gauge symmetry** (mittasymmetria) of SM: SU(3)$\times$SU(2)$\times$U(1)

- Strong: SU(3) (color):
- Electroweak: SU(2) (weak isospin), U(1) (hypercharge)

Elementary particle content of standard model



+ Last unobserved SM particle: Higgs

- 3 generations of lepton doublets
- 3 generations of quark doublets
- gauge bosons for 3 interactions

SM works **very** well; sticking points:

- Higgs predicted, not seen yet
- Basic SM has massless neutrinos. Observed: small masses $\Longrightarrow$ SM has to be modified, but this is not yet a big deal
- Aesthetic issues: "hierarchy problem", "naturalness", gravity, unification

Leptons, (gravity and) electroweak interaction only

electron e^-, $Q = -e$, $m = 0.511\text{MeV}$ (antiparticle positron) stable

muon (myoni) , $\mu^\pm$,$Q = \pm e$, $m = 105.7\text{MeV}$ (antiparticle same name)
decay time $\tau \approx 2.197 \times 10^{-6}$s, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$,
($c\tau = 658.654$m propagates e.g. in atmosphere; "stable" for particle detectors)

tau $\tau^\pm$,$Q = \pm e$, $m = 1776\text{MeV}$ (antiparticle has same name)
decay time $\tau \approx 290 \times 10^{-15}$s, lots of decay channels
(τ is very heavy $\Longrightarrow$ decay energy large $\Longrightarrow$ "weak" interaction not "weak" any more, decay very fast $c\tau = 87.11\mu$m)

Neutrinos ν_e, ν_μ, ν_τ and antineutrinos $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$: Only weak interaction
$\Longrightarrow$ very difficult to measure

- $Q = 0$
- Present knowledge: $m_i \neq 0, m_i \neq m_j$, but masses not known.
- Weak interaction eigenstates (ominaistila) ν_e, ν_μ, ν_τ **not** same as mass (energy) eigenstates $\Longrightarrow$ neutrinos **oscillate**

(Oscillation: e.g. $|\nu_\mu\rangle$ born in muon reaction. Mass eigenstates $|\nu_\mu\rangle = c_1|m_1\rangle + c_2|m_2\rangle$. Mass eigenstates $|m_i\rangle$ oscillate in time/distance with different frequencies. After few 1000km $|\nu_\mu\rangle$ has oscillated into superposition $c_\mu|\nu_\mu\rangle + c_e|\nu_e\rangle + c_\tau|\nu_\tau\rangle$)

Quarks; all interactions

Feel electroweak and strong interaction
In ordinary matter:

up u $\quad Q = +\frac{2}{3}e, \quad m = 1.5..3\text{MeV}$

down d $\quad Q = -\frac{1}{3}e, \quad m = 3..7\text{MeV}$

Proton: uud, neutron udd

charm c $\quad Q = +\frac{2}{3}e, \quad m \approx 1.25\text{GeV}$

strange s $\quad Q = -\frac{1}{3}e, \quad m \approx 95\text{MeV}$

top (truth) t $\quad Q = +\frac{2}{3}e, \quad m \approx 174\text{GeV}$

bottom (beauty) b $\quad Q = -\frac{1}{3}e, \quad m \approx 4.2\text{GeV}$

Confinement (quark/color)

- Quarks are not seen as “free” particles; mass not very precisely defined.
- Appear in
  - bound states (hadrons)
  - when matter melted to $T \gtrsim 200\text{MeV} \approx 2.3 \times 10^{12}\text{K}$ as Quark Gluon Plasma

Cathegories of hadrons

Mesons

- Quark-antiquark pair: q and $\bar{q}$ have opposite color charge
  $\Longrightarrow$ simpmlest color neutral system
- Simplest: pions $\pi^+ \sim u\bar{d}$, $\pi^- \sim \bar{u}d$, $\pi^0 \sim \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$
- $q \to \bar{q}, \bar{q} \to q \Longrightarrow q\bar{q} \to q\bar{q}$ $\Longrightarrow$ no separate “antimesons”

Baryons

- Consist of 3 “valence” (valenssi) quarks. (Why 3? Follows from SU(3) of color charge and antisymmetry for identical quarks (Pauli))
- Simplest: Proton: uud, neutron udd
- Antibaryons: 3 antiquarks

Valence and sea

The quark content above are **valence** quarks $\Longrightarrow$ quantum numbers.
Additionally **sea** quarks & gluons $\Longrightarrow$ quantum fluctuations
In pairs $\Longrightarrow$ do not change quantum numbers.

Lightest mesons and baryons

There are hundreds of hadrons in the PDG listings http://pdg.lbl.gov/

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

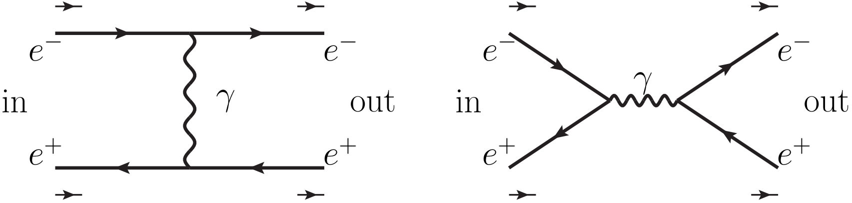
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Feynman diagrams

Example: scattering process $e^- e^+ \to e^+ e^-$ to lowest order in electromagnetic coupling is represented by



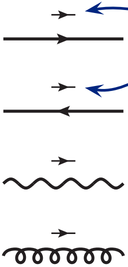
- graphical way of organizing perturbation theory calculation
  - every diagram corresponds to a precise mathematical expression (will learn these in 2nd half of course)
  - **Feynman rules** = how to relate diagram to this expression
  - Rules derived in QFT course, used here
- Provides convenient physical picture of process, even when one does not calculate them

Ingredients of a Feynman diagram

Feynman diagram is representation of perturbation theory:

Free, unperturbed part: "Propagator"

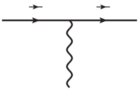
- fermion (arrow) (lepton, quark)
- antifermion
- photon, W, Z-boson
- gluon



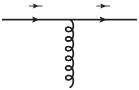
- arrow above line for direction of momentum
- antifermion = negative energy fermion moving backwards in time

Perturbation, interactions of particles "Vertex":

- fermion-gauge boson:



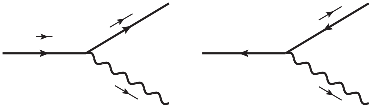
  - 1 fermion line in
  - 1 fermion line out
  - 1 gauge boson in/out



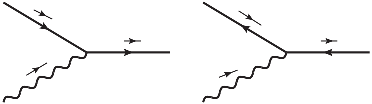
- $\sim e$, "small", perturbation
- There are also 3- and 4-gluon vertices

One vertex for different things

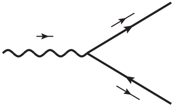
- Radiation (of photon, gluon)



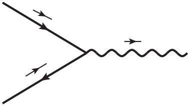
- Absorption of radiation



- Pair creation



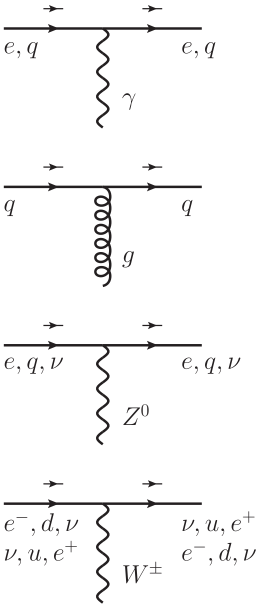
- Annihilation



Matter and radiation

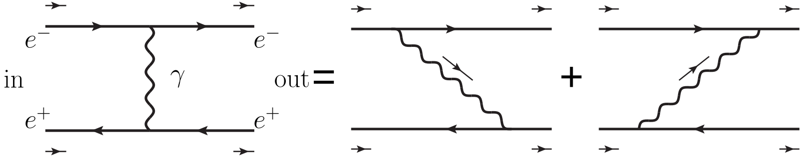
Most important process: fermionic matter interacting with gauge bosons.

- “electromagnetic current”, photon
  - Couples to e, μ, τ, quarks
- color charge/current, gluon
  - Couples to quarks, antiquarks only
- “neutral weak current” Z^0
  - Like photon, but also neutrinos
- “charged weak current” $W^{\pm}$
  - W-boson has electric charge $\Longrightarrow$ charge of fermion changes

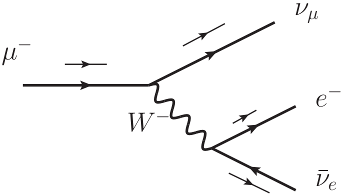


Remarks

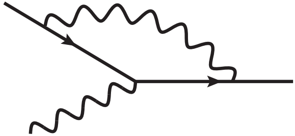
All time orderings included in same diagram



Example: unstable particle decay:



Example of **loop diagram**



(Weak charged current reaction)

- Direction of fermion arrow stays in vertex (baryon/lepton number cons.)
- Momentum arrow not always drawn
- Electric charge conserved in vertex

More remarks

Topics in the following weeks

- Each particle line has **4-momentum** (E, p_x, p_y, p_z) that is conserved at vertex. $\Longrightarrow$ will first have to learn how to calculate with these, i.e. **relativistic kinematics**
- Each diagram gives quantum mechanical **amplitude**; we will have to learn what these are used for; **cross sections, decay widths**
- We went through a quick introduction, will then come back to more detail on the particles in the standard model and their interactions, i.e. vertices.
- There are conserved charges (like electric charge) and other conserved quantities, we will then talk about **symmetries and conservation laws**
- Later in the course we will learn how to write down the expression corresponding to a diagram and to simplify it.