The Large Hadron Collider Project and Superconductivity

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Particle Physics

Particle physics is a modern name for centuries old effort to understand the laws of nature.

E. Witten

Aims to answer the two following questions:

What are the **elementary constituents of matter**?

What are the **forces** that control their behaviour at the most basic level?
proton-proton collisions at the LHC correspond to conditions here (<< 1ns)

Heavy-ion collisions at the LHC correspond to conditions here (<1 us)
Particle Accelerators

accelerate particles to extremely high energies.

High energies allow us

i) To look deeper into Nature \( (E \propto 1/\text{size}) \), ("powerful microscopes")

ii) To discover new particles with high(er) mass \( (E = mc^2) \)

iii) Study the young universe \( (E = kT) \)

Revisit the earlier moments of our ancestral universe ("powerful telescopes"), to observe phenomena and particles normally no longer observable in our everyday experience.

All in a controlled way - “in the laboratory”
To remove a proton from a nucleus need ~10 MeV ~10 million ×

To remove an electron from an atom need ~10 eV 10 ×

All forces in the world can be attributed to these four interactions
The “Standard Model”

Over the last 100 years: combination of Quantum Mechanics and Special Theory of relativity along with all new particles discovered has led to the Standard Model of Particle Physics.

The new (final?) “Periodic Table” of fundamental elements

- Matter is composed of fermions (6 quarks and 6 leptons)
- Three families of fermions of increasing masses, « normal » matter is made of the first family
- Interactions (strong nuclear, electromagnetic, weak) are carried by exchange of bosons (gluons, photons, weak bosons)
- Very successful description of nature, good precision
The “Standard Model”

Over the last 100 years: combination of Quantum Mechanics and Special Theory of relativity along with all new particles discovered has led to the Standard Model of Particle Physics.

The new (final?) “Periodic Table” of fundamental elements

A crowning achievement of 20th Century Science

The SM has been tested thousands of times, to excellent precision. Yet, its most basic mechanism, that of granting mass to particles, the Higgs boson (?), is still missing!

And where is GRAVITY?
Physics at LHC

Why does anything have substance?
Following on from Newton... what is mass?
Hunting the Higgs boson

Are there more particles to find?
Are matter and force particles different?
Supersymmetry: uniting the forces

What is the universe really made of?
An enigma for science - the other 96%
Dark Secrets of the Universe

Do we really only live in 3D?
Messages from the fifth dimension
String theory and extra dimensions

What was the universe like just after the Big Bang?
Quark-gluon soup?
Colliding heavy ions

What and where is antimatter?
Nature's favouritism
Antimatter detectives

What happens if we don't find the Higgs boson or supersymmetry?

No superconductivity - no answers to these questions!
Superconductivity and the BEH Mechanism

Introduce two independent complex scalar fields

Three of the four degrees of freedom in the Higgs field mix with the W and Z bosons, while the one remaining degree of freedom becomes the Higgs boson – a new scalar particle.
Exploring the unknown:
the Large Hadron Collider (LHC)

Experimentally:

1. Make particles interact and study the products and properties of the result of the interaction
2. Measure the energy, direction and type of the products as accurately as possible
3. Reconstruct what happened during the collision
A Collision of Two Protons
This Study Requires……

1. **Accelerators**: powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles.

2. **Detectors**: gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

3. **Computing**: to collect, store, distribute and analyse the vast amount of data produced by these detectors.

4. **Collaborative Science on Worldwide scale**: thousands of scientists, engineers, technicians and support staff to design, build and operate these complex “machines”.
A New Era in Fundamental Science was Launched in March 2010

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 $E_{CM} = 7$-14 TeV

LHC ring:
27 km circumference
“Bangs From a Bottle”
The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light (superconducting r.f. cavities)

And are guided around their circular orbits by powerful superconducting dipole magnets.

The dipole magnets operate at 8.3 Tesla (200’000 x Earth’s magnetic field) & 1.9K (-271° C) in superfluid helium.

Protons travel in a tube which is under a better vacuum, and at a lower temperature, than that found in inter-planetary space.
Liquid helium displays two phenomena which are both pillars in the design of LHC: superconductivity and superfluidity.

1908: Kamerlingh Onnes first liquefied Helium in Leiden (60 ml in 1 hr) and in 1911 he discovered superconductivity.

LHC today: 32000 liters of He liquefied per hour by eight big cryogenic plants - the largest refrigerator in the world.
Properties of Superfluid Helium

2.3K

2.17K
Kicks

Superconducting radio-frequency cavities
Protons “surf” the electromagnetic waves! And are accelerated.
The LHC Dipole Superconducting Magnet

Magnetic Field Needed
\[ p \text{ (TeV)} = 0.3 \, B(T) \, R(\text{km}) \]
For \( p = 7 \text{ TeV} \), \( R = 4.3 \, \text{km} \)
\[ \Rightarrow B = 8.4 \, \text{T} \]

Superconductivity is Needed!
Superconducting dipole magnets are cooled down in a bath of ~120 tons of superfluid helium: a very interesting engineering material.
The Detectors
Physics requirements drive the design: Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task. Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Overall design pf LHC general-purpose detectors was driven the choice of the (superconducting) magnetic field configuration.
Particles that are detected in an HEP Detector

Any new particles will manifest themselves through known particles

Quarks and gluons
collimated bunches of long-lived or stable particles labeled “jets”

Taus
Highly collimated low multiplicity jets

Photons
Electrons
Muons

Quarks
\[ u \quad c \quad t \quad d \quad s \quad b \]

Leptons
\[ e \quad \mu \quad \tau \quad \nu_e \quad \nu_\mu \quad \nu_\tau \]
Particles that are detected in an HEP Detector

Any new particles will manifest themselves as known particles

And Neutrinos!

In hadron colliders the initial momentum of colliding partons is not known. However the momentum transverse to the beam is ZERO.

Any net momentum transverse to the beam indicates “missing transverse energy” (masses << energy)

Significant missing transverse energy is indicative of “non-interacting” particles such as neutrinos or LSP.
Transverse View of the CMS Detector

1st Layer: Silicon Tracker (pixels and microstrips)

2nd Layer: Lead tungstate electromagnetic calorimeter

3rd Layer: Hadron Calorimeter

4th Layer: Muon system

4T Superconducting Solenoid
ATLAS Superconducting TOROID

Design goal: measure 1 TeV muons with 10% resolution

ATLAS: \( \langle B \rangle \sim 0.6T \) over 4.5 m \( \rightarrow s=0.5\text{mm} \) \( \rightarrow \) need \( \sigma_s=50\mu\text{m} \)

- **Ampere’s theorem:**
  \[ 2\pi RB = \mu_0 nl \rightarrow nl=2\times10^7 \text{At} \]

- **With 8 coils, 2x2x30 turns:** \( I=20kA \) (superconducting)

- **Challenges:**
  Design of structure capable of holding the magnetic forces
  High stored energy 1.5GJ,
  Spatial & alignment precision over large surface area
CMS Solenoid

CMS: $B=4\,T$ ($E=2.7$ GJ!)

- $dp_T/p_T \propto (1/BL^2) (\sigma_x/\sqrt{N_{\text{points}}})\, p_T$
- $B=\mu_0 nI$;
- 2168 turns/m $\rightarrow$ $I=20\,kA$
  (Superconducting)
- **Challenges:**
  4-layer winding to carry enough current,
  Design of reinforced superconducting cable
The CMS Superconducting Magnet

CMS Conductor Production
Total 20 + 1 (prototype) conductor units, each of 2550 m length
Completion of CMS Solenoid
The Construction of the LHC Detectors
(primarily CMS)
Cables, Pipes and Optical Fibres!

Nov 2007

Took 50’000 man hours
CMS Detector Closed
Experimental and Technological Challenge

1 billion proton-proton interactions per second

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

**Large Particle Fluxes**

~ thousands of particles stream into the detector every 25 ns
⇒ large number of channels (~ 100 M ch)
⇒ ~ 1 MB/25ns i.e. 40 TB generated per second!

**High Radiation Levels**

⇒ radiation hard (tolerant) detectors and electronics

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Extreme requirements in several domains

“If it doesn’t exist and we need it, we will invent it”

Limited budgets!

Look at what exists, innovate and automate to drive costs down
Pathway of an Innovation

Dirac’s Equation
a most beautiful equation of physics

\[ i \frac{\partial \psi}{\partial t} = (-i \alpha \cdot \nabla + \beta m) \psi \]

1928: description of electrons consistent with Einstein’s special theory of relativity and quantum mechanics

- Predicted existence of anti-particles (e.g. positron - basis of Positron Emission Tomography (PET))
- and explained spin (- basis of Magnetic Resonance Imaging (MRI))

1932: Operation of first cyclotron, the anti-electron (positron) discovered

Radionuclides used in PET scanning are produced by cyclotrons in hospitals – glucose labeled with positron emitters e.g. Fluorine 18. PET cameras today use APDs (and Si PMs) and heavy scintillating crystals and starting to be combined with MRI scanner (s.c. magnets).

The scientific basis for all medical imaging (functional & physiological) are steeped in nuclear/particle physics
Selection of Interesting Events

A collision is considered interesting if it contains high $p_T$ objects
(electrons, muons, jets, $E_T^{\text{miss}}$, ...)

Proton → Proton ←
Collisions
The Worldwide LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations.

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe.
The Grid at Work

Worldwide LHC Computing Grid connects 100,000 processors in 34 countries with ultra-high-speed data transfers

Millions of Gigabytes of data each year.
Going on to the Science
An ATLAS Z and MET Candidate Event

Candidate Event with a $Z \rightarrow \mu\mu$ and missing $E_T$

Run 167776, Event 129360643
Time 2010-10-28 10:41:18 CET
CMS Performance: Tracking and Muons

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{int} = 40$ pb$^{-1}$

Di-muons
CMS - 50 Years of Particle Physics

CMS Preliminary Data $\sqrt{s}=7$ TeV

- $M = 133.82 \pm 0.02$ MeV
- $\sigma = 10.6\%$
- $S/B_{m,0} = 0.81$

CMS Preliminary

- 900 GeV and 2.36 TeV
- PDG $K^0_S$ mass:
  - $497.614 \pm 0.022$ MeV

CMS preliminary 2010 $\sqrt{s} = 7$ TeV

- $\int L \, dt = 2.88$ pb$^{-1}$

CMS 7 TeV MinBias MC

- Yield: $1144.0 \pm 41.1$
- Mean: $1321.72 \pm 0.13$ MeV
- Sigma: $3.33 \pm 0.13$ MeV
- Statistical uncertainties only

CMS Experiment at LHC CERN

Data recorded: Jul 10 - Jul 11

Event selection: 160 events

J/ψ

$|y| < 2.4$

$\sqrt{s} = 7$ TeV

- $L_{int} = 278$ nb$^{-1}$

- $\sigma = 43$ MeV

W

- $|y| < 2.4$

- $E_T > 25$ GeV

Top

- $E_T > 25$ GeV

- $H_T > 80$ GeV

- $m_T > 37$ GeV

- $p_T > 36$ GeV

- $\varphi > 0.9$

- $\eta > -1.2$

- $p_T > 36$ GeV

- $\varphi > 0.8$

- $\eta > -1.2$

- $m_T > 36$ GeV

- $p_T > 36$ GeV

- $\varphi > 0.8$

- $\eta > -1.2$

- $m_T > 36$ GeV

SCC'11 tsv
The Physics Programme

- **Looking for signals of new physics.**
  - Waiting for Higgs: the origin of mass
  - Seeking SUSY: Could dark matter be revealed?
  - Extra dimensions: do we live in more dimensions than 4?
  - Compositeness: is there further sub-structure?
  - Unknown!

- **Of course, all these signals can only be claimed after understanding Standard Model channels (known physics as backgrounds)**
  - **QCD jets**, prompt γ’s, J/ψ, y, …. 
  - b-quark production
  - Drell-Yan, **W+Z production** (plus jets); multi-IVB (WW,WZ,ZZ)
  - Top quark
  - **Very large number of measurements indicate that the LHC experiments are “physics commissioned”**.
Measuring the Production of Quarks & Gluons

CMS Experiment at the LHC, CERN

Candidate Multi Jet Event at 2.36 TeV
Inclusive jet (quarks/gluons) production

The measured jet production rate is in good agreement with theoretical predictions- NLO QCD (within errors)
Detecting Z Bosons!

$Z \rightarrow \mu \mu$

CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

Muon $p_T = 67.3$, 50.6 GeV/c
Inv. mass = 93.2 GeV/c$^2$
W, Z production: Confronting Predictions

Data correspond to an examination of ~ 3 trillion pp collisions

1 Z → ll event per 70 million proton-proton collisions

Theory: NNLO, FEWZ and MSTW08 PDFs
Known physics is measured as predicted.
Searches beyond known physics
(only very few examples out of many...)

Urbis et Orbis
Central Heavy Ion Event

CMS Experiment at the LHC, CERN
Mon 2010–Nov–08 11:22:07 CET
Run 150431 Event 541464
C.O.M. Energy 7Z TeV
• Fragmentation of quarks and gluons into jets is strongly modified as they traverse the quark-gluon medium created in head-on (central) high energy Pb-Pb collisions - labeled “jet quenching”.

• Such effects were observed in at RHIC for single particle spectra and particle correlations.

• At the LHC one can fully reconstruct the jets!
Formation of Quark-Gluon Fluid

“Jet Quenching”: ATLAS

Even more central collision, more asymmetric dijet
Compositeness: do quarks have sub-structure?

An experiment similar to the one carried out by Rutherford exactly 100 years earlier

Search based on ratio of jet pairs (leading dijets)

\[ R_\eta = \frac{\sum \text{Dijets} \ | \eta| < 0.7}{\sum \text{Dijets} \ 0.7 < |\eta| < 1.3} \]

The observed limit is \( \Lambda < 4.0 \text{ TeV} \) at the 95% CL
Probing sizes < \( 5 \times 10^{-18} \text{ cm} \)
Is there a difference between matter and force particles?

The difference between matter particles and force particles is what we label “spin”. How profound is this difference?

Nature may indeed have put the two on the same footing!
Could be the “ultimate symmetry” thus labeled “supersymmetry”
And it is the last remaining symmetry that we do not quite know how and where Nature has used it

Predicts a doubling of all known fundamental particles !!!

Circumstantial evidence points to supersymmetry being relevant at the LHC! AND the lightest particle of this new species may explain “dark matter”
Supersymmetry: a New Zoology of Particles?

Searches require several (high-\(P_T\)) jets + (high) \(\text{MET}\) and charged leptons.
CMS: Search for Supersymmetry - Update

**CMS, 1.14 fb⁻¹, √s = 7 TeV**

- Data
- Standard Model
- QCD multi-jet
- (E, t, W, Z, →νν) + jets
- SUSY LMI

**HT > 350 GeV,**
2 Leading jets

\[ \eta < 2.5 \]

**Other jets** \[ E_T > 50 \text{ GeV} \]
\[ \eta < 3 \]

**ATLAS Searches** - 95% CL Lower Limits (Lepton-Photon 2011)

- **MSUGRA/CMSM**: 0-lep + \( E_T \) + jets
  \[ m = 800 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Simplified model (light \( \tilde{\chi}^0 \))**: 0-lep + \( E_T \) + jets
  \[ m = 1.87 \text{ TeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Simplified model (light \( \tilde{\chi}^0 \))**: 0-lep + \( E_T \) + jets
  \[ m = 916 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Simplified model (light \( \tilde{\chi}^0 \))**: 0-lep + \( E_T \) + jets
  \[ m = 906 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Simplified model (light \( \tilde{\chi}^0 \))**: 0-lep + b-jets + \( E_T \) + jets
  \[ m = 126 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \text{ (for } m(\tilde{b}) < 600 \text{ GeV)} \]
- **Simplified model (light \( \tilde{\chi}^0 \))**: 1-lep + b-jets + \( E_T \) + jets
  \[ m = 546 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \text{ (for } m(\tilde{b}) < 80 \text{ GeV)} \]
- **Pheno-MSSM**: light \( \tilde{\chi}^0 \): 2-lep SS + \( E_T \) + jets
  \[ m = 620 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Pheno-MSSM**: light \( \tilde{\chi}^0 \): 2-lep OS + \( E_T \) + jets
  \[ m = 620 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **GMSB (GGM) + Simpl. model**: \( \tilde{\chi}^0 \) + \( E_T \) + jets
  \[ m = 996 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **GMSB**: stable \( \tilde{\nu} \)
  \[ m = 30 \text{ GeV} \]
  \[ \tilde{\nu} - \tilde{\nu} \text{ mass} \]
- **Stable massive particles**: R-hadrons
  \[ m = 546 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Stable massive particles**: R-hadrons
  \[ m = 620 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **Stable massive particles**: R-hadrons
  \[ m = 620 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]
- **RPV** \( \lambda_{i j k} = 0.01, \lambda_{j i k} = 0.01 \): high-mass \( \tilde{g} \)
  \[ m = 696 \text{ GeV} \]
  \[ \tilde{g} - \tilde{g} \text{ mass} \]

Only a selection of the available results leading to mass limits shown.
Heavy vector bosons could arise from e.g.
- grand unified theories
- models with extra dimensions

**Di-electrons**

**ATLAS:** $W' \rightarrow l \nu$
$M_{W'} > 2.15 \text{ TeV} \ 95\% \ CL$

**CMS:** $ee$ and $\mu \mu$
$M_{Z'} > 1.94 \text{ TeV} \ 95\% \ CL$
**Microscopic Evaporating Black Holes**

**THE signature of low-scale quantum gravity** ($M_D << M_{Pl}$)
BH formation when the two colliding partons have distance smaller than $R_S$, the Schwarzschild radius corresponding to their invariant mass
Large cross section from geometry: $\sigma = \pi R_S^2 \sim \text{TeV}^2$ (up to ~100 pb!)

**Microscopic BHs decay instantaneously via Hawking evaporation**
emitting “democratically” a large number of energetic quarks, gluons, leptons, photons, W/Z, h, etc.

Expect lots of activity in the event, so
Use $S_T = \text{Sum} \ E_T$ of all objects
(including ME$_T$) with $E_T > 50$ GeV

![Candidate event with 10 jets](image)
Search for Microscopic BHs

No excess, so set limits \( M_{BH} > 3.5-4.5 \text{ TeV} \)
Search for the Higgs Boson
Standard Model (like) Higgs: LHC at 7 TeV

Hatched ranges are disfavoured at 95% CL
Outlook 2011-2012

Physics with
> 1 thousand trillion proton-proton interactions

Make more precise SM measurements – confront theory
Search for the Higgs Boson
Search for Supersymmetry
Search for conjectured new physics
Look and be prepared for the unexpected
Conclusions: The LHC Project

• The LHC project (the accelerator and experiments) was conceived & designed to attack fundamental questions in science:
  about the origin, evolution and composition of our universe.
  In particular, what is the origin of mass, what constitutes dark matter,
  do we live in more than 3 space dimensions,
  why is the universe composed of matter, and not antimatter.

• Unprecedented instruments in scale and complexity operating in an unprecedented & hostile environment.
• Driven by the science many technologies pushed to their limits.
• The Project has required a long and painstaking effort on a global scale – a tribute to human ingenuity and collaboration.
• The accelerator and the experiments are unparalleled scientific instrument(s) - powerful “microscopes” as well as powerful “telescopes”.
Outlook

After twenty years of design, construction the 2nd half of the journey of extraction of physics has started in earnest. A new era in modern physics has been launched. The accelerator and the experiments are now operating very well.

The LHC experiments have become physics producing engines! They have observed all particles of the standard model (save for neutrinos directly) and are already exploring new territory.

It is just the beginning - but tremendous encouragement for the future. A long and interesting journey lies ahead.

All expectations are that what we find at the LHC will reform our understanding of nature at the most fundamental level.

Only experiments reveal/confirm Nature’s inner secrets.