The physics programme of the LHC

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The Standard Model of fundamental interactions: MATTER

ALL ORDINARY MATTER BELONGS TO THIS GROUP.

THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.

NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.

LEPTONS

- electron
  - Electric charge $-1$.
  - Responsible for electricity and chemical reactions.
- electron neutrino
  - Electric charge $0$.
  - Rarely interacts with other matter.
- muon
  - A heavier relative of the electron.
- muon neutrino
  - Created with muons when some particles decay.
- tau
  - Heavier still.
- tau neutrino
  - Not yet observed directly.

QUARKS

- up
  - Electric charge $+\frac{2}{3}$.
  - Protons have 2 up quarks.
- down
  - Electric charge $-\frac{1}{3}$.
  - Neutrons have 1 up quark.
- charm
  - A heavier relative of the up.
- strange
  - A heavier relative of the down.
- top
  - Heavier still, recently observed.
- bottom
  - Heavier still.

ANTIMATTER

Each particle also has an antimatter counterpart ... sort of a mirror image.
<table>
<thead>
<tr>
<th>FORCE</th>
<th>COUPLES TO:</th>
<th>FORCE CARRIER:</th>
</tr>
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<tbody>
<tr>
<td>Electromagnetism</td>
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<td>photon (m=0)</td>
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.... plus a scalar boson, to break electroweak symmetry and give particles their mass

| mass | Higgs \((m=??)\) |
The forthcoming steps
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  - Higgs boson and EW symmetry breaking (EWSB)
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Think of the Higgs field as being a continuum embedding the whole Universe. Particles interacting with it will undergo a similar “slow-down” phenomenon. Rather than “slowing down”, however, the interaction with the Higgs medium gives them “inertia” => mass
The number “$v$” is a universal property of the Higgs field background. The quantity “$\lambda$” is characteristic of the particle moving in the Higgs field. Particles which have large $\lambda$ will have large mass, with $m \propto \lambda v$

Now the question of “why does a given particle have mass $m$” is replaced by the question “why does a given particle couple with the Higgs field with strength $\lambda \propto m / v$”

However at least now we have a mathematical model to understand how particles acquire a mass.
Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles, the so-called Higgs bosons
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What is required is that the energy available be sufficient ⇒ LHC !!!
The LHC was designed to answer one question:
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is electroweak symmetry broken as postulated in the Higgs mechanism of the SM?

- SM production and decay rates well known
- Detector performance for SM decays well understood
- $115 < m_H < 200$ from LEP and EW fits in the SM (LEP/SLC/Tevatron)
Summary of SM Higgs discovery potential

Within 2-3 yrs of effective running we should have an answer
IF Higgs seen with SM production/decay rates, but outside SM mass range:

• new physics to explain EW fits, or
• problems with LEP/SLD data

In either case,

• easy prey with low luminosity up to ~ 800 GeV, but more lum is needed to understand why it does not fit in the SM mass range!

IF NOT SEEN UP TO $m_H \sim 0.8$-1 TeV GeV:

$$\sigma < \sigma_{SM}: \Rightarrow \text{new physics}$$

or

$$\text{BR}(H \rightarrow \text{visible}) < \text{BR}_{SM}: \Rightarrow \text{new physics}$$

or

$m_H > 800$ GeV: expect $WW/ZZ$ resonances at $\sqrt{s} \sim$ TeV $\Rightarrow \text{new physics}$
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Since $m[\text{top}] = 170 \text{ GeV}$, $\lambda[\text{top}] = 1$: **coincidence**?
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The precise identification of the cause of electroweak symmetry breaking phenomenon, of its dynamics and of the origin of the flavour structure, are therefore crucial goals for the progress of our understanding of Nature
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- Solve open experimental issues of particle physics:
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- Address open theoretical questions:
  - a long list of “why?”
• what is **Dark Matter**?
• what is the origin of the matter-antimatter asymmetry of the Universe?
• what is the origin of neutrino masses?
• ..... 
• why SU(3)xSU(2)xU(1)? are there new forces? GUT?
• why 3 generations, why their properties?
  • mass spectra
  • mixing patterns
• pointlike? substructures? strings?
• ..... 
• why D=3+1?
• what is **Dark Energy**?
Furthermore:

• Detailed studies of high-density and high-temperature QCD matter, using Pb-Pb collisions at $\sqrt{S}=5.5\ \text{TeV/nucleon}$ (2.75 TeV in the 2010-2011 runs)

• nuclear matter in a deconfined phase, eqn of state of quark-gluon matter

• production/propagation/evolution of “high-$Q^2$” probes

• Measurement of total, elastic and diffractive proton-proton cross sections

• Measurement of forward particle production (of relevance for the modeling of cosmic ray showers in the atmosphere)

• Search for magnetic monopoles
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  - new evolution of Einstein’s picture of *space-time* symmetry  
  - predicts a partner for each known particle  
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- **New dimensions of space-time**: modifications of Newton’s law, new picture of Big Bang in its early evolution
For comparison:
- at the SppS collider, the first run (1982) was a few $10^{-3}$ nb$^{-1}$, followed 1 year later by 20 nb$^{-1}$ (W discovery)
- at the Tevatron collider, the first run (1985) was a few $10^{-3}$ nb$^{-1}$, followed 2 years later by 20 nb$^{-1}$

The LHC has surpassed this after few months of operations, and is still on an exponential ramp!
Plans for the 2010-11 data taking

- Run at half maximum energy, namely 3.5 TeV/beam
- Increase luminosity up to $10^{32}\text{cm}^{-2}\text{s}^{-1}$ (now: $10^{31}$) by early November
- Switch to Pb-Pb collisions (~4 weeks) in mid-November
- ~2 months technical stop over Xmas
- Restart, run steady at ~$10^{32}\text{cm}^{-2}\text{s}^{-1}$ through 2011, to collect 1 fb$^{-1}$
- 4-week Pb-Pb run at end 2011
First LHC results

- 13 journal publications, by all 4 large experiments
- 100s of analysis notes detailing public results presented to International Conferences
- Much improved determination of general properties of proton-proton collisions at 900 GeV, 2.7 TeV and 7 TeV
- First challenges for MC event generators and modeling of pp collisions at 7 TeV
- Rediscovered the full SM particle content (including W/Z bosons, top quark)
- Crossed over into the territory of sensitivity to new-physics phenomena beyond the reach of any previous experiment
Modeling of inclusive properties of pp collisions

Multiplicity distributions

antiΛ/Ks^0 ratio

Momentum spectra
Probing the quark structure:
limits on the mass of possible excited quarks

\[ m[q^*] > 1.26 \text{ TeV} \]
(best previous limit, from the Tevatron, was 0.87 TeV)
Prospects for 2011 run: Higgs

**ATLAS H→WW→ll**

Combination of 0j and 2j, H to WW to ll

- $m_H = 130$ GeV
- $m_H = 150$ GeV
- $m_H = 160$ GeV
- $m_H = 170$ GeV
- $m_H = 180$ GeV

**CMS H→WW→ll**

CMS Preliminary

Projection for $\sqrt{s} = 7$ TeV, $L = 1$ fb$^{-1}$

- Cut on Neural Network Output
- Cut Based Analysis

ATLAS preliminary estimate
Prospects for 2011 run: Supersymmetry

Jets+$E_T^{\text{miss}}$ Signature
The steps after 2011, in a nutshell

- At least 1 year shut-down in 2012, to prepare the LHC for 14 TeV:
  - consolidate the protection against quenches
  - test the ability of dipoles to sustain the maximum current, and re-train the weak ones
- 2-3 year run from 2013, at 14 TeV and L=few \(10^{33}\) cm\(^{-2}\)s\(^{-1}\), i.e. O(10 fb\(^{-1}\)/yr)
- Shut down to prepare the LHC for L=few \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
< 1973: theoretical foundations of the Standard Model
- renormalizability of SU(2)×U(1) with Higgs mechanism for EWSB
- asymptotic freedom, QCD as gauge theory of strong interactions
- KM description of CP violation

Followed by 30 years of consolidation:
- technical theoretical advances (higher-order calculations, lattice QCD, ...)
- experimental verification, via discovery of
  - Fermions: charm, 3rd family (USA)
  - Bosons: gluon, W and Z (Europe; ... waiting to add the Higgs ...)
- experimental consolidation, via measurement of
  - EW radiative corrections
  - running of $\alpha_s$
  - CKM parameters

It's unlikely it will take less than 30 yrs to clarify and consolidate the understanding of new phenomena to be unveiled by the LHC!
The LHC is ready for this exciting new era in particle physics!