Past few decades

“Discovery” of Standard Model

through precision measurements at the
- **Intensity frontier** (e.g. neutrino facilities, b-factories, rare decay experiments. . .)
- **Energy frontier** (through the interplay of hadron, lepton and lepton-hadron colliders)
Test of the SM at the Level of Quantum Fluctuations

LEP: indirect determination of the top mass

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

prediction of the range for the Higgs mass

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

- At the intensity frontier, results from neutrino experiments at reactors open new prospects
- At the energy frontier, the LHC brings us into unexplored territory
What’s new

- At the intensity frontier:
  Large mixing angle
  $\theta_{13}$ around 9 °
Daya Bay and RENO:

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Statistical</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Chooz</td>
<td>0.086</td>
<td>0.041</td>
<td>0.030</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>0.092</td>
<td>0.016</td>
<td>0.005</td>
</tr>
<tr>
<td>RENO</td>
<td>0.113</td>
<td>0.013</td>
<td>0.019</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>0.098</strong></td>
<td><strong>0.013</strong></td>
<td></td>
</tr>
</tbody>
</table>

$\sin^22\theta_{13}$
- At the energy frontier:
  New particle at 125/126 GeV consistent with Higgs Boson
- Sum of mass distributions for each event class, weighted by S/B
- B is integral of background model over a constant signal fraction interval
Evolution of the excess with time

ATLAS Preliminary

Local $\rho_0$

$\sqrt{s} = 7\text{ TeV (2011)}, \int Ldt = 4.8\text{ fb}^{-1}$

$\sqrt{s} = 8\text{ TeV (2012)}, \int Ldt = 5.9\text{ fb}^{-1}$

EPS July 2011
- Observed
- Expected

CERN Seminar 12/2011
- Observed
- Expected

Spring 2012
- Observed
- Expected

4 July 2012
- Observed
- Expected

Energy-scale systematics not included
… but that’s only the beginning! What’s next?

Measure the properties of the new particle with high precision
Road beyond the Standard Model

- **At the intensity frontier:**
  “Super” b-factories, rare decay experiments, . . . . , and

Neutrino Facilities

Next decades
Options:

• Conventional super-beams:
  – Wide-band, long baseline: e.g. LBNE, LBNO
    • $<E_\mu> \sim 2\text{—}3$ GeV; matched to LAr or magn.Fe calorimeter;
    • Long-baseline allows observation of first and second maximum
    • Near detector exploited to reduce systematic errors
  – Narrow-band, short baseline: e.g. T2HK, SPL
    • $<E_\mu> \sim 0.5$ GeV; matched to H$_2$O Cherenkov;
    • Short-baseline allows observation of first maximum
    • Near detector exploited to reduce systematic errors

• Beta-beam, short baseline:
  – $<E_\mu> \sim 0.5$ GeV; matched to H$_2$O Cherenkov;
  – Short-baseline allows observation of first maximum
  – Requires short-baseline super-beam to deliver competitive performance
Neutrino Factory:

- **Optimise discovery potential for CP and MH:**
  - **Requirements:**
    - Large $\nu_e$ ($\bar{\nu}_e$) flux
    - Detailed study of sub-leading effects
  - **Unique:**
    - (Large) high-energy $\nu_e$ ($\bar{\nu}_e$) flux
      - Optimise event rate at fixed $L/E$
      - Optimise MH sensitivity
      - Optimise CP sensitivity
Scenario of a staged programme:

- Large value of $\theta_{13}$, makes it likely that the next generation long-baseline experiments will determine the neutrino mass hierarchy;
  - However, sensitivity to CP violation will be limited;
- In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short baseline experiments (e.g. T2HK) may offer an attractive way forward:
  - In such an approach:
    - CP reach is limited by systematic effects;
    - Hints of CP violation would require follow up by the Neutrino Factory.
- The Neutrino Factory seems the facility of choice;
  - Consensus (?):
    - Will be required to:
      - Complete the Standard Neutrino Model and to test whether it is a good description of nature
- But, stored muon beams have not yet been shown to be capable of serving a world-class neutrino programme:
  - Require to push through R&D and complete IDS-NF, considering an incremental implementation in parallel; and
  - Establish a first, realistic, scientifically first-rate neutrino experiment based on a stored muon beam

K.Long
Next decades

Road beyond Standard Model

- At the energy frontier:
  through synergy of
  hadron - hadron colliders
  lepton - hadron colliders
  lepton - lepton colliders

LHC results will guide the way at the energy frontier
The predictable future: LHC Time-line

2009
- Start of LHC
  - Run 1: 7 and 8 TeV centre of mass energy, luminosity ramping up to few $10^{33}$ cm$^{-2}$ s$^{-1}$, few fb$^{-1}$ delivered

2013/14
- LHC shut-down to prepare machine for design energy and nominal luminosity
  - Run 2: Ramp up luminosity to nominal ($10^{34}$ cm$^{-2}$ s$^{-1}$), few fb$^{-1}$

2018
- Injector and LHC Phase-I upgrades
  - Run 3: Ramp up luminosity to nominal (10$^{34}$ cm$^{-2}$ s$^{-1}$), ~50 to 100 fb$^{-1}$ / year accumulate few hundred fb$^{-1}$

~2022
- Phase-II, CRAB cavities, focusing magnets and levelling
  - Run 4: Collect data until >3000 fb$^{-1}$

2030
- Study of the properties of the Higgs Boson or other EW symmetry breaking mechanism and Physics beyond the Standard Model
1) Continuously throughout the years (mainly during shutdowns):

**Performance-Improving Consolidation**

*i.e. replace (aging) components by better performing ones*

2) Depending on Physics Requirements:

**High Luminosity LHC (~2022)**

*i.e. upgrade to deliver a total of some 3/ab*
There is a program at the energy frontier with the LHC for at least 20 years:

- 8 TeV
- 14 TeV design luminosity
- 14 TeV high luminosity (HL-LHC)
beyond LHC?
High Energy Hadron – Hadron Collider
HE - LHC

Study of New Physics Phenomena
HE-LHC – LHC modifications

HE-LHC >2030

SPS+, 1.3 TeV, >2030

2-GeV Booster

Linac4
Very Long-Term Objectives: High-Energy LHC

HE-LHC – main Issues and R&D:

- High-field 20T dipole magnets based on Nb$_3$Sn, Nb$_3$Al, and HTS
- High-gradient quadrupole magnets for arc and IR
- Fast cycling SC magnets for ~1.3 TeV injector
- Emittance control in regime of strong SR damping and IBS
- Cryogenic handling of SR heat load (first analysis; looks manageable)
- Dynamic vacuum

S. Myers, L. Rossi
High Energy-LHC (HE-LHC)

CERN working group since April 2010
EuCARD AccNet workshop HE-LHC’10, 14-16 October 2010, Proc. CERN-2011-003

Key topics
- Beam energy 16.5 TeV; 20-T magnets
- Cryogenics: synchrotron-radiation heat radiation damping & emittance control
- Vacuum system: synchrotron radiation
- New injector: energy > 1 TeV

Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
<td>7</td>
<td>16.5</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>8.33</td>
<td>20</td>
</tr>
<tr>
<td>Dipole coil aperture [mm]</td>
<td>56</td>
<td>40</td>
</tr>
<tr>
<td># bunches</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>1 (x), 0.43 (y)</td>
</tr>
<tr>
<td>Number of IPs</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Beam current [A]</td>
<td>0.584</td>
<td>0.328</td>
</tr>
<tr>
<td>SR power per ring [kW]</td>
<td>3.6</td>
<td>65.7</td>
</tr>
<tr>
<td>Arc SR heat load dW/ds [W/m/ap]</td>
<td>0.21</td>
<td>2.8</td>
</tr>
<tr>
<td>Peak luminosity $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Events per crossing</td>
<td>19</td>
<td>76</td>
</tr>
</tbody>
</table>

E. Todesco

S. Myers                   ECFA- EPS, Grenoble
Lepton – Hadron Collider
LHeC

QCD, Leptoquarks,
Higgs properties?
LHeC options: RR and LR

RR LHeC: new ring in LHC tunnel, with bypasses around experiments

LR LHeC: recirculating linac with energy recovery, or straight linac

e-/-+ injector 10 GeV, 10 min. filling time
**Summary**

**LHeC**, in ep(A) collisions synchronous with pp running, could deliver fundamentally new insights on the structure of the proton (and nucleus) with high precision.

At LHeC, a light Higgs boson and its CP eigenstates could be uniquely accessed via WW and ZZ fusion - complementary to LHC experiments.

Sensitivity to $H \rightarrow bb$ is estimated by an initial simulation study: LHeC has the potential to measure $H \rightarrow bb$ coupling to $\sim 4\%$ accuracy with 60 GeV electron beam. Other production and decay channels have to be explored still using dedicated LHeC detector simulation, instead of the PGS used so far.

With the isolation of the $H \rightarrow bb$ signal at the LHeC, a window of opportunity opens for the exploration of the CP properties of the HVV vertex: LHeC offers a number of advantages

- Clear separation of HWW and HZZ couplings
- Very good signal to background ratio
- Identification of backward forward directions (and full azimuthal coverage)

Detector design is crucial for an efficient $H \rightarrow b\bar{b}$ signal selection and CC/NC multi-jet background rejection. **Prospects have just started to be explored.**
Lepton – Lepton Colliders
Both projects are global endeavours

Wide range of Physics Topics, e.g.

- Higgs couplings, in particular **self coupling**
- precision studies of Z, W, and **Top**
- new physics phenomena
Linear Collider layouts


ILC 0.5 TeV – 30 km
ILC 1 TeV – 50 km

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

CLIC 3 TeV: 48 km
CLIC 0.5 TeV: 13 km

July 23, 2011

S. Myers

ECFA-EPS,

Grenoble
Yearly Progress in Cavity Gradient Yield
as of April 24, 2012

2nd pass yield - established vendors, standard process

- >25 MV/m yield
- >35 MV/m yield

Yield '10 ~ '12:
- ~ 85% @ 25 MV/m
- ~ 80% @ 28 MV/m
- ~ 70% @ 35 MV/m

Yield in '08 ~ '09:
- ~ 70% @ 25 MV/m
- ~ 46% @ 35 MV/m

Global Design Effort
Conclusion of CLIC CDR studies

<table>
<thead>
<tr>
<th>Main linac gradient</th>
<th>Ongoing test close to or on target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncertainty from beam loading</td>
</tr>
<tr>
<td>Drive beam scheme</td>
<td>Generation tested, used to accelerate test beam, deceleration as expected</td>
</tr>
<tr>
<td></td>
<td>Improvements on operation, reliability, losses, more deceleration (more PETS) to come</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Damping ring like an ambitious light source, no show stopper</td>
</tr>
<tr>
<td></td>
<td>Alignment system principle demonstrated</td>
</tr>
<tr>
<td></td>
<td>Stabilisation system developed, benchmarked, better system in pipeline</td>
</tr>
<tr>
<td></td>
<td>Simulations seem on or close to the target</td>
</tr>
<tr>
<td>Operation</td>
<td>Start-up sequence defined</td>
</tr>
<tr>
<td>Machine Protection</td>
<td>Most critical failure studied</td>
</tr>
<tr>
<td></td>
<td>First reliability studies</td>
</tr>
<tr>
<td></td>
<td>Low energy operation developed</td>
</tr>
</tbody>
</table>

Vol 1: The CLIC accelerator and site facilities (H.Schmickler)
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, final editing ongoing, presented in the SPC In March 2012 (Daniel Schulte)

http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/
An Example ILC Construction Schedule

<table>
<thead>
<tr>
<th>11-7 (2.88km)</th>
<th>7-5 (5.54km)</th>
<th>5-3 (5.1km)</th>
<th>3-1 (2.6km)</th>
<th>1-2 (2.6km)</th>
<th>2-4 (4.6km)</th>
<th>4-6 (4.6km)</th>
<th>6-10 (2.88km)</th>
</tr>
</thead>
</table>

1. Installation of Supports
2. Machine component installation and testing
3. Shaft excavation
4. Cavern excavation
5. Tunnel Boring
6. Tunnel finishing
7. Initial geodetic survey
8. Electrical services
9. Piping & Ventilation
10. Cable Installation

Sources & DR’s

COMMISSION and BEGIN PHYSICS RUN

Beam Commissioning
High Priority Items for Linear Collider Projects

ILC and CLIC projects → LC project

Construction Cost

Power Consumption

Value Engineering
Very recently brought up: LEP3 circular Higgs factory \((e^+e^- \rightarrow Z^* \rightarrow Z+H)\)

- **Initial thoughts – very preliminary:**
  - EuCARD: [http://indico.cern.ch/conferenceDisplay.py?confId=193791](http://indico.cern.ch/conferenceDisplay.py?confId=193791)
  - ~15% higher energy than LEP2

- Installation in the LHC tunnel “LEP3”

<table>
<thead>
<tr>
<th></th>
<th>LEP2</th>
<th>LHeC</th>
<th>LEP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>b. energy (E_b) [GeV]</td>
<td>104.5</td>
<td>60</td>
<td>120</td>
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<tr>
<td>circumf. [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>4</td>
<td>100</td>
<td>7.2</td>
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<tr>
<td>#bunches/beam</td>
<td>4</td>
<td>2808</td>
<td>4</td>
</tr>
<tr>
<td>#e- /beam [10^{12}]</td>
<td>2.3</td>
<td>56</td>
<td>4.0</td>
</tr>
<tr>
<td>horiz. emit. [nm]</td>
<td>48</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>vert. emit. [nm]</td>
<td>0.25</td>
<td>2.5</td>
<td>0.10</td>
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<tr>
<td>bending rad. [km]</td>
<td>3.1</td>
<td>2.6</td>
<td>2.6</td>
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<tr>
<td>part. number (J_c)</td>
<td>1.1</td>
<td>1.5</td>
<td>1.5</td>
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<tr>
<td>mom. c. (a) [10^{-5}]</td>
<td>18.5</td>
<td>8.1</td>
<td>8.1</td>
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<tr>
<td>SR p./beam [MW]</td>
<td>11</td>
<td>44</td>
<td>50</td>
</tr>
<tr>
<td>(\beta_S) [m]</td>
<td>1.5</td>
<td>0.18</td>
<td>0.2</td>
</tr>
<tr>
<td>(\beta_S') [cm]</td>
<td>5</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>(\sigma_S) [\mu m]</td>
<td>270</td>
<td>30</td>
<td>71</td>
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<tr>
<td>(\sigma_S') [\mu m]</td>
<td>3.5</td>
<td>16</td>
<td>0.32</td>
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<tr>
<td>hourglass (F_{bg})</td>
<td>0.98</td>
<td>0.99</td>
<td>0.67</td>
</tr>
<tr>
<td>(E_{RF\text{, loss}}) [GeV]</td>
<td>3.41</td>
<td>0.44</td>
<td>6.99</td>
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<tr>
<td>(V_{RF\text{, tot}}) [GV]</td>
<td>3.64</td>
<td>0.5</td>
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<tr>
<td>(\delta_{\text{max, RF}}) [%]</td>
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<td>0.66</td>
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<tr>
<td>(\xi_S/\text{IP})</td>
<td>0.025</td>
<td>N/A</td>
<td>0.09</td>
</tr>
<tr>
<td>(\xi_S'/\text{IP})</td>
<td>N/A</td>
<td>0.08</td>
<td>0.08</td>
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<tr>
<td>(f_S) [kHz]</td>
<td>1.6</td>
<td>0.65</td>
<td>3.91</td>
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<tr>
<td>(E_{acc}) [MV/m]</td>
<td>7.5</td>
<td>11.9</td>
<td>20</td>
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<tr>
<td>eff. RF length [m]</td>
<td>485</td>
<td>42</td>
<td>606</td>
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<tr>
<td>(f_{\text{RF}}) [MHz]</td>
<td>352</td>
<td>721</td>
<td>1300</td>
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<tr>
<td>(\delta_{\text{SR}}) [%]</td>
<td>0.22</td>
<td>0.12</td>
<td>0.23</td>
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<tr>
<td>(\sigma_{\text{SR}}) [cm]</td>
<td>1.61</td>
<td>0.69</td>
<td>0.23</td>
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<tr>
<td>(L/IP) [10^{32} cm^{-2}s^{-1}]</td>
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<tr>
<td>number of IPs</td>
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<td>2</td>
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<tr>
<td>beam lifetime [min]</td>
<td>360</td>
<td>N/A</td>
<td>16</td>
</tr>
</tbody>
</table>

Alain Blondel, Frank Zimmermann et al.
Lepton Colliders: Muon Collider

• Compact facility accelerating muons with recirculating linacs

Major Challenges
1. Muon generation
2. Cooling of muons
3. Cost-efficient acceleration
4. Collider ring and backgrounds from decays

- Higgs Boson properties
and beyond ???
High Gradient Acceleration

• High gradient acceleration requires high peak power and structures that can sustain high fields
  – Beams and lasers can be generated with high peak power
  – Dielectrics and plasmas can withstand high fields

• Many paths towards high gradient acceleration
  – RF source driven superconducting structures $\approx 40\ \text{MV/m}$
  – RF source driven metallic structures $\approx 16\ \text{MV/m}$
  – Beam-driven metallic structures $\approx 1\ \text{GV/m}$
  – Laser-driven dielectric structures $\approx 10\ \text{GV/m}$
  – Beam-driven plasmas

R&D on new technologies mandatory
Example Roadmap for Multi-TeV Lepton Colliders

The LC roadmap illustrates options and connections between them. Selecting a path requires additional information such as LHC results and technology status.

Normal / super conducting

Direct laser-driven acceleration

Normal conducting - Two-Beam-based

Multi-TeV LC

350 GeV LC

Beam-Plasma

Laser-Plasma

Multi-TeV LC

500 GeV LC

Neutrino source (Project-X)

Neutrino ring

Muon collider (few TeV)

From: T. Raubenheimer, EPS 2011
Key message

All projects need continuing accelerator and detector R&D;

All projects need continuing attention concerning a convincing physics case; close collaboration exp-theo mandatory

so that the right decision can be made when the time comes to identify the next energy frontier accelerator (collider).

Today, we need to keep our choices open.
• Rich *variety of projects* under study at the *energy frontier* and the *intensity frontier*

• Global – Regional – National Projects

→ Need global collaboration and stability over long time scales

→ mandatory to have accelerator laboratories in all regions
→ Need to present and discuss all these projects in an international context before making choices
→ Need to present physics case(s) always taking into account latest results at existing facilities

→ Need to present (additional) benefits to society from the very beginning of the project
→ Need to have excellent communication and outreach accompanying all projects
The laws of physics, though, are eternal and universal. Elucidating them is one of the triumphs of mankind. And this week has seen just such a triumphant elucidation.

For non-physicists, the importance of finding the Higgs belongs to the realm of understanding rather than utility. It adds to the sum of human knowledge—

That is still a relatively small amount, though, to pay for knowing how things really work, and no form of science reaches deeper into reality than particle physics. As J.B.S. Haldane, a polymathic British scientist, once put it, the universe may be not only queerer than we suppose, but queerer than we can suppose. Yet given the chance, particle physicists will give it a run for its money.
Roadmap (Japan) just published
Roadmap discussion (US) next year
Update of the European Strategy for Particle Physics in 2012/13 ≡ Strategy of Europe in a global context
- Several Meetings with international participation
  → bottom-up process: community input requested
    1st open meeting September 2012, Cracow
- Finalization: May/June 2013

Started with the ICFA Seminar 3-6 October 2011 at CERN
Use as 1st step to harmonize globally Particle Physics Strategy
CERN today….into the future

- CLIC conceptual design report by 2012
- Participation in all LC activities
- LHeC conceptual design report early 2012
- R&D for high-field magnets (towards HE-LHC)
- Generic R&D (high-power SPL, Plasma Acc)
- Participation in Neutrino-Projects studied
CERN: opening the door...

- Membership for Non-European countries
- New Associate Membership defined
- CERN participation in global projects independent of location
Excellent results at this landmark conference ICHEP2012

It’s the right time for the next steps
Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe
Past decades saw precision studies of 5% of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95% of the Universe

exciting prospects