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

What happened then?

What is the universe made of?

What will happen in the future?

Big Bang

13.8 Billion Years

10^{28} \text{ cm}

Today
Gaugin’s Questions in the Language of Particle Physics

• What is matter made of?
  – Why do things weigh?

• What is the origin of matter? (LHC)
• What is the dark matter that fills the Universe? (LHC)
• How does the Universe evolve? (LHC)
• Why is the Universe so big and old? (LHC)
• What is the future of the Universe? (LHC)

Our job is to ask - and answer - these questions

Need physics beyond the Standard Model
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology.
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 ‘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
The ‘Standard Model’

The matter particles

Gravitation  electromagnetism  weak nuclear force  strong nuclear force

Where does mass come from?

The fundamental interactions

= Cosmic DNA
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

The LHC discovered the snowflake:
The Higgs Boson

Hiker sinks deep,
moves very slowly:
Particle with large mass
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?
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 $H$, we consider the range of masses in which it should be observable. We describe a number of strategies, such as direct search and indirect observation through its influence on other processes.

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.
To answer Gauguin’s questions:

The Large Hadron Collider at CERN
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

To answer these questions:

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter
ALICE: Primordial cosmic plasma
ATLAS: Higgs and dark matter
CMS: Higgs and dark matter
LHCb: Matter-antimatter difference
Scientists from around the World

MEMBER STATES

- Austria: 117
- Belgium: 120
- Bulgaria: 96
- Czech Republic: 244
- Denmark: 67
- Finland: 111
- France: 868
- Germany: 1342
- Greece: 237
- Hungary: 76
- Israel: 65
- Italy: 2045
- Netherlands: 168
- Norway: 67
- Poland: 350
- Portugal: 127
- Romania: 134
- Slovakia: 124
- Spain: 447
- Sweden: 85
- Switzerland: 228
- United Kingdom: 771

TOTAL MEMBER STATES: 7889

ASSOCIATE MEMBERS

- India: 357
- Lithuania: 35
- Pakistan: 65
- Turkey: 173
- Ukraine: 115

TOTAL ASSOCIATE MEMBERS: 745

OBSERVERS

- Japan: 314
- Russia: 1187
- USA: 1217

TOTAL OBSERVERS: 2718

OTHERS

- Bolivia: 4
- Bosnia & Herzegovina: 2
- Brazil: 135
- Bulgaria: 1
- Cameroon: 1
- Canada: 161
- Chile: 20
- China: 510
- Colombia: 45
- Croatia: 41
- Cuba: 12
- Ecuador: 6
- Egypt: 31
- El Salvador: 2
- Estonia: 15
- Georgia: 46
- Ghana: 1
- Hong Kong: 1
- Iceland: 3
- Indonesia: 11
- Iran: 51
- Iraq: 1
- Ireland: 16
- Kazakhstan: 5
- Kenya: 3
- Korea Rep.: 185
- Kyrgyzstan: 1
- Latvia: 1
- Lebanon: 23
- Luxembourg: 2
- Madagascar: 4
- Malaysia: 15
- Malta: 9
- Mauritius: 1
- Mexico: 82
- Mongolia: 2
- Montenegro: 11
- Morocco: 20
- Myanmar: 1
- Nepal: 10
- New Zealand: 5
- Nigeria: 3
- North Korea: 1
- Oman: 3
- Palestine (O.T.): 9
- Paraguay: 2
- Peru: 7
- Philippines: 3
- Saint Kitts and Nevis: 1
- Saudi Arabia: 2
- Senegal: 1
- Singapore: 4
- South Africa: 56
- Sri Lanka: 6
- Sudan: 1
- Swaziland: 1
- Syria: 1
- Taiwan: 51
- Thailand: 22
- T.F.Y.R.O.M.: 2
- Tunisia: 5
- Uruguay: 1
- Uzbekistan: 4
- Venezuela: 10
- Viet Nam: 13
- Zambia: 1
- Zimbabwe: 2

TOTAL OTHERS: 1872
2012: The discovery of the Higgs Boson

Mass Higgsteria
A Simulated Higgs Event @ LHC
Interesting Events
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
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
• …
Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark

<table>
<thead>
<tr>
<th>Mass of top 173 quark</th>
<th>168</th>
<th>178</th>
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<tbody>
<tr>
<td>World average</td>
<td>0</td>
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<td>Unstable</td>
<td></td>
<td></td>
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<tr>
<td>Need new Physics?</td>
<td></td>
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<tr>
<td>Stable</td>
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</tr>
</tbody>
</table>

Mass of Higgs boson

- 120
- 125
- 130
Should it have Collapsed already?

Fluctuate over barrier in the early Universe?

Quantum fluctuations

We are here

Tunnel through barrier now?

Not if infinite barrier: Supersymmetry?

The Big Crunch
What lies beyond the Standard Model?

Supersymmetry

• Stabilize electroweak vacuum

• Successful prediction for Higgs mass
  – Should be < 130 GeV in simple models

• Successful predictions for couplings
  – Should be within few % of SM values

• Naturalness, GUTs, string, …, dark matter

New motivations From LHC Run 1
Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates
  \[ 0 \quad \frac{1}{2} \quad 1 \quad \frac{3}{2} \quad 2 \]
  
  Higgs - Electron - Photon - Gravitino - Graviton
  (Every particle is a ‘ballet dancer’)
  (pirouette at different speeds)
- Would help fix particle masses
- Would help unify forces
- Predicted light Higgs boson
- Could provide dark matter for the astrophysicists and cosmologists
Minimal Supersymmetric Extension of the Standard Model
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
What is the Dark Matter in the Universe?

Astronomers say that most of the matter in the Universe is invisible

Dark Matter

Made of unknown particles?

We are searching for them at the LHC
Searches for Dark Matter

Dark Matter

Annihilation in the early Universe

Annihilation to particles in cosmic rays

New Physics

Standard Model

Production at particle colliders

Direct dark matter detection
Classic Dark Matter Signature

Missing transverse energy carried away by dark matter particles
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:
  - 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?
Would vanish instantly

Eat up the entire Earth?

Will LHC experiments create black holes?

Cosmic rays have not harmed us!
The LHC is the world’s most powerful microscope …

… and also a telescope addressing Gauguin’s questions