Outline

I. Introduction
II. Prerequisites
III. Introduction to QED
IV. $e^+e^-$ annihilation experiments below the $Z$ resonance
V. Weak interaction and phenomenological approach to the SM
VI. Standard Model
VII. Experimental tests of the Standard Model
VIII. Strong Interaction
IX. Flavor oscillations
X. Search for Physics beyond the Standard Model
I. **Introduction**

1. Standard Model: Building blocks of matter and their interactions
2. Experimental tools
3. Natural units

What you already know from „Physik 5“

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**Literature**

- O. Nachtmann: *Elementarteilchenphysik*, Vieweg
- C. Berger: *Elementarteilchenphysik*, Springer.
1. Standard Model *) of Particle Physics

Based on the principle of local gauge invariance

\[ SU(3) \times SU(2) \times U(1) \]

12 gauge fields

Not yet directly observed

*) S. L. Glashow, A. Salam and S. Weinberg, 1967/8

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History of Experimental Tests of Standard Model

1967/8  Standard Model, S. L. Glashow, A. Salam and S. Weinberg
1971  Renormalizability of non-abelian gauge theories, G. 't Hooft and M. Veltman
1973  Discovery of Neutral Currents: „Z-Boson exchange“ (Gargamelle, CERN)
1974  Discovery of the 4th quark (SLAC / BNL)
1979  Discovery of the gluon (DESY)
1983  Observation of W and Z bosons (UA1/2, CERN)
1989  Start of LEP I: Z factory
   Z properties, measurement of radiative corrections, prediction of topmass
1995  Discovery of the Top-Quark at TEVATRON
1996  Start of LEP II:
   W Pair production and Higgs search (until Nov 2000)
2001  Start of TEVATRON Run II:
   Precision measurement of Top-Quark and W-Boson properties, B physics
2009  Start of LHC: Discovery of the Higgs boson?
1.1 Leptons and Quarks

Point-like, spin $\frac{1}{2}$, elementary building blocks of matter $< 10^{-18}$ m

<table>
<thead>
<tr>
<th>Flavor-Generation</th>
<th>$Q$ [$e$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptons</strong></td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td></td>
</tr>
<tr>
<td><strong>Quarks</strong></td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>$+\frac{2}{3}$</td>
</tr>
<tr>
<td>$d$</td>
<td>$-\frac{1}{3}$</td>
</tr>
<tr>
<td>$c$</td>
<td></td>
</tr>
<tr>
<td>$s$</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td></td>
</tr>
</tbody>
</table>

Doublets reflect structure of weak interaction

**Anti-particles** with opposite charge to each lepton/quark
Lepton Properties

- All leptons exist as free particles
- Lepton number conservation

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ L_\mu = 0 \rightarrow -1 \rightarrow 1 \]

Neutrino oscillations ⇔ Lepton flavor violation

\[ \nu_\mu \rightarrow X \rightarrow \nu_\tau \]

<table>
<thead>
<tr>
<th></th>
<th>mass ( c^2 )</th>
<th>lifetime</th>
<th>Lepton number</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- )</td>
<td>511 keV</td>
<td>( \infty )</td>
<td>( L_e = 1 )</td>
</tr>
<tr>
<td>( \mu^- )</td>
<td>106 MeV</td>
<td>2.2 ( \mu )s</td>
<td>( L_\mu = 1 )</td>
</tr>
<tr>
<td>( \tau^- )</td>
<td>1.78 GeV</td>
<td>0.3 ps</td>
<td>( L_\tau = 1 )</td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>&lt; 2 eV</td>
<td>( \infty )</td>
<td>( L_e = 1 )</td>
</tr>
<tr>
<td>( \nu_\mu )</td>
<td>&lt; 190 keV</td>
<td>( \infty )</td>
<td>( L_\mu = 1 )</td>
</tr>
<tr>
<td>( \nu_\tau )</td>
<td>&lt; 18.2 MeV</td>
<td>( \infty )</td>
<td>( L_\tau = 1 )</td>
</tr>
</tbody>
</table>

Direct measurements

In the Standard Model neutrinos are assumed to be massless. Recently clear evidence for neutrino oscillations have been observed: explained with non-zero masses. Mass difference are very small: \( m_\nu < 3 \text{ eV for all Neutrinos} \)

Impressive limits for lepton flavor violation of charged leptons:

\[ BR_{\mu \rightarrow e \gamma} = \frac{\Gamma(\mu \rightarrow e \gamma)}{\Gamma(\mu \rightarrow e \nu_e \nu_\mu)} < 1.2 \cdot 10^{-11} \]

\[ BR_{\mu \rightarrow e \nu e} = \frac{\Gamma(\mu^- + (Z,A) \rightarrow e + (Z,A))}{\Gamma(\mu^- (Z,A) \rightarrow \nu_\mu + (Z-1,Z))} < 8 \cdot 10^{-13} \]

proposed: \( BR_{\mu \rightarrow e \gamma} < 5 \cdot 10^{-14} \) proposed: \( BR_{\mu \rightarrow e \nu e} < 8 \cdot 10^{-17} \) (Al)

Standard model process:

Effect of neutrino mass is "GIM suppressed" by a factor of \( (\Delta m_e^2/M_W)^2 \sim 10^{-50} \) and hence unobservable

SUSY-GUT scenarios predict larger BR for LFV decays.
Quark Properties

- Quarks are confined in hadrons: mesons (q̅ q) or baryons (qqq)
- Quark masses cannot be measured directly; mass is well defined only for free particles
- Heavy quarks: Constituent quark masses. Determination from observed hadron mass spectra + assumed binding potential

For the light quarks (u,d,s,) the masses are estimates of the “current masses” which appear in the QCD Lagrangian
- Quarks carry color charge

Interesting question: do we need massive quarks to build massive hadrons?

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass (GeV)</th>
<th>Flavor number</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, d</td>
<td>~5 and ~8</td>
<td>I=±1/2</td>
</tr>
<tr>
<td>s</td>
<td>80 - 130</td>
<td>S=-1</td>
</tr>
<tr>
<td>c</td>
<td>1.15 - 1.35</td>
<td>C=+1</td>
</tr>
<tr>
<td>b</td>
<td>4.6 – 4.9</td>
<td>B=-1</td>
</tr>
<tr>
<td>t</td>
<td>~175</td>
<td>T=+1</td>
</tr>
</tbody>
</table>

Flavor changing weak currents

There are no flavor changing neutral currents (no FCNCs).

Questions:

- Why are there three generations?
- Mass hierarchy?
- Charges = 0, 1/3e, 2/3e or e?
- Is there a symmetry which explains the flavor sector?

If we are honest, we don't really understand the flavor sector of the SM
1.2 Fundamental interactions

<table>
<thead>
<tr>
<th>IA</th>
<th>Mediator boson</th>
<th>strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Gluon / massless</td>
<td>1</td>
</tr>
<tr>
<td>Elektromagnetic</td>
<td>Photon / massless</td>
<td>$\sim 10^{-2}$</td>
</tr>
<tr>
<td>weak</td>
<td>$W^\pm Z^0$ / massive</td>
<td>$\sim 10^{-6}$</td>
</tr>
<tr>
<td>Gravitation</td>
<td>Graviton / massless</td>
<td>$\sim 10^{-39}$</td>
</tr>
</tbody>
</table>

- Forces are mediated by virtual field quanta (bosons)
- Virtual bosons transfer energy and momentum for which in general $m_{\text{boson}}^2 \neq E^2 - p^2$ (off mass-shell)

a.) Electro-magnetic interaction

\[
\alpha = \alpha_{\text{QED}} = \frac{e^2}{4\pi\varepsilon_0 \hbar c^2} = \frac{e^2}{4\pi} \\
\hbar = c = 1
\]

\[
M_e \sim \sqrt{\alpha} \cdot \frac{1}{q^2} \cdot \sqrt{\alpha} \cdot J_p \sim \frac{\alpha}{q^2}
\]

Diff. cross section:

\[
d\sigma = |M_e|^2 \times \text{PS} \sim \frac{\alpha^2}{q^3} \times \text{PS}
\]

(Rutherford formula)
b.) Strong interaction

Color charges and gluons.

- Quarks and anti-quarks carry 3 different (anti) color charges

- Interaction is mediated by 8 massless colored gluons (spin 1)

- Color symmetry is exact: strong interaction only depends on color and is independent of quark flavor

- Color charge of gluons \( \Rightarrow \) gluon-gluon coupling: triple gluon vertex

How strong is “strong”? Use decay times of the following kinematically similar \( \Sigma \) decays:

<table>
<thead>
<tr>
<th>( \Sigma ) decays</th>
<th>Q-value</th>
<th>Decay time</th>
<th>IA</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma^0(1192,uds) ) → ( \Lambda\gamma )</td>
<td>74 MeV</td>
<td>( 10^{-19} ) s</td>
<td>e.m.</td>
</tr>
<tr>
<td>( \Sigma^+(1189,uus) ) → ( p\pi^0 )</td>
<td>189 MeV</td>
<td>( 10^{-10} ) s</td>
<td>weak</td>
</tr>
<tr>
<td>( \Sigma^0(1385,uds) ) → ( \Lambda\pi^0 )</td>
<td>208 MeV</td>
<td>( 10^{-23} ) s</td>
<td>strong</td>
</tr>
</tbody>
</table>

For the decay times one finds

\[
\tau = \frac{\hbar}{\Gamma} \sim \frac{1}{|M_{\ell}|^2} \sim \frac{1}{\alpha_{\mu}^2}
\]

\( \alpha_{\mu} \) = effective coupling of decay process

Neglecting kinematics:

\[
\frac{\tau(\Sigma \rightarrow \Lambda\gamma)}{\tau(\Sigma \rightarrow \Lambda\pi^0)} \approx \frac{\alpha_{\mu}^2}{\alpha_{em}^2} \approx 10^4
\]

with \( \frac{\alpha_{em}}{137} \Rightarrow \alpha_s \approx 1 \)
c.) Weak interaction

Mediated by massive bosons:

\[
M_W \sim g_w \frac{1}{q^2 - M_W^2} 
\]

\[
M_Z \approx \frac{g_Z^2}{M_Z^2} 
\]

\[
Z \approx W 
\]

\[
\mu^- \rightarrow p \pi^0 \approx G_F \approx 10^{-5}\text{GeV}^{-2} 
\]

Effective weak coupling \( \alpha_w \) is small

Estimate the strength from \( \Sigma \rightarrow p \pi^0 \) decay

\[
\frac{\alpha_w^2}{\alpha_{em}} \approx 10^{-5} \ldots 10^{-4} 
\]

Electroweak unification

\[
g_w = \frac{e}{\sin \theta_W} 
\]
1.3 Higgs Boson = additional scalar Field

Scalar Higgs field couples to the boson fields and fermion fields and generates through the coupling masses:

\[
\frac{g^2 v^2}{4} W_\mu W^\mu + \frac{(g'^2 + g^2) v^2}{8} Z_\mu Z^\mu - g_F \frac{v}{\sqrt{2}} \bar{\psi} \psi
\]

- boson mass terms
- fermion mass terms

\[
M_W = \frac{1}{2} v g, \quad M_W = \frac{g}{\sqrt{g^2 + g'^2}} = \cos \theta_W
\]

\[
M_Z = \frac{1}{2} \sqrt{g^2 + g'^2}, \quad g \sin \theta_W = g' \cos \theta_W
\]

Higgs production in Proton-Proton Collisions

[Diagram showing Higgs production in Proton-Proton Collisions]
Current Higgs Limits:

Moore's Law for Particle Physics

From W.K.H. Panofsky: The evolution of particle accelerators and colliders
Large Hadron Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Momentum at collision</strong></td>
<td>7 TeV/c</td>
</tr>
<tr>
<td>Momentum at injection</td>
<td>450 GeV/c</td>
</tr>
<tr>
<td>Dipole field at 7 TeV</td>
<td>8.33 Tesla</td>
</tr>
<tr>
<td>Circumference</td>
<td>26658 m</td>
</tr>
<tr>
<td><strong>High beam energy in LEP tunnel</strong></td>
<td>superconducting NbTi magnets at 1.9 K</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>DC beam current</td>
<td>0.56 A</td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td>350 MJ</td>
</tr>
<tr>
<td><strong>High luminosity at 7 TeV</strong></td>
<td>very high energy stored in the beam</td>
</tr>
<tr>
<td>beam power concentrated in small area</td>
<td></td>
</tr>
<tr>
<td><strong>Normalised emittance</strong></td>
<td>3.75 $\mu$m</td>
</tr>
<tr>
<td>Beam size at IP / 7 TeV</td>
<td>15.9 $\mu$m</td>
</tr>
<tr>
<td>Beam size in arcs (rms)</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td><strong>Limited investment</strong></td>
<td>small aperture for beams</td>
</tr>
<tr>
<td>Arcs: Counter-rotating proton beams in two-in-one magnets</td>
<td>56 mm</td>
</tr>
<tr>
<td><strong>Magnet coil inner diameter</strong></td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between beams</td>
<td>194 mm</td>
</tr>
</tbody>
</table>

LHC Dipole Magnet

- Dipole current: 12 KA (super-conducting, T=1.9 k), B = 8.3 T
- Energy stored in 1 dipole: 7.6 MJ
- in all 1232 dipoles: 9.4 GJ
First circulating beams on September 10th 2008

10:30
Beam1 around the ring (~1h).
~3 turns.

15:00
Beam2 around the ring.
3…4 turns.
First Beam Induced Particles (here in LHCb)

10.9. 2008  11:32:26  +50 ns

Track reconstruction algorithm: M. Schiller (HD)

LHC Accident

- During ramping of one sector (S34, 8.7kA): development of resistive zone (200 nΩ) in the super-conductive bus bar between quadrupole and neighboring dipole → loss of superconductivity

  ➡ Electrical arc developed, evaporated the power bar and punctured the He enclosure.
  
  ~2 t of LHe released into the insulating vacuum.
  
  Of the 340 MJ stored in S34 only 2/3 went into dump resistors.

  ➡ Rapid pressure rise inside magnets. Relief valves opened but could not handle the overpressure. Pressure wave (estimated 4 - 5 bars) propagated until it reached vacuum barriers. Several tons of load on the barriers: displaced magnets, breaking anchors.

  ➡ 6 of 15t of LHe of S34 released into the tunnel (30000 m³ He)
Repair is progressing very well - expect beam in October!
International Linear Collider

![Diagram of the International Linear Collider]

- Center of mass energy: $\sqrt{s}=500 \ldots 1$ TeV
- Field gradients: $\sim 35$ MV/m
- Remember: synchrotron radiation for circular machines

$$P = \frac{2\alpha}{3R^2} \beta^4 \gamma^4 \Rightarrow \beta \approx \frac{2\alpha}{3R^2} \left(\frac{E}{m}\right)^4$$

2.2 Particle detectors

Prototype of a modern compact particle detector

![Prototype of a modern compact particle detector]
3. Natural units

\[ \hat{\hbar} = c = 1 \]

With this choice one has the freedom to choose the unit of one other physical quantity. Typically: \([E] = \text{GeV}\)

\[ \Rightarrow \text{Units of all other quantities are defined} \]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>HEP unit</th>
<th>SI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>$1.6 \cdot 10^{-10} \text{ J}$</td>
</tr>
<tr>
<td>Mass</td>
<td>GeV</td>
<td>$1.78 \cdot 10^{-27} \text{ kg}$</td>
</tr>
<tr>
<td>Time</td>
<td>GeV$^{-1}$</td>
<td>$6.58 \cdot 10^{-25} \text{ s}$</td>
</tr>
<tr>
<td>Length</td>
<td>GeV$^{-1}$</td>
<td>$0.197 \text{ fm}$</td>
</tr>
<tr>
<td>Area</td>
<td>GeV$^{-2}$</td>
<td>$0.389 \text{ mb}$</td>
</tr>
<tr>
<td>Charge $e$</td>
<td>$\sqrt{4\pi\alpha}$</td>
<td>$1.6 \cdot 10^{-19} \text{ C}$</td>
</tr>
<tr>
<td>Temp $Tk$</td>
<td>GeV$^{-1}$</td>
<td>$1.16 \cdot 10^{16} \text{ K}$</td>
</tr>
</tbody>
</table>

Useful const.: $\hbar c = 197 \text{ MeV \cdot fm}$

\[ (\hbar c)^2 = 0.389 \text{ GeV}^2 \text{ mb} \]