Large Hadron Collider (LHC)
Elementary particle physics

is the basis for understanding

the smallest constituents of matter
in the whole universe

size of observable universe > $10^{+26}$ m
size of quarks < $10^{-18}$ m

\[
\text{ratio} = 10^{44}
\]

age of universe 14 Gy $= 10^{+18}$ s

time to transverse a proton $= 10^{-23}$ s

content of the universe $= 10^{80}$ atoms
Overview

What is elementary particle physics?
What do we know already? Standard Model, Big Bang
Open questions: dark matter, antimatter asymmetry

LHC accelerator.

LHC detector.

LHC first results.
Which are the constituents of matter?
What are their features?

How do the forces work, which keep the constituents together?
What do we know already?

- Atoms consist of electrons and nuclei, **bound by electrical forces**
- Nuclei consist of protons and neutrons, **bound by strong forces**
- Protons and neutrons consist of quarks, **bound by strong forces**
- Electrons and quarks are **elementary particles**
What is an “Elementary particle”

What is a “Particle”? 

Localized state as described by quantum mechanics, taking into account Heisenberg's uncertainty principle (localization in space and momentum, time and energy...)

Features: mass, spin (angular momentum in rest frame), Charge = strength of interaction (electrical, weak, strong)

What does “elementary” mean?

No known constituents
No geometrical size (but, “size” is given by Heisenberg's uncertainty)

Historical remark: Each epoch recognized different objects as elementary. (e.g. 4 elements in the early greek culture).
Elementary particles: ordinary matter

Electrons: 511 keV
Neutrinos: 0 eV < mass < 2.2 eV
Up Quarks: 2 MeV
Down quarks: 5 MeV

All spin $\frac{1}{2}$.

Electrons and quarks make up most of the ordinary matter.

example of composite particle: proton
To build structures (nucleons, atoms, molecules) we need forces between elementary particles.

But in the quantum world, also forces are quantized, this gives raise to the force carrier particles.

The force carrier particle of the electromagnetic force is called the photon $\gamma$. 
Elementary particles: 4 interactions

As of today we know about 4 different forces. In the quantum world we call them interactions.

- **Electromagnetic interaction**: Photon ($\gamma$), particles: quark (q), electron (e)
- **Strong interaction**: Gluon (g), particles: quark (q) only
- **Weak interaction**: $W^+$, $Z^0$, $W^-$, particles: quark (q), electron (e), neutrino (v)
- **Gravitation**: (mass)

May be there are more types of interactions?
Interaction carriers can exist as independent objects.

They may transform into a pair of particle and antiparticle.

They have normally no mass: $m=0$ (always move with speed of light).

However weak interaction: $W, Z$ are heavy.

→ weak force is indeed weak and short ranged

→ controls sun burning!

Higgs mechanism explains, why they are heavy. (see later)
Elementary particles: more quarks and electrons

- muons and tauons: same as electrons, but more massive
- mu-Neutrinos, tau-Neutrinos: same as neutrinos
- strange, charmed, bottom and top Quarks: same as up, down quarks, but more massive

- all spin $\frac{1}{2}$
- all discovered in the 2nd half part of last century.
  (some were unexpectedly observed, others were predicted by theory)

- all together there are 3 generations of elementary particles.
Elementary particles: 3 generations of quarks and leptons

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quarks</th>
<th>(electr. charge)</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>+2/3 up</td>
<td>-1/3 down</td>
<td>0 $\nu_e$</td>
</tr>
<tr>
<td>2.</td>
<td>+2/3 charm</td>
<td>-1/3 strange</td>
<td>0 $\nu_\mu$</td>
</tr>
<tr>
<td>3.</td>
<td>+2/3 top</td>
<td>-1/3 bottom</td>
<td>0 $\nu_\tau$</td>
</tr>
</tbody>
</table>

May be there are more generations?

And in addition there is a copy of this table with inverted charge sign = antiparticles
Elementary particles: annihilation

A pair of particle and antiparticle may annihilate into an interaction carrier analog: quark and antiquark annihilate in gluons ...

example: proton
Elementary particles: more about antimatter

Predicted by relativistic quantum mechanics (P. Dirac 1930): for every particle exists an antiparticle with
- matter and antimatter annihilate to radiation energy. \( e^+ + e^- \rightarrow \gamma \), \( \gamma \rightarrow e^+ + e^- \).
- matter and antimatter are created symmetrically
- same mass
- inverse electrical, strong and weak charge
- inverse angular momentum to momentum direction (helicity)
- same gravitational forces

Discovered by Anderson (CalTech) and Blackett (Cambridge) 1932/3
by analysing composition of cosmic rays

Nobel prize: Dirac 1933 (together with Schroedinger)
Anderson 1936 (together with Hess)
Blackett 1948
6 quarks, 6 leptons, plus antiparticles
electromagnetic, weak and strong interactions
with interaction carriers $\gamma$, $W$, $Z$, gluons

With these ingredients we are able to explain ...

- structure of all matter on earth.
- radioactivity and controlled burning of the sun
- most processes some time after the big bang

However ....
The Big Bang

- 15 thousand million years
- 1 thousand million years
- 300 thousand years
- 3 minutes
- $10^{-10}$ seconds
- $10^{-34}$ seconds
- $10^{-43}$ seconds
- $10^{32}$ degrees
- $10^{27}$ degrees
- $10^{18}$ degrees
- $10^{10}$ degrees
- $10^9$ degrees
- 6000 degrees
- 18 degrees
- 3 degrees K

- radiation
- particles
- heavy particles carrying the weak force
- quark
- anti-quark
- electron
- positron (anti-electron)
- proton
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium
Standard Model is not complete: What is dark matter?

1933 measured Zwicky the rotation velocities of the galaxies in the galaxy cluster "Coma Berenice":

He found strong discrepancies to the expectation according to Newton's law → it needs much more mass, than visible

Curve B: measured
Curve A: expected from the visible mass
→ There must be more mass, called “dark matter”

Today there is more evidence (measurements of dark mass distributions, structure formation, background radiation)

Today we are still searching for the elementary constituents of this dark matter:
▶ direct detection in the Lab?
▶ indirect detection by annihilation radiation?
▶ production and detection at LHC?
Standard Model is not complete: Matter – antimatter - asymmetry?

So far everything is symmetric with respect to matter and antimatter

However, the universe is not symmetric!

In the early universe creation and annihilation reactions happened frequently $\gamma \rightarrow e^+ + e^-$. $e^+ + e^- \rightarrow \gamma$
→ similar numbers of electrons, positrons and gammas (and quarks and gluons etc.)

today: Most particles and antiparticles have annihilated.
There are $10^9$ times more photons than matter particles in the universe!
But, there is a tiny fraction of matter left, we are made of matter!
And, there is (almost) no antimatter left in the universe!

Why is there no antimatter left, but only matter?
Was there a tiny amount of more matter than antimatter in the early universe? Why?
LHC is built into a circular tunnel with 26 km circumference in the Geneva region.
Large Hadron Collider at CERN: accelerator tunnel

superconducting magnets guide beams around the accelerator circle

(in some places high Tc SC used)
How does an accelerator work?

An accelerator experiment in particle physics consists of:

1. generate electrically charged **particles**: **Source**
   normally e-, e+, p, Anti-p, (Muons)

2. accelerate **particles** to very high speed (high energy)

   concept: accelerate by **electrical fields**
   guide by **magnetical fields**

3. **particles** will collide with **fixed target** material,
   or with other **particles**: **collider**

4. **detectors** observe reaction products and measure their features.
Synchrotron

- Inject particles from source
- Electrical field → acceleration
- Magnetical field → guide along circle

The magnetic field must be raised continuously during the acceleration process

- Extract high energy particles
Synchrotron used as a collider

At LHC both particle types are protons, normally
Colliding proton bunches: how to do research?

- Detector to measure the primary and secondary particles created by the p-p smash
- Protons consists of quarks and the strong interaction field
- One p-p collision is called an event. Need lots of events for statistical analysis
Large Hadron Collider am CERN, operational since Dec. 2009

Parameters:

circumference 27 km
initial particle energy 450 GeV
nominal particle energy 7000 GeV
particle energy achieved: 3500 GeV

number of SC magnets: 9300
accelerating cavities: 8 per beam

colliding bunches of protons:
2808 bunches every 25 ns
1020 achieved with 50 ns spacing

bunch diameter 16 µm, length 3 cm
$10^{11}$ protons per bunch

typical measuring cycle: 8 hours

accelerators built by Cern, detectors mainly built by national university labs (10'000 users!)
Large Hadron Collider at CERN: accelerator tunnel

superconducting magnets.

construction time of accelerator and experiments: 1992 – 2008
Large Hadron Collider am CERN: magnets

2 vacuum beam pipes

superconducting magnet coils:
magnetic field: 8.33 Tesla
electrical current approx. 11000 A

cooling by
superfluid Helium
at temperature of 1.9 Kelvin
CERN and the whole accelerator complex

CERN represents an international organization since 1954
- supported by 20 (+1) European member states
- new: non-European states can become members
- 2500 employees
- 10,000 physicists from all over the world
  make use of this infrastructure
- yearly budget about 1100 Mio CHF.
Colliding proton bunches: how to do research?

- Detector to measure the primary and secondary particles created by the p-p smash
- Protons consists of quarks and the strong interaction field
- One p-p collision is called an event. Need lots of events for statistical analysis
Detectors: How to discover new particles and measure their features?

Decay length $L$ is usually very short (<mm), impossible to detect directly.

By combining energy and momentum of the daughter particles, we can determine mass (and charge and other features) of the parent particle.

\[ m^2 c^4 = \sum E_i^2 - \sum p_i^2 c^2 \]

→ need accurate particle detectors to measure $E$ and $p$!
Example (one of 4 LHC detectors)
LHCb: study $b$ quarks and $B$ mesons

$b$ quark: one of six known elementary quarks.

$B$ meson: bound state of $(b,d)$

designed, built and operated by 758 members, from 54 institutes in 15 countries

built at Uni Zurich
LHCb detector part designed and built at Zurich University 2002 - 2007

Another 5 – 10 – 20 years of operation and analysis to come!
Why study $b$ quarks and $B$ mesons?

because $B$ mesons show large matter antimatter asymmetry (mechanism predicted by Kobayashi and Maskawa, Nobel prize 2008)

remember: we want to know, why there is a bit more matter than antimatter in the universe!
Matter antimatter asymmetry observed in LHCb

matter: $B^0 \rightarrow K^+\pi^-$

antimatter: $\bar{B}^0 \rightarrow K^-\pi^+$

→ Matter and Antimatter behave differently!

But, this effect seems to be too small to explain matter asymmetry in universe!
Limits of the theory of the standard model?

Search for deviations from Standard Model predictions due to *virtual contributions of new heavy particles in loop processes*

Box diagram

\[
\begin{align*}
\bar{b} & \quad \bar{u}, \bar{c}, \bar{t} & \quad \bar{d}, \bar{s} \\
B^0 & \quad \text{?} & \quad \bar{B}^0 \\
\text{d, s} & \quad \text{u, c, t} & \quad \text{b}
\end{align*}
\]

Penguin diagram

\[
\begin{align*}
\bar{b} & \quad \bar{s} & \quad \phi \\
B^0 & \quad \text{?} & \quad \bar{K}_s^0, \phi \\
\text{d, s} & \quad \text{d, s}
\end{align*}
\]

Andreas Schopper, Moriond 2012
Limits of the theory of the standard model:
Rare B decays: $B_s \rightarrow \mu^+ \mu^-$

box diagram may contain new supersymmetric particles
(MSSM: minimal supersymmetric model)

<table>
<thead>
<tr>
<th>mode</th>
<th>limit</th>
<th>at 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow \mu^+ \mu^-$</td>
<td>expected bg+SM</td>
<td>$7.2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>expected bg only</td>
<td>$3.4 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>observed</td>
<td>$4.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+ \mu^-$</td>
<td>expected</td>
<td>$1.13 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>observed</td>
<td>$1.03 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
Limits of the theory of the standard model:
Rare B decays: $B \rightarrow K^* \mu^+ \mu^-$

Measure forward-backward asymmetry of the two mu as a function of $m^2(\mu,u)$

Depends on features of the loop particle
Standard model production processes measured at higher energy of LHC

Production Cross Section, $\sigma_{\text{tot}}$ [pb]

- $W$:
  - $\geq 1j$
  - $\geq 2j$
  - $\geq 3j$
  - $\geq 4j$

- $Z$:
  - $\geq 1j$
  - $\geq 2j$
  - $\geq 3j$
  - $\geq 4j$

- $W\gamma$:
  - $E_T^{\gamma} > 10$ GeV
  - $|\eta^{\gamma}| < 2.4$
  - $\Delta R(\gamma,l) > 0.7$

- $Z\gamma$:
  - $E_T^{\gamma} > 30$ GeV
  - $|\eta^{\gamma}| < 2.4$

- $W\gamma$:
  - $H(127)$
  - $\rightarrow ZZ$

- $WZ$:
  - $36$ pb$^{-1}$

- $ZZ$:
  - $36$ pb$^{-1}$
  - $1.1$ fb$^{-1}$
  - $4.7$ fb$^{-1}$

CMS 95%CL limit
CMS measurement (stat+syst)
Theory prediction

References:
- JHEP10(2011)132
- CMS-PAS-EWK-10-012
- PLB701(2011)535
- CMS-PAS-EWK-11-010
- CMS-PAS-HIG-11-025
Standard model production processes measured at higher energy of LHC
1964 the so called Higgs mechanism was proposed by Robert Brout and Francois Englert, independently by Peter Higgs, and by Gerald Guralnik, C. R. Hagen, and Tom Kibble.

This theory creates formally masses for the weak interaction carriers, W and Z (→ weak interaction is short range).

The whole space is filled up with a field, the Higgs field, which also gives masses to all quarks and leptons. It does not explain the size of the masses.

The Higgs has spin=0. The theory does not predict the mass of the Higgs $m_H$.

From earlier experiments we know, that $m_H > 114.4$ GeV and from indirect theoretical calculations that $m_H < 158$ GeV.
Looking for the Higgs particle (2)

Search for the Higgs with the CMS Detector at LHC:

Reconstruct Higgs from 2 detected photons.

→ Higgs not found yet!

From this and other measured data we derive now, that $m_H < 145 \text{ GeV}$ (or $m_H > 466 \text{ GeV}$).

We continue to search for the Higgs, results expected until end of 2012.
Looking for the Higgs particle (3) with ATLAS

<table>
<thead>
<tr>
<th>Higgs Decay channel</th>
<th>$m_H$ Range</th>
<th>L [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-$m_H$, good mass resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>4.9</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow \ell\ell\ell'$</td>
<td>110-600</td>
<td>4.8</td>
</tr>
<tr>
<td>low-$m_H$, limited mass resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\nu\ell\nu$</td>
<td>110-200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$VH \rightarrow b\bar{b}$</td>
<td>110-130</td>
<td>4.6</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^- \rightarrow \ell\ell4\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^- \rightarrow \ell\tau_{had}3\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^- \rightarrow \tau_{had}\tau_{had}2\nu$</td>
<td>110-150</td>
<td>4.7</td>
</tr>
<tr>
<td>high-$m_H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$</td>
<td>200-280-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow \ell\ell q\bar{q}$</td>
<td>200-300-600</td>
<td>4.7</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\nu q\bar{q}'$</td>
<td>300-600</td>
<td>4.7</td>
</tr>
</tbody>
</table>

combined limits on production cross section:

similar from CMS, with fluctuation at slightly lower energy
We are presently operating LHC and are gathering data from the pp collision products.

It will take a few years until we have convincing results.

- There is no immediate hint on limits of the SM or on new physics
- Is the Higgs existing? what is its mass and other features?
- If we don't find it, how can we explain massive W and Z particles?
- Are there any other, so far unknown particles or interactions?
- Do we find any candidates for dark matter constituents?
More generally:

- We hope to make the standard model more complete.
- At some point we might understand the difference of the 4 interactions

But why are there quarks and leptons and 4 interactions?

And why have the interactions exactly the right strength in order to make the universe and live possible the way it is?