Particle physics

International teachers program

July 2017

part III

European Organisation for Nuclear Research

„Magic is not happening at CERN, magic is explained at CERN“ - Tom Hanks

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### Standard model of particle physics

#### Elementary particles

- **Constituents of matter**
  - Fermions ($S=1/2$)

- **Force carries**
  - Bosons ($S=1$)

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<td>$u^\uparrow$</td>
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<td>$d^\downarrow$</td>
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<td>$\nu_e^0$</td>
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<td>$V_\tau$</td>
<td>$V_\tau$</td>
<td>$V_\mu$</td>
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- Particles:
  - $u$, $d$, $s$, $b$, $c$, $t$, $\nu_e$, $\nu_\mu$, $\nu_\tau$, $Z^0$, $W^\pm$
• **Elementary particles**

  • Constituents of matter
    • Fermions (S=1/2)

  • Force carries
    • Bosons (S=1)

Doublets under weak interaction
Higgs
• Higgs mechanism has essential role in theory of electroweak interactions

• Why is Higgs mechanism so important for particle physics?

• All gauge bosons massless in standard model!
  • However, W & Z Bosons are massive particles!

• Conservation of probability!
Higgs

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- Why is Higgs mechanism so important for particle physics?

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Scattering of longitudinally polarised W bosons:

Interaction probability $> 1$ for large $Q^2$!

Destructive interference $\rightarrow$ probability $< 1$
Masses of gauge bosons

- All gauge bosons are massless within theory!
  - If mass added explicitly: **breakdown of theory!!**
    - → Gauge invariance is lost
- Dynamic emergence of mass:
  - Interaction with scalar field
    - Field spreads through entire universe
  - Leads to mass terms in equations
- Symmetry of potential minimum, *spontaneously* broken
  - Breaking of electroweak symmetry!
    - Manifestation of electromagnetism & weak interactions
- Similar processes known from solid state physics (superconductivity)

\[ V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}. \]
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The Higgs particle

- Higgs mechanism requires **particle with spin = 0** (scalar)

- Boson of higgs field, mediator of interactions with Higgs field
The Higgs particle

- Higgs mechanism requires **particle with spin = 0 (scalar)**
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CERN (ATLAS & CMS): 2012
How the particles grew massive

• Mass of particles depends on coupling strength with Higgs field:
  • Directly responsible for masses of vector bosons: \( g_V \sim m_V^2 \)
    • Broken symmetry → goldstone bosons → available degrees of freedom absorbed in 3 massive and 1 massless gauge boson (=> base rotation)

• What about fermions?
  • Yukawa interaction with Higgs field
  • Explicitly added
  • \( g_F \sim m_F \)
Higgs coupling - mass dependence

- Coupling or $\sqrt{\text{coupling}}$
- $V$ & $F$ on straight line
Properties of the Higgs boson - Spin & Parity

Is it really the standard model Higgs particle?

Spin:
- integer, as decaying to $\gamma\gamma$

Parity:
- Even or Odd?

Comparison of measurement with various predictions!
- Agreement displayed as 'likelihood'
- Many 'pseudo experiments' => random fluctuations of predictions
**Standard model of particle physics**

- **Elementary particles**
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### Diagram

- **Quarks**
  - $u$: up, $c$: charm, $t$: top
  - $d$: down, $s$: strange, $b$: bottom
  - $\frac{2}{3}$, $\frac{1}{2}$, $\frac{1}{3}$ charges

- **Leptons**
  - $e$: electron, $\mu$: muon, $\tau$: tau
  - $0$, $\frac{1}{2}$ charges

- **Bosons**
  - $\gamma$: photon, $Z^0$: Z boson, $W^\pm$: W boson, $H$: Higgs boson
  - $125,9$ GeV
Standard model of particle physics

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Doublets under weak interaction
In summary

• Masses are dynamically generated
• Unification of electromagnetic & weak interactions
• Breaking of electroweak symmetry consistently described
• Massive & Massless gauge bosons
  • Difference between gauge boson masses
In summary

• Masses are dynamically generated

• Unification of electromagnetic & weak interactions

• Breaking of electroweak symmetry consistently described

• Massive & Massless gauge bosons
  • Difference between gauge boson masses

• Why is fermion mass $\neq 0$?

• Why are fermion masses so different from each other?

• What determines „mass hierarchy“? [2 MeV (u) -- 173 GeV (t) ]
One more statement on the Higgs particle

• Leon Lederman (ex director general of Fermilab), Nobelprice 1988
  • Published book on particle physics & the Higgs particle (1993)
  • Introduced „God particle“

• But why?
One more statement on the Higgs particle

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• But why?

"so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive”

but "the publisher wouldn't let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing."
Is the universe stable until the end of time?

- Does vacuum energy of Higgs field correspond to local or global minimum?
  - If local: is there a state of lower energy?
  - Could the universe tunnel into the lower energy state?
- Depends on masses of top quark & Higgs boson

\[ V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}. \]
Is the universe stable until the end of time?

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\[ V(\phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}. \]

- Average tunnel time \( \sim 10^{100} \) years
- Probably OK for us ;)

Kristof Schmieden
Neutrinos
Sources of neutrinos

• **Sun / Supernovae**: Nuclear fusion
  \[ _1^1 H + _1^1 H \rightarrow _2^2 H + e^+ + \nu_e + 0, 42 \text{ MeV} \]

• **Nuclear reactors**: fission
  • $\beta$ - decay of spallation products and neutrons $\rightarrow \nu_e$

• **Atmosphere**:
  • Decaying muons from cosmic rays $\rightarrow \nu_\mu, \nu_e$

• **Accelerators**:
  • Muon decays $\rightarrow \nu_\mu, \nu_e$
Neutrino oscillations

- Detection of stellar neutrinos in Homestake experiment:
- Measured neutrino flux 50% of expectation from sun’s luminosity

Davis Jr.: 1960ies
Neutrino oscillations

- Detection of stellar neutrinos in Homestake experiment: Measured neutrino flux 50% of expectation from sun’s luminosity

- Detection of stellar neutrinos in Kamiokande
  - Confirms Homestake results

- Detection of atmospheric neutrinos
  - Flux of neutrinos arriving from “top” and “bottom” differs by ~50%
  - What happens to the neutrinos within the earth?

Davis Jr.: 1960ies

Super Kamiokande: 1998
Neutrino oscillations

- Detection of stellar neutrinos in Homestake experiment: Davis Jr.: 1960ies
  - Measured neutrino flux 50% of expectation from sun’s luminosity

- Detection of stellar neutrinos in Kamiokande
  - Confirms Homestake results
  
- Detection of atmospheric neutrinos
  - Flux of neutrinos arriving from "top" and "bottom" differs by ~50%
  - What happens to the neutrinos within the earth?

- Neutrinos can oscillate from one flavour to another!
  - Note: only electron & muon neutrinos are detected in those experiments
Neutrino oscillations

• Analogy to quark sector

• **Mass eigenstates \(!=\) flavour eigenstates**

• Mixing allowed \(\rightarrow\) oscillations

• Requires: \(m_\nu > 0\) & \(m_\nu^1 \neq m_\nu^2 \neq m_\nu^3\)

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix} =
\begin{pmatrix}
\cos \Theta_m & \sin \Theta_m \\
-\sin \Theta_m & \cos \Theta_m
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix},
\]

Electron neutrino

Muon neutrino

Tau neutrino

\[
P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta(0) | \nu_\alpha(L) \rangle|^2 \approx \sin^2 \left( \frac{\Delta m^2 c^4}{4E} \frac{L}{\hbar c} \right) \cdot \sin^2 (2\Theta_m)
\]
Neutrino oscillations - detection

- Various reactor and accelerator based experiments
  - Detectors in varying distance to sources
    - Double Chooz, KamLand, DayaBay / T2K, Opera, Minos
  - Measurement: disappearance of neutrino flux
Neutrino oscillations - detection

- Various reactor and accelerator based experiments
  - Detectors in varying distance to sources
    - Double Chooz, KamLand, DayaBay / T2K, Opera, Minos
  - Measurement: disappearance of neutrino flux

- Opera: Detected appearance of tau-neutrinos!

  - Neutrino beam ($\mu$, e) from CERN sent 740km to Gran Sasso (IT)
  - Detection of tau-neutrinos in neutrino beam (5x)

Opera: 2010-2014
How do neutrinos gain mass?

- And why is mass so little? (< 2eV)
- Like fermions: coupling to Higgs field?
  - Requires left & right handed neutrinos
    - Only left-handed neutrinos observed!
- Other mechanism?
- One option: See-Saw mechanism:
  - Neutrinos are Majorana particles (their own anti-particles)
  - In addition very heavy right handed neutrinos (sterile Neutrinos)
    - Require very small mass for known neutrinos
  - Violated lepton number conservation & B-L
    - Possible explanation of the existence of matter via lepto-genesis
See saw mechanism

- **Idea**: one or more right handed neutrino fields, inert under weak interaction (sterile)
- Mass matrix in 1 generation between sterile and Dirac neutrinos:

\[
\begin{pmatrix}
0 & M \\
M & B
\end{pmatrix}
\]

- Dirac mass ~ EW scale
- Majorana mass ~ GUT scale

Eigenvalues ~ Neutrino masses:

\[
\lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}
\]

\[
\lambda_- \approx -\frac{M^2}{B} \quad \sim 1\text{eV}
\]

\[
\lambda_+ \approx B \quad \sim 1\text{eV}
\]

If one eigenvalue goes up, the other goes down => see saw
**Standard model of particle physics**

- **Elementary particles**
  - Constituents of matter
    - Fermions ($S=1/2$)
  - Force carries
    - Bosons ($S=1$)

### Particles

- **Quarks**
  - U (up)
  - C (charm)
  - T (top)
  - D (down)
  - S (strange)
  - B (bottom)
- **Leptons**
  - E (electron)
  - $\mu$ (muon)
  - $\tau$ (tau)
  - $\nu_e$ (electron-neutrino)
  - $\nu_\mu$ (muon-neutrino)
  - $\nu_\tau$ (tau-neutrino)
- **Bosons**
  - Photon ($\gamma$)
  - Higgs boson ($H$)
  - Z boson ($Z^0$)
  - W boson ($W^\pm$)

### Generation

- 1st generation
  - 2nd generation
  - 3rd generation

### Energies

- U (up): $2.3 \text{ MeV}$
- C (charm): $1.275 \text{ GeV}$
- T (top): $173.07 \text{ GeV}$
- D (down): $4.8 \text{ MeV}$
- S (strange): $95 \text{ MeV}$
- B (bottom): $4.18 \text{ GeV}$
- $\nu_e$: $<2 \text{ eV}$
- $\nu_\mu$: $<0.19 \text{ MeV}$
- $\nu_\tau$: $<18.2 \text{ MeV}$
- Z boson: $91.2 \text{ GeV}$
- W boson: $80.4 \text{ GeV}$
Standard model of particle physics

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Doublets under weak interaction
Success of SM

Standard Model Production Cross Section Measurements

**ATLAS** Preliminary

**Run 1** \( \sqrt{s} = 7, 8 \text{ TeV} \)

**LHC pp** \( \sqrt{s} = 7 \text{ TeV} \)

- **Theory**
- **Data** 4.5 – 4.7 fb\(^{-1}\)

**LHC pp** \( \sqrt{s} = 8 \text{ TeV} \)

- **Theory**
- **Data** 20.3 fb\(^{-1}\)

**95% CL upper limit**

- **Zjj**
- **\( H \to \gamma\gamma \)**
- **Wt**
- **t\bar{t}Z**

**Standard Model Production Cross Section Measurements**

Status: July 2014

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Run 1 \( \sqrt{s} = 7, 8 \text{ TeV} \)

**Theory**

**Data** 4.5 – 4.7 fb\(^{-1}\)

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- **\( H \to \gamma\gamma \)**
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**Standard Model Production Cross Section Measurements**

**Status: July 2014**
Few loose ends to tie up ...
Gravitation

• Gravitation can not be described within the standard model

  • Problem in theories: general relativity and quantum mechanics can not be merged consistently

• Why is gravity so weak?

  • Dominates on macroscopic scales
    • Neglectable on particle level!
    • $10^{-38}$ weaker as electromagnetic interaction!

• Extra dimensions?
Gravitation

- Why is gravitation so weak?

- Extra dimensions?
  - Predictions of 'black holes'
  - Particles that could be created at the LHC
  - Scattering off compact dimensions
  - Kaluza-Klein towers / excitations (= standing wave in extra dimension)

Not observed to date :(
One fundamental object:

- String

- Size ~ Planck length: $10^{-35}\text{m}$

Could be open or closed

Attached to „world-Brane“

Oscillation mode corresponds to observable particles

Branes live in 11 dimensional space

M-theory

Very simple & elegant approach

- Unification of all forces (including quantum description of gravitation)

Extremely hard to calculate. Until today no predictions that could be verified
What about anti-matter?

- Known asymmetry between matter & anti-matter can not explain matter anti-matter asymmetry in the universe

- CP - violation in weak interaction
  
  - physics processes distinguish between matter & anti-matter
  
  - LHCb investigates this

- There has to be a yet unknown interaction in addition to the SM ones!
What about anti-matter?

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- There has to be a yet unknown interaction in addition to the SM ones!

  - => How much energy contains the universe?
    - Cosmology lecture

assuming only known asymmetry between particles & anti-particles: generated matter / anti-matter in big bang > total energy density of universe
Intermezzo - Cosmology

- Study of cosmic microwave background:
  - Universe cools down → neutral atoms → transparent for em. rad.
  - Radiation from this era: while traveling through the universe, wavelength stretched with expansion of space itself
    - x-rays → microwaves

- Fit of ΛCDM model to data. Parameters:
  - Baryon-density, matter density, curvature of space, ...
Apropos: dark matter
Apropos: dark matter

- gravitational centre
- Per „weak-lensing“
Apropos: dark matter

- X-ray emission from hot gas
- highest baryon density

• gravitational centre
  • Per „weak-lensing“
Apropos: dark matter

- Several candidates + extensions of SM trying to describe DM

Planck: 2015

- dark matter ?
- baryons
- dark energy ???
Apropos: dark matter

• Properties:
  • Massive (gravitation)
  • Weak interaction
Apropos: dark matter

• Properties:

  • Massive (gravitation) → Neutrinos?

  • Weak interaction
Apropos: dark matter

- Properties:
  - Massive (gravitation)
  - Weak interaction

→ Neutrinos?

**Nope!** Only non-relativistic particles contribute to structure formation in the universe.
Apropos: dark matter

- **Properties:**
  - Massive (gravitation)
  - Weak interaction
  - ~non relativistic

- **Candidates:**
  - WIMPs (Lightest supersymmetric particle?)
  - Axions
  - Sterile neutrinos
A word on super symmetry

- New symmetry:
  - Each Boson ($S=0,1$) is assigned a fermion ($S=1/2$) and vice versa

![Particle zoo](https://cpc.hep.man.ac.uk/latex/lec03/partzoo.png)

Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle.
A word on super symmetry ... or two

• „Completes“ SM → all possible symmetries utilised

• New particles influence „running“ of couplings
  • Grand unification possible

![Diagram showing the running of couplings for different theories]

---

Warum Supersymmetrie?

1) Eine fundamentale Raum-Zeit-Symmetrie
2) ‘Schutz’ des (skalaren) Higgs-Bosons (M ~ 10^{12} GeV) vor dem Einfluss von Vakuumfluktuationen (~10^{19} GeV)
3) Vereinigung von elektroschwacher und starke WW bei ~10^{17} GeV
4) Mögliche Erklärung der kosmologischen Materie-Antimaterie-Asymmetrie
5) Dunkle Materie?
A word on super symmetry ... or two

• „Completes“ SM → all possible symmetries utilised

• New particles influence „running“ of couplings
  • Grand unification possible

• New conserved quantity: R-parity (+1 for particles, -1 for super-partners)

  • Lightest super symmetric particle must be stable!
  • Candidate for dark matter
A word on super symmetry ... or two

• „Completes“ SM → all possible symmetries utilised

• New particles influence „running“ of couplings
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![Graph showing the running of coupling constants](image)

• New conserved quantity: R-parity (+1 for particles, -1 for super-partners)

• Lightest super symmetric particle must be stable!
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![Graphs comparing SM and MSSM](image)

• Parameter space for super symmetry is huge
  • Parameters determine particle masses, can be (nearly) arbitrary
  • Can not be excluded
Axions

- Solve "strong CP problem"
- QCD allows CP violating reactions. Strength parametrised by parameter $\theta$
  - CP violation $\rightarrow$ electric dipole moment of the neutron
  - Experimentally: $\text{EDM}(n) < 10^{-25} \text{ e\cdotcm}$
  - Why? Seems non "natural" (fine tuning)
**Axions**

- Solve "strong CP problem"

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  - CP violation $\rightarrow$ electric dipole moment of the neutron
  - Experimentally: $\text{EDM}(n) < 10^{-25}$ e·cm
  - Why? Seems non "natural“ (fine tuning)

- Introducing yet another complex scalar field
  - Corresponding symmetry is spontaneously broken (as in Higgs mechanism)
  - $\theta$ becomes 'dynamically' exactly 0
  - Requires additional massive particle: **Axion**
    - Candidate for dark matter

Peccei, Quinn: 1977
All dark is intriguing

Planck: 2015

Dark matter?

Baryons

Dark energy ???

- Dark energy is completely not understood
  - Connection to theory of inflation?
  - Vacuum fluctuations?
  - Quintessence?
Many open question / issues

• Gravitation!
  • Why is gravitation so weak?

• Why is there no anti matter in the universe?

• Dark sector? (dark matter, dark energy)

• What is the nature of neutrinos?

• Why do we have exactly 3 particle generations?

• Why do particles have different masses?

The End
Literaturverzeichnis


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Kristof Schmieden
The Standard Model of particle physics

Years from concept to discovery

Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino

HIGGS BOSON

Source: The Economist

Theorised/explained
Discovered

1880 90 1900 10 20 30 40 50 60 70 80 90 2000 12