Introduction
Science
World Collaboration

Accelerating Science and Innovation

R.-D. Heuer, CERN
CERN Summer Student Programme, July 1, 2009
Introduction

Accelerating Science and Innovation

CERN
The Mission of CERN

- **Push back** the frontiers of knowledge
  
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe’s existence?

- **Develop** new technologies for accelerators and detectors
  
  Information technology - the Web and the GRID
  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures
CERN in Numbers

- 2256 staff
- ~ 700 other paid personnel
- ~ 9500 users
- Budget (2009) 1100 MCHF

- 20 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
- 1 Candidate for Accession to Membership of CERN: Romania
- 8 Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and Unesco
CERN in Numbers

Distribution of All CERN Users by Nation of Institute on 17 February 2009

MEMBER STATES
AUSTRIA 63
BELGIUM 105
BULGARIA 48
CZECH REPUBLIC 173
DENMARK 56
FINLAND 85
FRANCE 857
GERMANY 1029
GREECE 95
HUNGARY 57
ITALY 1458
NETHERLANDS 175
NORWAY 72
POLAND 165
PORTUGAL 110
SLOVAKIA 48
SPAIN 291
SWEDEN 73
SWITZERLAND 332
UNITED KINGDOM 697

OTHER STATES
ARGENTINA 10
ARMENIA 14
AUSTRALIA 13
AZERBAIJAN 1
BELARUS 19
BRAZIL 70
CANADA 137
CHILE 5
CHINA 69
COLOMBIA 13
CROATIA 20
CUBA 6
CYPRUS 6
EGYPT 1
ESTONIA 11
GEORGIA 10
ICELAND 1
IRELAND 12
IRAN 12
IRELAND 12
ITALY 1
KOREA 1
LITHUANIA 9
MEXICO 29
MONTENEGRO 1
MOROCCO 5
NEW ZEALAND 5
PAKISTAN 22
PERU 1
ROMANIA 1
ROMANIA 50
SERBIA 17
SLOVENIA 16
SOUTH AFRICA 8

5989
2787
707
CERN in Numbers

Distribution of All CERN Users by Nationality on 17 February 2009
CERN Technologies - Innovation

Three key technology areas at CERN

Accelerating particle beams

Detecting particles

Large-scale computing (Grid)
CERN Technologies - Innovation

Example: medical application

Accelerating particle beams

Detecting particles

Charged hadron beam that loses energy in matter

Large-scale computing (Grid)

Grid computing for medical data management and analysis
CERN Education Activities

Scientists at CERN
Academic Training Programme

Young Researchers
CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

Physics Students
Summer Students Programme

CERN Teacher Schools
International and National Programmes

Latin American School of High Energy Physics
Chile, 2007

School of Computing
Norway, 2008
Features of Particle Physics

Duration of large particle physics projects:

decade(s)
from science case
via concept, R&D, and design
to realisation and exploitation

Excellent training grounds
in particle physics,
accelerator and detector technologies,
computing
Duration of Projects

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis is based on the United States where very large p̅p experiments are being studied at the moment. Indeed, the performance limitations of possible p̅p or p̅n channels seems overdue, however far off in the future a program for such a p̅LEP project may yet be in time. What we shall do, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course, that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.
Features of Particle Physics

Interplay and Synergy

of different tools
  (accelerators – cosmic rays – reactors . . .)

of different facilities
  different initial states
    lepton collider (electron-positron)
    hadron collider (proton-proton)
    lepton-hadron collider

at the energy frontier: high collision energy
and intensity frontier: high reaction rate
Test of the SM at the Level of Quantum Fluctuations

possible due to
• precision measurements
• known higher order electroweak corrections

\[ \propto \left( \frac{M_t}{M_W} \right)^2, \ln\left( \frac{M_h}{M_W} \right) \]

indirect determination of the top mass
**Status Summer Conferences 2007**

### Standard Model Analysis

| Measurement | Fit $|\Delta O^{\text{meas}}/\Delta O^{\text{fit}}|/\sigma^{\text{meas}}$ |
|-------------|--------------------------------------------------|
| $\Delta \alpha_{\text{had}}^{(6)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| $m_Z \ [\text{GeV}]$ | 91.1875 ± 0.0021 | 91.1875 |
| $\Gamma_Z \ [\text{GeV}]$ | 2.4952 ± 0.0023 | 2.4957 |
| $\sigma_{\text{had}}^0 \ [\text{nb}]$ | 41.540 ± 0.037 | 41.477 |
| $R_l$ | 20.767 ± 0.025 | 20.744 |
| $A_{\ell b}^{0,l}$ | 0.01714 ± 0.00095 | 0.01645 |
| $A_l(P_{\gamma})$ | 0.1465 ± 0.0032 | 0.1481 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21586 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1722 |
| $A_{\ell b}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{\ell b}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_{\ell b}$ | 0.923 ± 0.020 | 0.935 |
| $A_b$ | 0.670 ± 0.027 | 0.668 |
| $A_{l}(\text{SLD})$ | 0.1513 ± 0.0021 | 0.1481 |
| $\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\ell b})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W \ [\text{GeV}]$ | 80.398 ± 0.025 | 80.374 |
| $\Gamma_W \ [\text{GeV}]$ | 2.140 ± 0.060 | 2.091 |
| $m_t \ [\text{GeV}]$ | 170.9 ± 1.8 | 171.3 |

**Fit to 17 high-$Q^2$ observables plus $\Delta \alpha_{\text{had}}$:**

$\chi^2/\text{ndof} = 18.2/13 \ (15.1\%)$

**Largest $\chi^2$ contribution:**

$A_l(\text{SLD})$ vs. $A_{\ell b}(\text{LEP})$

**Decided in favour of leptons:**

Without this point, the fit is too good!

A$_{\ell b}(b)$ has largest pull: 2.9σ!

however . . .

. . . one piece missing within Standard Model

plus many open questions
Key Questions of Particle Physics

- origin of mass/matter or origin of electroweak symmetry breaking
- unification of forces
- fundamental symmetry of forces and matter
- unification of quantum physics and general relativity
- number of space/time dimensions
- what is dark matter
- what is dark energy
Science
Particle Physics at CERN: Experiments and Theory
CERN and the European Strategy for Particle Physics

Accelerating Science and Innovation
Main emphasis: High energy frontier
But:
rich program of accelerator based particle physics
**Fixed Target Physics**

### Heavy-ion Physics
- Heavy ion fixed-target physics
- Study of matter at extreme energy density
- Search for state of quasi-free partons: quarks and gluons → quark-gluon plasma (QGP)?

### Hadron Structure Physics
- Spin structure of nucleon (w/ μ beam)
- uds + g QCD spectroscopy (w/ hadron beam)
Fixed Target Physics

Antiproton Physics

Cold antiprotons
(“manufacturing anti-matter”)
1. PS $p \rightarrow pp$ $10^{-6}$/collision
2. AD deceleration + cooling stochastic + electron
3. Extraction @ ~ 0.1c
4. Produce thousands of anti-$H$

Anti-$H$ annihilations detected
ATHENA ($\rightarrow$ ALPHA)
anti-$H$ ($pe^*$) + matter $\rightarrow \pi^+\pi^- + \gamma\gamma$

Neutral Current Charge

π
Silicon micro strips
CsI crystals
511 keV $\gamma$

π

Neutrino Physics

CERN NEUTRINOS TO GRAN SASSO
732 Km

$\nu\nu\nu\nu\nu$

$\mu\mu\mu\mu$

$\tau\tau\tau\tau$

511 keV $\gamma$

Neutral Current

Charge Current

OPERA
At thermal energy of $kT=30$ keV the Maxwellian averaged cross section of this $^{151}$Sm ($t_{1/2}=93$ yr) was determined to be $3100\pm160$ mb, significantly larger than theoretical predictions. Nucleosynthesis in giant branch stars.
The European Strategy for particle physics

General issues

1. European particle physics is founded on strong national institutes, universities and laboratories and the CERN Organization; Europe should maintain and strengthen its central position in particle physics.

2. Increased globalization, concentration and scale of particle physics make a well coordinated strategy in Europe paramount; this strategy will be defined and updated by CERN Council as outlined below.
The European Strategy for particle physics

The process:

CERN Council Strategy Group established

Open Symposium (Orsay, Jan 31/Feb 1, 2006)

Final Workshop (Zeuthen, May 2006)

Strategy Document approved unanimously by Council July 14, 2006
3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. Luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.
Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

Exploration of a new energy frontier
Proton-proton collisions at $E_{CM} = 14$ TeV
A few characteristics:

The LHC features 1232, 15 m long, 9 T, superconducting dipoles
The tunnel is 27 km in circumference
protons can thus be accelerated to 7 TeV, allowing

14 TeV proton-proton collisions

in the centre-of-mass

The proton beams consist of compact bunches of $10^{11}$ protons each, 25 ns apart, leading to a collision rate normalized to the cross section of

$Luminosity = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
First beam around the ring Sept. 10, 2008
Incident Sept. 19, 2008
Inauguration October 21, 2008
Capture with optimum injection phasing, correct reference

September 10, 2008

Great success for Collider and for Experiments: working well
Busbar splice

Specification: resistance below $n\Omega$
Busbar splice

- Upper Tin/Silver Soldering alloy Layer
- Inter-Cable Tin/Silver Soldering Alloy Layer
- Lower Tin/Silver Soldering Alloy Layer
- Upper Copper Profile
- Cable Junction Box Cross-section
- Complete Junction
- Superconducting Cable in Copper Stabilizer
Two ‘general purpose’ $4\pi$ detectors for pp collisions at high $L$; some capabilities for PbPb

ATLAS and CMS

One dedicated PbPb detector with some capabilities for pp

ALICE

One dedicated detector for studying B mesons (CP violation; rare decays), produced in the forward (backward) hemisphere

LHCb

Precision (1%) measurement of total cross section (and more) TOTEM

Study of forward $\pi^0$ production LHCf
Experimental Challenge

High Interaction Rate: \( N = L \sigma = 10^{34} \times 100 \times 10^{-27} \)

pp interaction rate \( 10^9 \) interactions/s
data for only \(~100\) out of the 40 million crossings can be recorded per sec (100 – 150 MB/sec)
need fast, pipelined, intelligent electronics and sophisticated data-acquisition

High Energy and Large Particle Multiplicity

\(~ <20\) superposed events in each crossing
\(~ 1000\) tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
large detectors, a large number of channels

High Radiation Levels

radiation hard (tolerant) detectors and electronics
Physics Requirements

Follow from requirements to observe Higgs boson whether it is heavy or light, to observe Supersymmetry if it is there (missing energy), to find other new physics if it is there; all this in the presence of a huge background of standard processes (QCD)

Very good muon identification and momentum measurement trigger efficiently and measure charge of a few TeV muons

High energy resolution electromagnetic calorimetry
~ 0.5% @ $E_T$~50 GeV

Powerful inner tracking systems
factor 10 better momentum resolution than at LEP

Hermetic calorimetry
good missing $E_T$ resolution

(Affordable detector)
Deflection ~ $BL^2/p \Rightarrow$ need high $B$ (s.c.) and large magnets; need high resolution position measurements ($10 - 100\,\mu$) at large $p$; also energy and position measurement through total absorption (photon, electron, hadron)
Selectivity - physics

Cross sections for various physics processes vary over many orders of magnitude

- Inelastic: $10^9$ Hz
- $W \rightarrow l \nu$: $10^2$ Hz
- $t \bar{t}$ production: 10 Hz
- Higgs (100 GeV/c$^2$): 0.1 Hz
- Higgs (600 GeV/c$^2$): $10^{-2}$ Hz

Selection needed: $1:10^{10-11}$

Before branching fractions...
CERN can only provide ~20% of the required computing capacity. Therefore, the LHC relies on many computing centres around the world interconnected using Grid technology. CERN leads two major global Grid projects:

- **WLCG**: World-wide LHC Computing Grid Collaboration
- **EGEE**: Enabling Grid for E-sciencE project for all sciences

The LHC Computing Grid project launched a service with 12 sites in 2003. Today 200 sites in 40 countries with 20,000 PCs. WLCG depends also on OSG and other Grid projects.
Physics Requirements

At the LHC the SM Higgs provides a good benchmark for the performance of a detector.

LEP200: $M_H > 114.4$ GeV
Standard Model Higgs

$\int L \, dt = 10 \, fb^{-1}$

$\int L \, dt = 30 \, fb^{-1}$

ATLAS
(no K-factors)

$\mu_H > 114.4 \, GeV$

$H \rightarrow \gamma \gamma$

$ttH (H \rightarrow bb)$

$H \rightarrow ZZ^\ast \rightarrow 4l$

$H \rightarrow WW^\ast \rightarrow l\nu l\nu$

$qqH \rightarrow qq WW^\ast$

$qqH \rightarrow qq \tau \tau$

Total significance

$\int L \, dt = 30 \, fb^{-1}$

(no K-factors)

ATLAS

$10^2$

$10^3$

$m_H (GeV)$

$10$

$5\sigma$

$m_H > 114.4 \, GeV$

$10$

$1$
1. Is there a Higgs?
2. What is the Higgs mass?
3. Is the Higgs a SM-like weak doublet?
4. Is the Higgs elementary or composite?
5. Is the stability of $M_W$ explained by a symmetry or dynamical principle?
6. Is supersymmetry effective at the weak scale?
7. Will we discover DM at the LHC?
8. Are there extra dimensions? Are there new strong forces?
9. Are there totally unexpected phenomena?
10. What is the mechanism of EW breaking?

**Initial phase of LHC will tell which way nature wants us to go**
Initial phase of LHC will tell which way nature wants us to go

Possible ways beyond initial LHC:

Luminosity upgrade (sLHC)

Doubling the energy (DLHC)
   new machine, R&D on high field magnets ongoing

Electron-Positron Collider
   ILC
   CLIC

Electron-Proton Collider
   LHeC
The European Strategy for particle physics

one possible way: luminosity upgrade

3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.
will partly be used to gradually increase performance of LHC, i.e. towards luminosity upgrade \((L \sim 10^{35})\) sLHC:

- New inner triplet -> towards \(L \sim 2\times10^{34}\)
- New Linac (Linac4) -> towards \(L \sim 5\times10^{34}\)
  
  *construction* can/will start now \(\rightarrow \sim 2012/13\)

- New PS (PS2 with double circumference)
- Superconducting Proton Linac (SPL)
  
  start *design* now, ready for decision \(\sim 2011/12\)
  aimed for \(L \sim 10^{35}\) around 2016/17 if physics requires

- Detector R&D (seed money)

**Important:** international collaboration
What are the conditions at SLHC?

- 300 – 400 pile-up events at start of spill (unless luminosity leveling)
- Want to survive at least 3000 fb⁻¹ dataset
- B-layer at 37 mm:
  - ~30 tracks per event
  - >10¹⁶ 1MeV muons
  - Few 10⁸ neutrons

Detector R&D for sLHC mandatory
Concerted efforts are starting now

Steinar Stapnes  SLHC detectors, 2008
4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.

5. It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.
High Energy Colliders: CLIC \( (E_{cm} \text{ up to } \sim 3\text{TeV}) \)

- High acceleration gradient: \( \sim 100 \text{ MV/m} \)
  - “Compact” collider – total length < 50 km at 3 TeV
  - Normal conducting acceleration structures at high frequency

- Novel Two-Beam Acceleration Scheme
  - Cost effective, reliable, efficient
  - Simple tunnel, no active elements
  - Modular, easy energy upgrade in stages


Drive beam - 95 A, 300 ns from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns from 9 GeV to 1.5 TeV
High Energy Colliders: ILC ($E_{cm}$ up to $\sim 1$TeV)

**ILC @ 500 GeV**


<table>
<thead>
<tr>
<th>Max. Center-of-mass energy</th>
<th>500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Luminosity</td>
<td>$\sim 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam Current</td>
<td>9.0 mA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Average accelerating gradient</td>
<td>31.5 MV/m</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>0.95 ms</td>
</tr>
<tr>
<td>Total Site Length</td>
<td>~30 km</td>
</tr>
<tr>
<td>Total AC Power Consumption</td>
<td>~1.5 MW</td>
</tr>
</tbody>
</table>

2-stage process Technical Design Phase I/II (2010/2012)
Strategy to address LC key issues

Recent progress: much closer collaboration
first meeting: February 08

GDE

CLIC

CLIC collaboration

Two weeks ago:
Meeting of ILC and CLIC Steering Committees
Result:
even closer collaboration towards one project

LC detector R&D project established at CERN

detector/physics issues
LC Detector challenges: calorimeter

ZHH $\rightarrow$ qqbbbb

High precision measurements demand new approach to the reconstruction:

- particle flow (i.e. reconstruction of ALL individual particles)

this requires

- unprecedented granularity
  in three dimensions

R&D needed now for key components

Detector R&D mandatory and well under way

red: track based

green: calorimeter based
Precision Higgs physics

Determination of absolute coupling values with high precision
Dark Matter and SUSY

- Is dark matter linked to the Lightest Supersymmetric Particle?

LC and satellite data (WMAP and Planck): complementary views of dark matter.

LC: identify DM particle, measures its mass;

WMAP/Planck: sensitive to total density of dark matter.

Together with LHC they establish the nature of dark matter.

Neutralinos is not the full story
Recent development: ECFA endorsed a series of workshop for the study of ep collisions in LHC.
Bottom line: Synergy

- Big questions = ambitious questions
- Need to clear the cloud of T-hadron physics to obtain
- Many experiments are conceivable, but not achievable
- No single experiment would achieve it, need a broad program

Great opportunities ahead
Window of opportunity for decision on the way forward 2010-2012 (?)
Accelerating Science and Innovation

World Collaboration
Cooperation works rather well world wide, so…any changes needed for the future?

facilities for HEP (and other sciences) becoming larger and expensive

funding not increasing

fewer facilities realisable

time scales becoming longer

laboratories are changing missions

→ more coordination and more collaboration required
Future major facilities in Europe and elsewhere require collaborations on a global scale; Council, drawing on the European experience in the successful construction and operation of large-scale facilities, will prepare a framework for Europe to engage with the other regions of the world with the goal of optimizing the particle physics output through the best shared use of resources while maintaining European capabilities.
We are **NOW** entering a new exciting era of particle physics

**Turn on of LHC** allows particle physics experiments at the **highest collision energies** ever

Expect
- revolutionary advances in understanding the microcosm
- changes to our view of the early Universe

**CERN**
unique position as host for the LHC
Results from LHC will guide the way

Expect
- period for decision taking on next steps in 2010 to 2012 (at least) concerning energy frontier
  -(similar situation concerning neutrino sector $\Theta_{13}$)

We are NOW in a new exciting era of accelerator planning-design-construction-running and need
- intensified efforts on R&D and technical design work to enable these decisions
- global collaboration and stability on long time scales
  (reminder: first workshop on LHC was 1984)
Particle Physics can and should play its role as spearhead in innovations as in the past now and in future