The Large Hadron Collider
Project at CERN

Joachim Mnich
DESY

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Outline

- What?  Introduction
- Why?  Physics Motivation
- How?  Technological Challenges
- Where are we today?  Status and Expectations
- European Organization for Nuclear Research
- Founded in 1954
- 20 European Member States
- Located close to Geneva across the franco-swiss border
- Largest particle physics laboratory world-wide
### The Large Hadron Collider (LHC)

**LHC time table:**

- **Early 1980’s:** first ideas about a multi-TeV proton collider at CERN
- **Oct 1990:** ECFA workshop on LHC in Aachen
- **16 Dec 1994:** CERN council approves the LHC
- **Feb 1996:** approval of ATLAS and CMS
- **Apr 1998:** start civil engineering
- **7 Mar 2005:** first dipole magnet installed
- **26 Apr 2007:** last dipole installed
- **10 Sep 2008:** first circulating beams
- **Oct 2009:** first pp-collisions expected
The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- Highest ever energy per collision
  
  14 TeV in the pp-system

  cf. Tevatron at 2 TeV

- High luminosity (rate of pp-interaction)
  
  up to $10^{34}$/cm$^2$/s

- Conditions as $10^{-13}$ – $10^{-14}$ s after the Big Bang

- 4 experiments:
  - ATLAS
  - CMS
  - LHCb specialised on b-physics
  - ALICE specialised for heavy ion collisions

- LHC and experiments were constructed in global collaborations
Overall view of the LHC experiments.

≈ 100 m underground
Why? Physics Motivation
Theoretical Particle Physics

- **Relativity**
  - Mass is energy and energy is mass
  - Producing heavy particles requires high energy

- **Quantum mechanics**
  - Particles are waves and waves are particles
  - High momentum p (or energy) means smaller wave length

- **Uncertainty principle**
  - Position and momentum are not defined with arbitrary accuracy

- **...and God still plays dice**
  - Elementary quantum processes are not deterministic, only probabilities are calculable
  - Experiments must be repeated frequently

\[ E = mc^2 \]
\[ \lambda = \frac{h}{p} \]
\[ \Delta x \Delta p \approx \hbar \]
13 billion years
First supernovae

5 billion years
Galaxy and star formation

1 billion years
Transparent universe

10^13 seconds
Formation of atoms

100 seconds
Nucleosynthesis of Helium
Disappearance of positrons

10^-10 seconds
Formation of protons and neutrons

10^-34 seconds
Disappearance of antiquarks
Cosmic inflation?

10^-43 seconds
Quantum gravity epoch

Time

Energy
All known matter consists of four fundamental particle (fermions)

- There exist 2 copies of each fermion (called generations or families)
  - Identical, except for the mass

Antimatter:
- Each fermion has a partner with opposite charge
  e.g. the positron (e^+) is the antiparticle of the electron (e^-)
Standard Model of Particle Physics

Fundamental Interactions (forces):

1) Gravitation
   - Elementary particles: too weak, not part of the Standard Model

2) Electromagnetic Interactions
   - Electrostatic Magnetism
     - Bind electrons and nuclei to atoms and atoms to molecules

3) Weak Interactions
   - Important in certain nuclear and particle reactions, e.g. neutron decay $n \rightarrow p + e^- + \nu_e$

4) Strong Interactions
   - Bind quarks in protons and neutrons

\[ F = G \frac{mM}{r^2} \]
\[ F = \frac{1}{4\pi \varepsilon_0} \frac{qQ}{r^2} \]
# Standard Model of Particle Physics

- **Fundamental Interactions are mediated by the exchange of particles**
  - Spin 1, therefore called bosons
- **Fundamental particles are mathematically described by symmetries**
  - Local gauge symmetries

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediating Particle</th>
<th>Mass [GeV]</th>
<th>Symmetry Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitation</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Photon γ</td>
<td>0</td>
<td>U(1)</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm, Z$ Bosons</td>
<td>80, 91</td>
<td>SU(2)</td>
</tr>
<tr>
<td>Strong</td>
<td>Gluons g</td>
<td>0</td>
<td>SU(3)</td>
</tr>
</tbody>
</table>
Open Questions

- The Standard Model is very successful in describing phenomena up to a few 100 GeV

- But it leaves many open questions, e.g.
  - Why there are 3 copies of the fundamental fermions? Related to particle-antiparticle asymmetry in the universe?
  - What is the reason for $U(1) \times SU(2) \times SU(3)$ Is there only one fundamental interaction at high energy?
  - Gravitation? At high energy $10^{19}$ GeV gravitation matters
  - Origin of Mass?
  - Dark Matter
  - ...

- Experiments at the LHC are expected to provide some answers to these fundamental questions
Origin of Mass: The Higgs Boson

- Concept of local gauge symmetries requires massless exchange particles
  - Uncertainty principle: massive exchange particle = limited reach of interaction
  - Ok for photon and gluons
  - Manifestly violated in case of W & Z Bosons!

- Solution is Higgs mechanism
  - Vacuum is filled with a field
  - Gives mass to W, Z bosons and fermions
  - Requires existence of the Higgs boson
  - Important: its mass must be less than 1 TeV
  LHC will definitely decide on this issue!
Dark Matter and Supersymmetry

- **Astronomy:**
  - Only about 5% of our universe are made of known matter!
  - ≈ 20% dark matter
  - ≈ 75% dark energy

- **Theory of Supersymmetry:**
  - Symmetry between force and matter particles
  - Predicts a mirror world of new particles (a shadow world like anti-matter)
  - Solves many of the open questions
  - Contains a particle for Dark Matter
2000: „Concept“ of the CMS tracking detector

Sergio Cittolin
A Collider for the Terascale

- **Electron-Positron Collider**
  - Like DORIS & PETRA at DESY or LEP at CERN
  - Point-like particles
  - But limited in energy by synchrotron radiation

- **Proton-(anti)proton collider**
  - Higher energy reach limited by magnet bending power
  - But much harder for experiments
Challenges for the LHC: Magnets

- Superconducting dipole magnets to keep 7 TeV protons on a circular path \( (r \approx 3 \text{ km}) \)
  \[ |B| = 8.33 \text{ Tesla} \]
- 1232 dipole magnets needed each is 15 m long (+ quadrupoles, sextupoles, etc.)
  - 1.9 K operating temperature
  - Supraliquid Helium
  - Largest cryogenic facility in the world
- Quench protection
  - Stored energy in one dipole: 8 MJ corresponds to a 40 t truck at 50 km/h

- LHC dipole design incorporates reversed field for oppositely rotating proton beams
LHC Dipoles

- Around 1999: construction of dipoles start
Dipoles in the LHC Tunnel
Cryogenics

- First cool down of an LHC sector (> 3 km) in April 2007
- 1.9 K: colder than the universe
Challenges for LHC Detectors

- Protons are composite particles
  - Bags filled with quarks and gluons
  - Quark-quark and gluon-gluon collisions are the fundamental processes
  - Screened by interactions of other quarks & gluons
- LHC is filled with 2835 + 2835 proton bunches
  - Collisions every 25 ns
  - 40 MHz crossing rate
- $10^{11}$ protons per bunch
  - 25 pp interactions per crossing (pile-up)
  - Each bunch collision produces $\approx 1600$ charged particles
A Collision Producing a Higgs Boson

- Identify each track
  requires a highly granular detector

- Reconstruct every track
  takes a lot computing power

- with 25 pile-up interactions

- Remove low energy tracks
  ($p_T < 25$ GeV)

- $H \rightarrow ZZ \rightarrow 4$ muons
Example: CMS Tracking Detector

- Silicon strip detector

- 16000 such modules built
- 220 m² of silicon surface (almost a tennis court…)
- Largest silicon detector ever built
A Dream Becomes Reality...
Looking for a Needle in a Haystack

- Protons are large particles, 10^{-15} m diameter
- Not pointlike as e.g. electrons (diameter < 10^{-18} m)
- Huge proton-proton interaction rate at the LHC
  - 10^9 per second
  - 10^8 per second in initial phase
- However, most interesting processes are rather rare
- E.g. about 1 Higgs boson per minute will be produced

Higgs at the LHC
Finding the Higgs Boson

- **Online trigger**
  - Only a tiny fraction of the collision can be stored for detailed inspection
    - Interaction rate $\approx 10^9$ events/s
    - Max. record rate $\approx 100$ events/s  event size $\approx 1$ MByte $\Rightarrow 1000$ TByte/year
  - Trigger rejection $\approx 10^7$

- **Collision interval** is 25 ns corresponds to 5 m cable delay

- **Trigger decision** takes a few $\mu$s (1st level)
  $\Rightarrow$ store massive amount of data in front-end pipelines
  $\Rightarrow$ massive parallel computing
The Worldwide Computing Grid

- 1000 TByte/year and experiment are still huge + simulation + calibration + reconstruction + …
- Grid Computing a world-wide computing centre
Principle of Particle Physics Detectors

- Slice through the CMS detector

Magnetic field to bend charged particles
ATLAS and CMS

- ATLAS and CMS are the two large multi-purpose detectors at the LHC
- Each collaboration counts about 2500 scientists & engineers from about 40 different countries
International Collaboration
International Collaboration

- Brass casings of decommissioned shells of the Russian Northern Fleet

- Converted to brass absorbers for the CMS calorimeter
ATLAS: A Toroidal LHC ApparatuS
ATLAS with inner Detectors
## Comparison ATLAS and CMS

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<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>≈ 46 m</td>
<td>≈ 22 m</td>
</tr>
<tr>
<td>diameter</td>
<td>≈ 25 m</td>
<td>≈ 15 m</td>
</tr>
<tr>
<td>weight</td>
<td>≈ 7000 t</td>
<td>≈ 12000 t</td>
</tr>
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</table>
LHCb

- Experiment to address the question of matter-antimatter asymmetry
ALICE

- Experiment addresses new state of matter: the quark-gluon plasma

- Heavy ion collisions, eg. Pb-Pb
Where are we today? Status and Expectations

- First circulating beams on September 10, 2008
LHC Accident

- **Major accident on September 19, 2008**
  - Bad connection between 2 magnets (resistance >> 1 nΩ)
  - Heat load ≈ 10 W cannot be cooled away
  - Thermal runaway
- **Quench protection of magnets worked well**
- **But light arc between magnets**
  - Destroyed a Helium vessel
  - 2 tons of He effused
  - Shock wave in tunnel
Damage

53 magnets inspected, repaired & reinstalled
Plans

- Improve protection systems
- Restart LHC in September 2009
- First collisions in October 2009
- Operation until end 2010
  - reduced energy (5 TeV)

- Detectors are ready and preparing for data taking with cosmic rays
Possible Higgs Discovery in 201x

$H \rightarrow \gamma \gamma$:
$m_H = 130$ GeV
$\sigma_{m_H} \approx 1$ GeV

$H \rightarrow ZZ \rightarrow 4\mu$:
$m_H = 200 (300, 500)$ GeV

large combinatorial background

background subtracted

Note the increasing signal width
Supersymmetry

- LHC will eclipse previous experiments and chart new territory in the parameter space

- Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters
Summary

PHYSICS AT THE TERASCALE

- LHC is one of the largest scientific endeavours ever undertaken
- 25 years of preparation involving thousands of scientists all over the world
- Likely to be exploited for decades
- Results will change our view of the universe
- Backup slides
Vision

- Revolutionary advances in understanding the microcosm
- Connect microcosm with early Universe

Particle Physics at the **Energy Frontier** with highest collision energies ever will change our view of the universe
A Collision Producing a Higgs Boson
Higgs Boson Decay

Higgs couples proportional to masses
⇒ preferentially decaying into heaviest particle kinematically allowed

Branching ratio versus $m_H$:

- **Low mass** ($115 < m_H < 140$ GeV)
  
  $H \rightarrow bb$ make up most of the decays
  
  problem at the LHC because of the huge QCD background!

- **Intermediate** ($140 < m_H < 180$ GeV)
  
  $H \rightarrow WW$ opens up
  
  use leptonic W decay modes

- **High mass** ($m_H > 180$ GeV)
  
  $H \rightarrow ZZ \rightarrow 4$ leptons
  
  golden channel!