What are we?
Where do we come from?
Where are we going?

The aim of particle physics:
What is matter in the Universe made of?
Evolution of the Universe

Big Bang

What happened then?

What is the universe made of?

What will happen in the future?

Today

10^{28} \text{ cm}
Gaugin’s Questions in the Language of Particle Physics

- What is matter made of?
  - Why do things weigh?
- What is the origin of matter?
- What is the dark matter that fills the Universe?
- How does the Universe evolve?
- Why is the Universe so big and old?
- What is the future of the Universe?

Our job is to ask - and answer - these questions.

Need physics beyond what we know.
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology
Electricity and Magnetism

- Electricity:
  - Named using the Greek word for amber
  - Fish, lightning, …
  - Static electricity and electric currents

- Magnetism:
  - Named for the region of Greece where lodestones were found
  - Used for navigation from 12th century

Who could have foreseen their importance for technology?
James Clerk Maxwell

- Professor at King’s 1860 – 1865
- The first colour photograph
- Unified theory of electricity and magnetism
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- …

“One scientific epoch ended and another began with James Clerk Maxwell” - Albert Einstein
Electromagnetic Waves

- Discovered by Hertz in 1887

- A lot to answer for . . .

- Nobody knows where fundamental physics may lead
The First Elementary Particle

- Discovered by J.J. Thomson in 1897

- The electron – the basis of the electronic industry

- An accelerator in your home: old-style TV sets used beams of electrons
Photon: the Electromagnetic Quantum

• Quantum hypothesis introduced by Planck:
  \[ E = hf \]

• 1905: Physical reality postulated by Einstein to explain photoelectric effect

• First force particle discovered
From Cosmic Rays to Accelerators

Discovered a century ago …

… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail
The Discovery of the Positron

- Predicted by Dirac in 1928
- Discovered in cosmic rays by Anderson in 1932
- Bent opposite to electron, small mass
- Now used in Positron Emission Tomography (PET) for medical diagnosis
The Discovery of the Muon

• NOT predicted
• Observed in cosmic rays by Kunze in 1932
• Larger bending radius than the positron
• Ionizes less than proton
• Passing though us all the time
• “Who ordered that” – I.I. Rabi

"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle with a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1
1950s: a Zoo of ‘Particles’

With new accelerators and detectors, the "particle zoo" grew to more than $\sim 200$ 'elementary particles'.

**Mesons**
- $\pi^+ - \pi^- - \pi^0$: Pions
- $\eta'$
- $\eta$: Eta
- $\phi$: Phi
- $\rho^+ - \rho^- - \rho^0$: Rho

**Baryons**
- $\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$: Delta
- $\Lambda^0$: Lambda (strange!)
- $\Sigma^+, \Sigma^0, \Sigma^-$: Sigma (strange!)
- $\Xi^0, \Xi^-$: Sigma (very strange!)
1960s: Order out of Chaos: Quarks

1) 3 types of “quarks”: up, down, strange
2) Carry electric charges: +2/3, -1/3, -1/3
3) Appear in combinations:
   Meson = quark + antiquark
   Baryon = quark(1) + quark(2) + quark(3)

Also suggested independently by Zweig, Peterman @ CERN

Quarks held together by gluons?
The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

Perfect agreement between theory and experiments in all laboratories
Towards the Standard Model

- Gauge theories are renormalizable
- Kobayashi and Maskawa show how to include CP violation in the Standard Model
- Neutral currents in Gargamelle
- J/Ψ discovered
- Tau lepton and charmed particles discovered
Gluon Radiation in $e^+e^-$ Annihilation

- Discovery method suggested by JE, Mary Gaillard, Graham Ross:
  - Jets of hadrons produced by gluons DESY (Hamburg) in 1978
  - Second force particle discovered
Radioactivity due to charged-current weak interactions (β decay)

W boson - carrier of weak interactions

Predicted to weigh ~ 80 GeV

Discovered at CERN in 1983 by Carlo Rubbia et al
Particles: the Story so far
The ‘Standard Model’

The matter particles

Gravitation  electromagnetism  weak nuclear force  strong nuclear force

Where does mass come from?

= Cosmic DNA

The fundamental interactions
Why do Things Weigh?

Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson? (the physicists’ Holy Grail)
Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

Hiker sinks deep,
moves very slowly:
Particle with large mass

The LHC discovered
the snowflake:
The Higgs Boson
The Higgs Boson & Beyond

How the Higgs boson was found
What does the Higgs boson tell us?
What else may lie above and beyond it?
1975

A Phenomenological Profile of the Higgs Boson

• First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE Higgs BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPoulos **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
The Large Hadron Collider at CERN

To answer Gauguin’s questions:
The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:
• Origin of mass
• Nature of Dark Matter
• Primordial Plasma
• Matter vs Antimatter
2012: The discovery of the Higgs Boson

Mass Higgsteria
A Simulated Higgs Event @ LHC
Interesting Events
July 4th 2012

The discovery of a new particle
Higgsdependence Day!
The Particle Higgsaw Puzzle

Is LHC finding the missing piece?
Is it the right shape?
Is it the right size?
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = \( v \)?

\[
\lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon}, \quad g_V = 2 \left( \frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}} \right)
\]

- Blue dashed line = Standard Model

**Global fit**

\[ \text{ATLAS and CMS LHC Run 1} \]

\[ \text{ATLAS+CMS} \]

- \([M, \epsilon]\) fit
- 68\% CL
- 95\% CL
Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]


Without Higgs …

… there would be no atoms
  – massless electrons would escape at the speed of light

… there would be no heavy nuclei

… weak interactions would not be weak
  – Life would be impossible: everything would be radioactive

Its existence is a big deal!
• «Empty» space is unstable
• Dark matter
• Origin of matter
• Sizes of masses
• Properties of neutrinos
• Cosmological inflation
• Quantum gravity
• …
The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- Further strong evidence for dark matter
Rotation Curves

- **In the Solar System**
  - The velocities decrease with distance from Sun
  - Mass lumped at centre

- **In galaxies**
  - The velocities do not decrease with distance
  - Dark matter spread out
Biggest Collider in the Universe?

Collision between 2 clusters of galaxies:
Gas interacts, heats and stops
Dark matter passes through

Clowe et al, 2006
What is the Dark Matter in the Universe?

Astronomers say that most of the matter in the Universe is invisible. Dark Matter is made of unknown particles? We are searching for them at the LHC.
Minimal Supersymmetric Extension of the Standard Model
Classic LHC Dark Matter Signature

Missing transverse energy carried away by dark matter particles
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either

More of same?
Unexplored nooks?
Novel signatures?
Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory
General Interest in Antimatter Physics

Physicists cannot make enough for Star Trek or Dan Brown!
How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
  - same mass
  - opposite internal properties:
    1. electric charge
  - Discovered in cosmic rays
  - Studied using accelerators
  - Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers
Unify the Fundamental Interactions: Einstein’s Dream …

… but he never succeeded

Unification via extra dimensions of space?
Will LHC experiments create black holes?

Eat up the entire Earth?

Would vanish instantly

Cosmic rays have not harmed us!
Lovers of physics
Beyond the SM: be patient!
Summary

Visible matter

Dark Matter & Dark Energy

Standard Model