Present and future scientific programme at CERN

• Introduction on CERN
• The LHC programme
• The non LHC programme
• Brief summary
CERN

« An establishment of an international laboratory for the purpose of carrying out an agreed programme of research of a pure scientific and fundamental character relating to high-energy physics »

CERN Convention, 1954
High-energy Physics/ Particle Physics

Aim to discover what the universe is made of and how it works.

-What are the elementary constituents of matter?

-What are the fundamental forces that control their behaviour at the most basic level?
CERN Member States

The Twenty Member States of CERN

Member States (Dates of Accession)

The Large Hadron Collider (LHC)

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
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<tbody>
<tr>
<td><strong>LEP</strong></td>
<td>e^+ e^-</td>
<td>200 GeV</td>
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<tr>
<td><strong>LHC</strong></td>
<td>p p</td>
<td>14 TeV</td>
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<td></td>
<td>Pb Pb</td>
<td>1312 TeV</td>
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</table>
ATLAS Cavern

Warszawa/Joël Feltesse
\[ E = MC^2 \]

At Large Hadron Collider:

Before collision

proton
E = 7 TeV

proton
E = 7 TeV

After collision
In the heart of matter

- Matter is built up from “elementary” particles, the mass is concentrated inside the atomic nucleus.
- Stable matter in the universe is made of 4 elementary particles.
The Standard Model

\[ M_e \sim 0.5 \text{ MeV} \]
\[ M_\nu \sim 0 \]
\[ M_t \sim 175,000 \text{ MeV}! \]

\[ M_\gamma = 0 \]
\[ M_Z \sim 100,000 \text{ MeV} \]
The standard model has been tested at the permil level at LEP and in many other facilities in the world.
Origin of mass and the Higgs mechanism

Simplest theory – all particles are massless !!

A field pervades the universe

Particles interacting with this field acquire mass – stronger the interaction larger the mass

The field is a quantum field – the quantum is the Higgs boson

Finding the Higgs establishes the presence of the field
What do we know about the Higgs?

Probability for $m_H$ combining direct and indirect information

$114.4 < M_{\text{higgs}} < 237 \text{ GeV}$
The Standard model is a low energy approximation of a more fundamental theory

- SM contains too many apparently arbitrary features.
- SM does not incorporate gravity.
- Only five percent of the universe is made of normal, visible matter described by the standard model! What is the nature of the dark matter which prevades our galaxy and the universe?
All this calls for

A more fundamental theory of which SM is low-E approximation → New Physics

Difficult task: solve SM problems without contradicting experimental data

Best candidates:

- Supersymmetry
- Extra-dimensions
- String theory

all predict New Physics at $\approx$ TeV scale

need a machine to explore the $\sim$ TeV energy range
SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

For every particle there exists an antiparticle. For example: proton and antiproton, electron and positron, etc..

Similarly, Supersymmetry predicts that for every known particle there exists a superpartner particle

<table>
<thead>
<tr>
<th>SM particle</th>
<th>SUSY partner</th>
<th>spin</th>
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<tbody>
<tr>
<td>$\ell$</td>
<td>sleptons $\tilde{\ell}$</td>
<td>0</td>
</tr>
<tr>
<td>q</td>
<td>squarks $\tilde{q}$</td>
<td>0</td>
</tr>
<tr>
<td>g</td>
<td>gluino $\tilde{g}$</td>
<td>1/2</td>
</tr>
<tr>
<td>$W^\pm$ (+Higgs)</td>
<td>charginos $\chi^{\pm}_{1,2}$</td>
<td>1/2</td>
</tr>
<tr>
<td>$\gamma, Z$ (+Higgs)</td>
<td>neutralinos $\chi^{0}_{1,2,3,4}$</td>
<td>1/2</td>
</tr>
</tbody>
</table>

$+$ 5 Higgs: $h, H, A, H^\pm$

In the simplest models:
- The Lightest Supersymmetric Particle (LSP) is stable.
- All Supersymmetric particles decay to LSP.
- The LSP is a neutralino.
- The neutralino is a natural candidate for dark matter.

$m_h < 135$ GeV
The Result of a Collision
**ATLAS**

- **Diameter**: 25 m
- **Barrel toroid length**: 26 m
- **End-cap end-wall chamber span**: 46 m
- **Overall weight**: 7000 Tons

**Properties**

- Shielding: 300 mg/cm³
ATLAS Collaboration

34 Countries
151 Institutions
1700 Scientific Authors

U.S. participation in numbers:
34 Institutions (22.5% of the total)
283 Scientific authors total (16.6%)
233 Scientific authors holding a PhD or equivalent (17.9%)

The CMS Detector

- **Silicon Microstrips**
- **Pixels**
- **PbWO4 crystals**
- **Drift Tube Chambers**
- **Resistive Plate Chambers**
- **Cathode Strip Chambers**
- **Resistive Plate Chambers**
- **Superconducting Coil**
- **Iron Yoke**
- **Hcal**
- **Plastic scintillator/brass sandwich**
- **Calorimeters**
- **Total weight**: 12,500 t
- **Overall diameter**: 15 m
- **Overall length**: 21.6 m
- **Magnetic field**: 4 Tesla

**Tracker**

**Muon Barrel**

**Muon Endcaps**

3 g/cm³
LHCb is an experiment to look for a sign of New Physics through CP violation in B meson decays
From atoms to quarks

Leptons are fundamental
e.g.

- electron
- muon
- neutrinos

Hadrons are made of quarks,
e.g.

\[ p = uud \]
\[ \Lambda^0 = uds \]
\[ \Lambda^0_b = udb \]
\[ \pi^+ = u\bar{d} \]
\[ \kappa^+ = u\bar{s} \]
\[ B^+ = u\bar{b} \]

Baryons

Mesons
CP Violation in Evolution of Universe

\[ \frac{N_B - N_B^-}{N_B + N_B^-} = \left( \frac{\text{Number of baryons (}N_B\text{)}}{\text{Number of photons (}N_\gamma\text{)}} \right) = 0 \]

\[ = 10^{-9} \sim 10^{-10} \neq 0 \]
Problem

Observed CP violation in particle physics (kaon and B-meson) so far can be explained by the Standard Model.

The Standard Model cannot explain the observed ratio of $N_B/N_\gamma$

Further more…

Physics beyond the Standard Model, such as Supersymmetry with much more particles, generates a new source of CP violation
LHCb is an experiment to look for a sign of New Physics through CP violation in B meson decays

**Why B meson decays?**
For some decay modes, Standard Model CP violation effects are well predicted. Large effects are predicted in B meson decays.

I.e. any deviation is a clear sign of New Physics

**Why at LHC?**
LHC will be the most powerful source of b hadrons, producing not only $B^0$ and $B^\pm$ but also $B_s$, $B_c$ and b-baryons.
Let’s go backwards

How did the strong interaction give rise to the composite particles which constitute the universe?
Laboratory experiment

1. Accelerated ions in the LHC collide head on

2. The energy of collision is materialized into quarks and gluons

3. Quarks and gluons interact via the strong interaction: matter equilibrates

4. The system expands and cools down

5. Quarks and gluons condensate into hadrons
What we should be prepared to

Alice event: 0, Run: 0
Nparticles = 3550  Nhits = 1171925

Alice event: 0, Run: 0
Nparticles = 36276  Nhits = 1943104

60° < θ < 62°

One collision:
Pb+Pb @ 5.5 TeV
dN/dy = 8,000

23 Juin 2003

Warszawa/Joël Feltesse
The LHC physics goals

Search for the Standard Model Higgs boson over $\sim 115 < m_H < 1000$ GeV.

Search for physics beyond the SM (Supersymmetry, Extra-dimensions, …) up to the TeV-range

Precise measurements:
- $W$ mass
- top mass, couplings and decay properties
- Higgs mass, spin, couplings (if Higgs found)
- etc...

B-physics: CP violation, rare decays, B0 oscillations

Study of phase transition at high density from hadronic matter to plasma of deconfined quarks and gluons.

Etc. etc. .....
There is a bit more than the LHC

- Proton physics
- Kaon physics (CP violation, rare decays)
- Heavy ion physics on fixed target

- Future neutrino physics
- ISOLDE
- Cold anti-hydrogen
The structure of the Proton

Proton is not, in fact, simply made from three quarks (uud)

There are actually 3 “valence” quarks (uud) + a “sea” of gluons and short-lived quark-antiquark pairs
Quark & gluon spin

Nucleon spin: $\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle$

Quark "spin": $\Delta \Sigma = \Delta u + \Delta d + \Delta s$  \hspace{1cm} Gluon "spin": $\Delta G$

Orbital angular momentum of q & g: $L_z$

Very naïve: $\Delta \Sigma \sim 1$  \hspace{1cm} Ellis-Jaffe $\sim 0.6$

EMC: $\Delta \Sigma = 0.12 \ (0.17) \ \Delta s = -0.19 \ (0.06)$

"spin crisis !!"
Neutrinos

Neutrinos are the most mysterious of the known particles of the universe. Neutrinos are elusive and full of surprises. They interact so weakly with other particles that trillions of them pass through our bodies each second without leaving a trace. They have a tiny mass different from zero!! They oscillate.
How $m_\nu > 0$ results in $\nu$ oscillation

**Quantum Mechanics**

weak $\rightarrow$ mass $\rightarrow$ weak

$\nu_{\mu}$ production

$\nu_{\tau}$ detected, although $\nu_{\mu}$ was produced!

*M.C. Escher, Metamorphose III (1967-68), part of a “long baseline” xylograph (19 cm x 680 cm)*
CERN Neutrinos to Gran Sasso
CNGS PROGRAM:

- Provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for $\nu_\tau$ appearance in a pure $\nu_\mu$ beam
- Search for the subleading $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of $\Theta_{13}$)

- $\nu_\tau$ appearance experiments

Warszawa/Joël Feltesse
OPERA Final Design with 2 SuperModules

31 target planes / Super-Module (206336 bricks, 1766 tons)
CERN: the World’s Most Complete Accelerator Complex (not to scale)
The Terra incognita of exotic nuclei

- 250 stable nuclei
  - N=Z light
  - N>Z heavy

- 2000 « artificial » nuclei synthesized since Joliot-Curie

- 5000 to 7000 bound nuclei expected
Nucleosynthesis paths

- s process
- rp process
- Big Bang
- r process
- Stellar evolution
- Super-nova
“Cold” antihydrogen production

Reduce energy of antiprotons by 13 orders of magnitude!
Step 1 towards spectroscopy
PRODUCTION AND DETECTION OF COLD ANTIHYDROGEN

**AD**
- p- Production (GeV)
- Deceleration (MeV)
- Trapping (keV)
- Cooling (~ meV)

**Na-22**
- e+ Production (MeV)
- Moderation
- Accumulation (eV)

\[ 10^4 \, \text{p}^- \quad 10^8 \, \text{e}^+ \]

p- and e+ in mixing trap (cooling)

Antihydrogen formation

Detection of annihilation
## Main lines of present and future CERN scientific programme

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
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<td><strong>LHC/LHCb</strong></td>
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<td>INSTALLATION/COMMISSIONING</td>
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<td>RUNNING</td>
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<td><strong>LHC/ALICE</strong></td>
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<td><strong>SPS/COMPASS</strong></td>
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Warszawa/Joël Feltesse
Summary

• Looking for the most elementary constituents of matter is fascinating. It is a journey of exploration into the mystery and beauty of the universe at the smallest and the largest scale.

• Since 50 years CERN has been at the forefront of international research in particle physics. With the LEP Programme CERN has become the world leader laboratory. This will continue with the LHC which should open a new window in particle physics and cosmology.
Additional slides
The LHC experiments

• The multipurposes detectors: ATLAS and CMS
• The CP violation LHCb experiment :LHCb
• The heavy nuclei experiment: ALICE
The LEP $\text{e}^+\text{e}^-$ Collider at CERN

1989-2000 : $\sqrt{s} = m_Z \rightarrow 209$ GeV
Precise measurements of Z particle and $m_W$, and search for new particles (Higgs !)

Many spectacular measurements: agreement theory-data at the permil level!
Event rate in ATLAS:
\[ N = L \times \sigma (pp) \approx 10^9 \text{ interactions/s} \]

Mostly soft (low \( p_T \)) events

Interesting hard (high-\( p_T \)) events are rare

Selection of 1 in \( 10,000,000,000,000,000 \)

\( \rightarrow \) very powerful detectors needed
Kaons @ CERN

• Kaon physics has a long tradition at CERN

• Direct CP-Violation amounts to a different probability for a particle and its anti-particle to disintegrate into the same final state

• Since the discovery of CP violation a question was pending: “Does Direct CP-Violation exist?”

• The CERN/NA48 experiment employing intense beam of neutral kaons has settled the question
The Future of kaon physics at CERN

- The focus now shifts to those decays where very precise theoretical predictions can be made.
- In particular, the Collaboration plans to address the “Holy Grail” of kaon rare decays: \( K \rightarrow \pi \nu \nu \)
- Any deviation from the precise Standard Model prediction will be a sign of New Physics.
Direct CP-Violation

NA48 97-2001: \( \text{Re } \varepsilon'/\varepsilon = 14.7 \pm 2.2 \times 10^{-4} \)

World Average: \( \text{Re } \varepsilon'/\varepsilon = 16.7 \times 10^{-4} \)