Introduction to the Standard Model

Summer Student Lecture 2015 – Part I

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DESY

Preface

- This lecture cannot replace a university course on particle physics
- Very different level of knowledge: Hard to devise a course that fits all....
  → Some parts more interesting to beginners, some more to the more advanced
- Concentrating on *general concepts and a broad overview*
- **Please do ask questions!**

Content

- 0) Introduction
  - What is the Standard Model?
  - Coupling constants, masses and charges
  - Units and scales

- 1) Interactions
  - Relativistic kinematics
  - Symmetries and conserved quantities
  - Dirac equation
  - Feynman diagrams
  - Cross section measurements

- 2) Quantum electrodynamics: Tests of QED
  - low energy: Magnetic momentum of the electron
  - tests at high energy colliders

Content

- 3) Electroweak interactions
  - Discovery of electroweak bosons
  - Tests of angular distributions
  - Feynman rules
  - Handed-ness of electroweak interactions
  - More tests of the electroweak SM

- 4) Strong Interaction: Quantum-Chromodynamics
  - Quarks and Hadrons
  - QCD at colliders
  - PDFs and parton showers

0) Introduction: What is the Standard Model?

- Describes elementary particles and interaction in self-consistent way

picture from wikipedia

0) Introduction: What is the Standard Model?

- Describes elementary particles and interaction in self-consistent way

- **Force particles versus matter particles**
  Gauge bosons versus Leptons/Quarks
  Spin 1 versus spin ½ particles

- **Gluon versus photon/Z/W boson**
  Strong interaction versus electro-weak interaction

- **Photon versus Z/W boson**
  Electromagnetic versus weak interactions

- **Leptons versus Quarks**
  Charge 1 versus charge 1/3
  Colorless versus colored particles

- **Generations**
  rising masses – lowest generation: stable matter

0) Introduction: What is the Standard Model?

- Interactions between particles

0) Introduction: SM – A success story with flaws I

- Predictions based on theory found to be experimentally valid
  Experimental findings could be well incorporated into theory

A few exceptions / puzzles based on experimental observation:

- **Gravity**. The standard model does not explain gravity. “Graviton” neither discovered nor does it fit cosmological observations / general relativity.
- **Dark matter and dark energy**. Standard model describes only 5% of the matter of the universe. Dark matter (26%) and dark energy (69%) [from cosmological observations and general relativity] unexplained – no candidates for dark matter, SM vacuum energy mismatches dark energy.
- **Neutrino masses**. Very small masses for neutrinos, not expected
- **Matter-antimatter asymmetry**. SM unable to explain, how and/or why matter dominates over anti-matter in our universe.

0) Introduction: SM – A success story with flaws II

- Some parts of the SM are added "ad-hoc" – or "by hand"
  this means a certain parameter or mechanism needs to be postulated – not in contradiction to any observations and theoretically valid, but still not "satisfying" aesthetically

- **Hierarchy problem**. Fine tuning of Higgs mass versus quantum corrections over several orders of magnitude.
  (e.g. cancellation of the size ~10^{16})

- **Strong CP problem**. Theoretically, the SM should contain a term that breaks CP symmetry - relating matter to antimatter – in QCD. Experimentally, however, no such violation has been found, implying that the coefficient of this term is very close to zero → unnatural.

- **Number of SM parameters**. Standard model depends on 19 numerical parameters. Their values are known from experiment, but the origin of the values is unknown.

Aim of the lecture: Understand better how SM was established and what its problems are

0) Coupling constants, masses and charges

- Interaction can be described as exchange of field quanta

- **Graviation**

- **Coulomb-force in electromagnetism**

- **Generic interaction**

Only charged particles
participate in interaction

Quarks:
carry electrical charge
color charge
weak charge

Massive leptons:
carry electrical charge
weak charge

Neutrinos:
carry weak charge

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0) The Heisenberg principle

- Interaction carried by “force carrier”

- Heisenberg principle: limits the precision with which (certain) pairs of physical quantities can be determined
- relation energy ↔ times:
- since in a particles rest frame the energy is given by the mass, this implies that only stable particles have an exact mass!

Life time τ

Decay width Γ

0) The Heisenberg principle II

- Energy/mass of “force carrier” related to reach of interaction

0) The Heisenberg principle III

- Interaction carried by “force carrier”
- relation momentum ↔ position:
- Another possible application: the maximum possible momentum transfer in a reaction limits the size of structures you can resolve
  (what counts is the momentum transfer in the center-of-mass frame)
- Examples: you need a momentum transfer of 200 MeV to resolve structures of the size of a proton (1 fm)

0) Units and scales

- “natural units” → $c = 1 \quad \hbar = 1$
  (masses, energies and momenta measured in GeV)

[Taken from:
Quarks and Leptons:
An Introductory Course in Modern Particle Physics
Francis Halzen/Alan D. Martin]

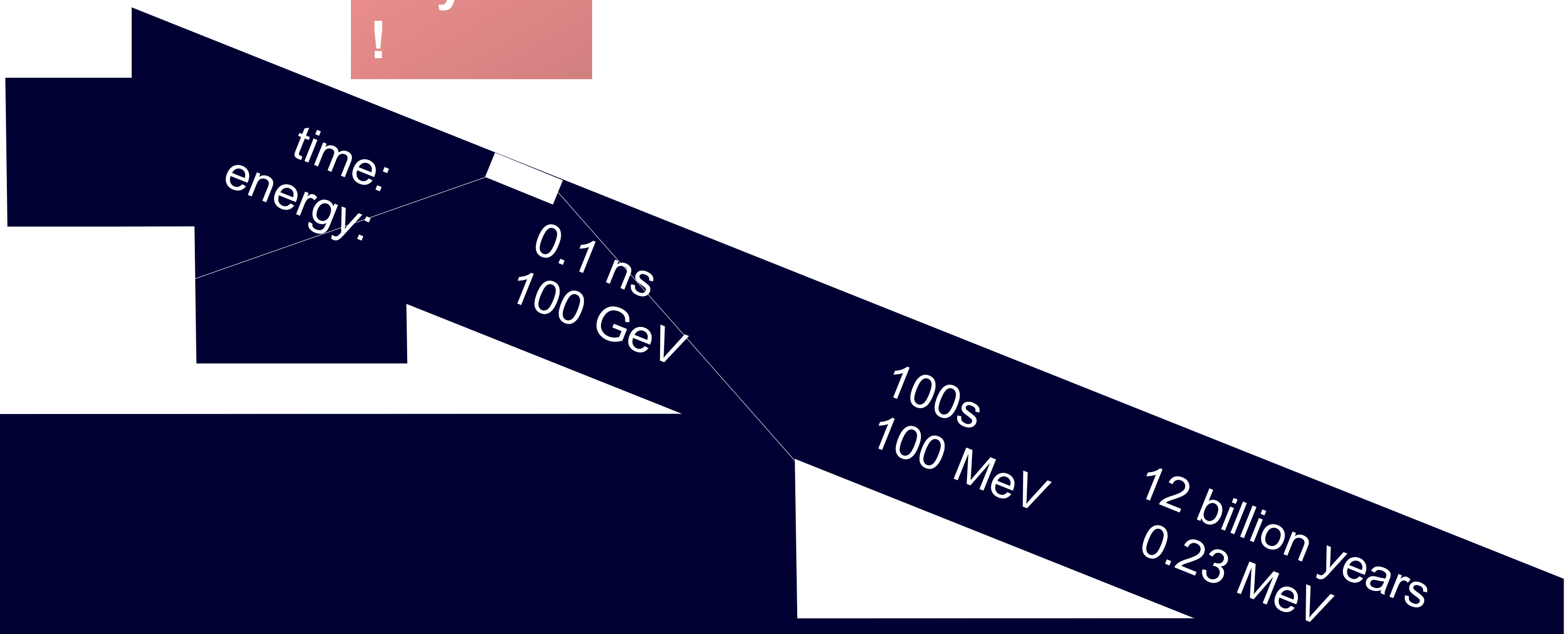
0) Units and scales

Astronomy:
looking back in time

energy physics:
looking back in

0000000000000000000001 s

“Neue Physik” !



time:
energy:

0.1 ns
100 GeV

100s
100 MeV

12 billion years
0.23 MeV

“discovery machine” LHC

1) Interactions: Relativistic kinematics

- particle quantities are described as 4-vectors:

  energy/momentum: $p=(E,\vec{p})$

  time/space: $x=(t,\vec{x})$

- product of 4-vectors is invariant: $p_1\cdot p_2=(E_1\cdot E_2-\vec{p}_1\cdot\vec{p}_2)=\mathrm{constant}$

  → can use the "easiest" reference frame for calculations

- special case: $p\cdot p=(E^2-\vec{p}\cdot\vec{p})=(E_0^2-0)=m^2$

  with $\beta=v/c$ and $\gamma=1/\sqrt{1-\beta^2}$: $E=\gamma m$ and $|\vec{p}|=\beta\gamma m$

1) Interactions: Relativistic kinematics I

-
  - Interaction can be described as exchange of field quanta
-

1) Quick reminder: Dirac Equation

- Based on Schroedinger equation:
- Not valid for relativistic particles → Klein-Gordon equation (spin-1)
- Dirac equation:

$$\boxed{\frac{1}{c}\frac{\partial\psi}{\partial t}+\boldsymbol{\alpha}\cdot\nabla\psi+\frac{im_0c\beta}{\hbar}\psi=0.}$$

Pauli-Matrices

with α and σ being vectors:

Dirac-Matrices: γ

Dirac-Spinor: ψ → (negative)positive energy solution: (anti-)particles

Dirac-Current: $j^\mu = -e\,\overline{\psi}\gamma^\mu\psi$ → current is conserved $\partial_\mu\left(\bar{\psi}\gamma^\mu\psi\right)=0.$

1) Symmetries and conserved quantities

- From Quantum mechanics: Symmetry connected to conserved quantity

  various quantities conserved in SM interactions

1) Feynman diagrams

- Interaction can be described as exchange of field quanta

1) Feynman diagrams

1) Feynman diagrams

1) Higher orders

-
    - 0) I
-
-

1) Loop diagrams

- Possible is also the occurrence of “virtual” particles in loops

Need to be able to couple to propagator

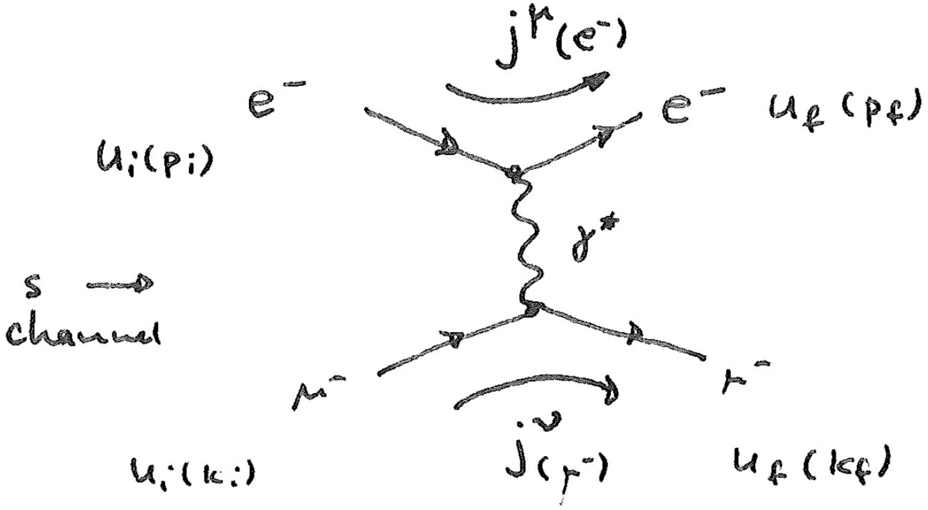
?

One loop

0) Feynman diagrams: example of eμ scattering

consider as an example $e^- \mu^-$ scattering

↓ t-channel



$$j^\mu(e^-) = -e\,\bar\Psi_f\,\gamma^\mu\,\Psi_i$$

$$= -e\,\bar u_f(p_f)\,\gamma^\mu\,u_i(p_i)\;e^{i(p_f-p_i)x}$$

$$e^{-iqx}$$

$$M^0 = -j^\mu(e^-)\,\frac{1}{q^2}\,j_\mu(\mu^-) = -e^2\,\bar u(p_f)\,\gamma^\mu u(p_i)\,\frac{1}{q^2}\,\bar u(k_f)\,\gamma_\mu\,u(k_i)$$

⇑

Photon propagator

- Average over spins in initial state, sum spins in final state
- Replace outgoing e- by backwards traveling e+ → amplitude for ee → μμ

0) Feynman diagrams: example of eμ scattering I

- Get simpler expressions:

0) Feynman diagrams: example of eμ scattering I

- Measurements:

→ How measured?

How to measure a cross section

How to measure a differential cross section

More on differential cross sections

- differential cross section can be compared to theory predictions
  - can exclude predictions that describe the total cross section but differ in shape
- meaningful comparison only possible if uncertainties are known!
  - statistical uncertainties (from signal and background events!)
  - systematic uncertainties (efficiency, branching ratio, luminosity)
  - are there correlations between the bins? (e.g. uncertainty on luminosity shifts all data points the same way → correlated)