### The Higgs Boson and the New Era in Particle Physics

What does the Higgs boson tell us about what may lie above and beyond it?



John Ellis



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



The aim of particle physics, CERN & the LHC: What is the Universe made of?

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#### From Cosmic Rays to Accelerators

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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' = Cosmic DNA The matter particles e - neutrino down electon up μ - neutrin strange charm uon top τ - neutrino bottom au Where does The fundamental interactions mass come from?

Gravitation

electromagnetism

weak nuclear force

strong nuclear force

### Gauguin'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 ULHC Run 2

LHC Run 2

LHC Run 2

- How does the Universe evolve?
- Why is the Universe so big and old? LHC Run 2
- What is the future of the Universe?

Our job is to ask - and answer - these questions

## 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



The LHC looked for the snowflake: The Higgs Boson 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-

### 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.

### A Simulated Higgs Event @ LHC



300,000 years

3 minutes

1 microsecond

1 picosecond



Formation of atoms Formation of nuclei Formation of protons & neutrons Appearance of mass?

#### 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 A billion collisions a second

Primary targets:
Origin of mass
Nature of Dark Matter
Primordial Plasma
Matter vs Antimatter

Collisions at 8 TeV in Run 1 13/14 TeV in LHC Run 2: 3 times earlier in the history of the Universe

#### The Emptiest Space in the Solar System

Vacuum similar to interplanetary space: the pressure in the beam-pipes is ten times lower than on the Moon.

### Cooler than Outer Space



LHC 1.9 degrees above absolute zero = - 271 C Outer space 2.7 degrees above zero = - 270 C



CMS: Higgs and dark matter **Matter** LHCb: Matter-antimatter difference

Some 3000 scientists and engineers A thousand PhD students 38 countries More components than a moon rocket

#### Assembling ATLAS

### The Discovery of the Higgs Boson

### Mass Higgsteria

# Interesting Events



# Higgsdependence Day!



### Unofficial Combination of Higgs Data







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### 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



### Standard Model Particles: Years from Proposal to Discovery



Source: The Economist

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!

# Dixit Swedish Academy

Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1] http://www.nobelprize.org/nobel\_prizes/physics/laureates/2013/ advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879



- « Empty » space is u LHC Run 2
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity

LHC Run 2 LHC Run 2

LHC Run 2

LHC Run 2

SUSY

THE STANDARD MODEL IS NOT ETTOIL





#### Dark Matter in the Universe

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

#### Supersymmetric particles?

We are looking for them with the LHC

#### What lies beyond the Standard Model?

# Supersymmetry

Stabilize electroweak vacuum

New motivations From LHC Run 1

- Successful prediction for Higgs mass
   Should be < 130 GeV in simple models</li>
- Successful predictions for couplings

   Should be within few % of SM values
- Naturalness, GUTs, string, ..., dark matter

### Classic Dark Matter Signature



Missing transverse energy carried away by dark matter particles

### 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

### How to Create the Matter in the Universe? Sakharov

Need a difference between matter and antimatter observed in the laboratory Need interactions able to create matter predicted by theories not yet seen by experiment Need the expansion of the Universe a role for the Higgs boson?

Will we be able to calculate using laboratory data?



#### Unify the Fundamental Interactions: Einstein's Dream ...

#### - ... but he never succeeded

#### Unification via extra dimensions of space?









Run Number: 265532, Event Number: 3280065

Date: 2015-05-20 22:51:50 CEST



#### First low-energy collisions of Run 2



CMS Experiment at LHC, CERN Data recorded: Wed May 20 22:51:10 2015 CEST Run/Event: 245155 / 123300843 Lumi section: 363 Orbit/Crossing: 94976371 / 208

#### First high-energy collisions of Run 2





#### Next Steps at the High-Energy Frontier?

![](_page_43_Figure_1.jpeg)

![](_page_44_Picture_0.jpeg)

# Future Circular Colliders

![](_page_44_Picture_2.jpeg)

#### Conversation with Mrs Thatcher: 1982

Think of things for the experiments to look for, and hope they find something different

#### What do you do?

Wouldn't it be better if they found what you predicted?

Then we would not know how to answer Gauguin's questions