How electron got its mass

(Nobel prize for Physics 2013)

Amol Dighe
Department of Theoretical Physics
Tata Institute of Fundamental Research

Public Lecture, Nehru Centre
Worli, Mumbai, Nov 23, 2013

Nobel Prize in Physics, 2013

François Englert
Brussels,
Belgium

Peter Higgs
Edinburgh,
UK

Citation

"... for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles,

and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

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Outline

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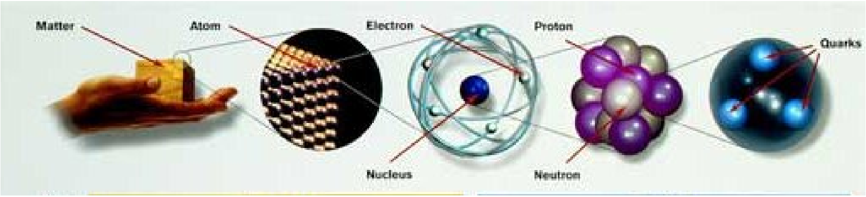
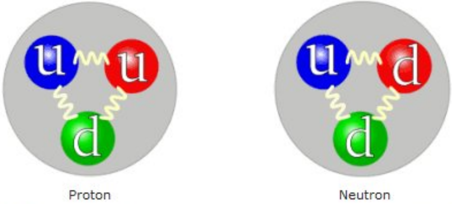
Zooming on the elementary particles



- Atom $\rightarrow$ electrons
- Atom $\rightarrow$ nucleus $\rightarrow$ proton/neutron $\rightarrow$ quarks



Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

Describing forces between particles

- Why do electrons go around the nucleus ?
  Electromagnetic force
- What keeps quarks bound inside the nucleus ?
  Strong nuclear force
- What causes radioactive beta decay of the nucleus ?
  Weak nuclear force

Standard Model of Particle Physics

- Study of Elementary particles and Fundamental forces
- Fundamental forces arise from the exchange of elementary "force" particles (called "Gauge bosons")

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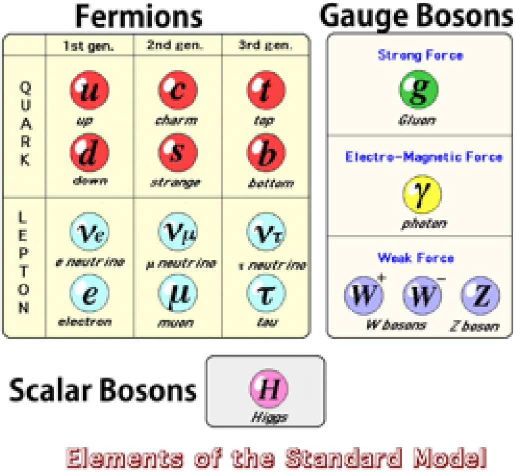
The Standard Model of Particle Physics



- We observe all these particles !

Fermions and bosons

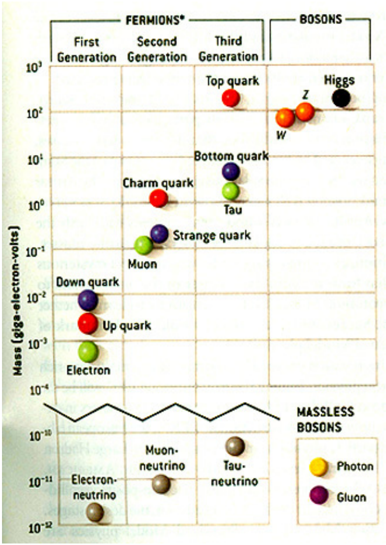
Enrico Fermi

Fermions:
Spin 1/2, 3/2, ...
Similar particles cannot stay together
Quarks, leptons
(e.g. electrons)

Satyendra Nath Bose

Bosons:
Spin 0, 1, 2, ...
Similar particles like to stay together
Force carriers, Higgs
(e.g. photons)

Masses of the particles



- All fermions have masses
- Photon and gluons massless
- $W^{\pm}$ and Z have large masses ($\sim 100\times$ proton mass)

Outline

What is the big deal with mass ?

Maybe the origin of mass is over-rated

- Why cannot the particles just have masses to begin with ?
- Why can “mass” not be an intrinsic property of a particle ? (After all, we accept “charge” as an intrinsic property !)

This is not a philosophical question, but a scientific one.

What is the big deal with mass ?

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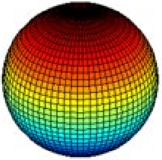
Symmetry: a way to understand world around us

- Symmetry: change in description that does not change the object / process





- Symmetries allow us to describe things in a compact form

Symmetries also tell us about physical laws:

Symmetry		Conservation law
Space translation	$\Rightarrow$	Linear momentum
Time translation	$\Rightarrow$	Energy
Rotation	$\Rightarrow$	Angular momentum

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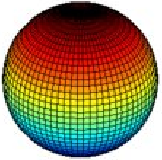

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The symmetry of electromagnetism

Gauge symmetry $U(1)_Q$:

- Electron wavefunction Ψ may be changed by a phase:

$$\Psi(x) \rightarrow e^{i\ Q\ \Theta(x)}\Psi(x)$$

without changing laws of physics

$$\Downarrow$$

- Coulomb's law, Lorentz force law, Maxwell's equations (Essentially, all electrodynamics)

Gauge symmetry: foundation of the Standard Model

- Gauge symmetry: changes in the descriptions of particles that do not change the final observations
- Very powerful principle: when you identify the Gauge symmetry, you can describe the behaviour of all particles and forces
- In 1962, the Gauge symmetry of the Standard Model was not identified, but given the success of gauge symmetries in describing electromagnetism and weak interactions (except the mass problem) in many many experiments, there had to be some Gauge symmetry !

Gauge symmetry is extremely important: like the conservation of energy and momentum. Cannot throw it away !

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So what's the problem ?

Implications of Gauge symmetry

- Fundamental particles (fermions) need to be massless
- Force carriers (Gauge bosons) need to be massless
  $\Rightarrow$ Weak interactions need to be long range

Observations

- Fundamental particles (quarks, leptons) have masses
- Photon and gluon massless, but $W^{\pm}$, Z have large masses
  (Weak interactions short-range, confined to the nucleus)

A consistency problem !

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Outline

The status of the Standard Model around 1962

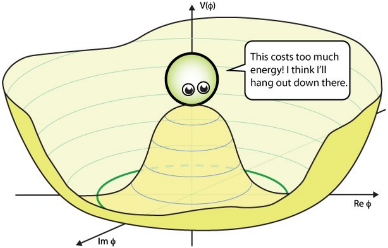
What was known

- Many particles that decayed via weak interactions
- Electron, muon and their neutrinos
- Weak interactions are short range
- Unification of electromagnetic and weak interactions

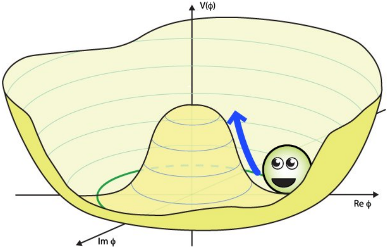
What was not known

- Quark model or family structure
- How do particles get mass, without disturbing the Gauge symmetry ?

Spontaneous symmetry breaking (SSB)



Symmetry ⇓ breaking



Yoichiro Nambu
Nobel 2008

- The symmetry may be obeyed by the interactions, but not by the vacuum itself
- This allows a way out of "gauge symmetry vs. mass" conundrum
- However the problem is not solved yet !

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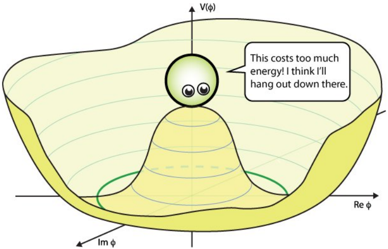

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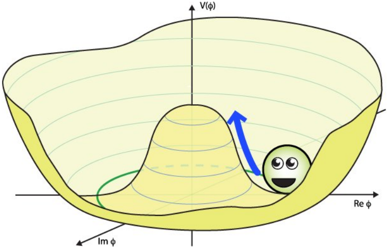

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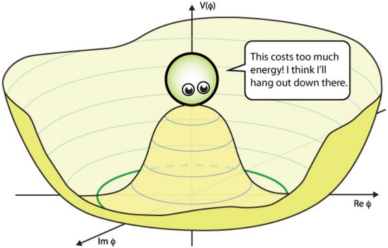
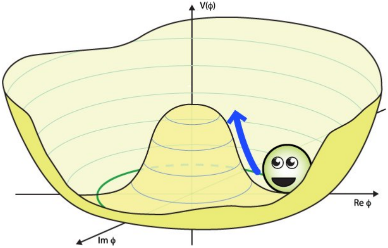


Symmetry $\Downarrow$ breaking



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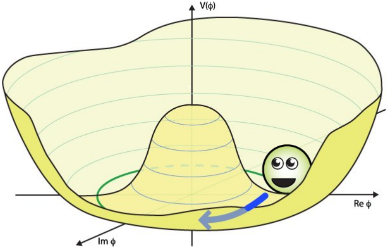
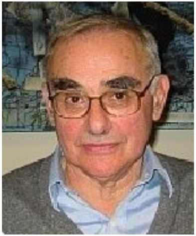
The Goldstone problem

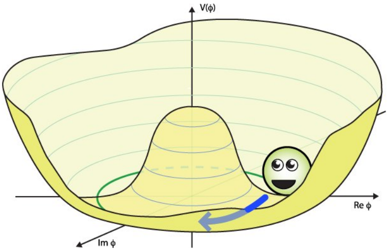


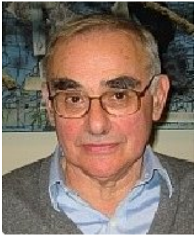


Jeffrey Goldstone

- Spontaneous symmetry breaking produces a massless particle ("Goldstone boson")
- If there is SSB, where is this particle ?
- The problem is also applicable to superconductivity. (Inside a superconductor, photon acts like a particle with a mass.)

The Goldstone problem





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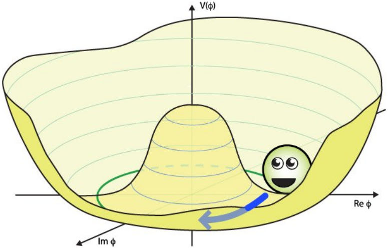

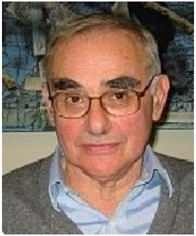

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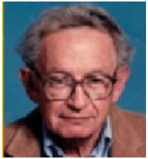
The Anderson solution for superconductivity (1962)



Philip Anderson

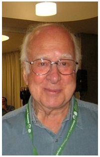
PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

- The massless photon and the massless Goldstone boson can combine to give the photon an effective mass
- That's why magnetic field is "short-range" in a superconductor (Meissner effect)

The particle physics mechanism (1964)



Higgs Kibble Guralnik Hagen Englert Brout

- Brout and Englert: Gauge bosons get mass because they combine with the Goldstone bosons from the SSB.
- Higgs: After the massless Goldstone bosons are gone, the remaining part acts like a boson with a mass.
- Guralnik, Hagen and Kibble: Goldstone theorem is inapplicable for Gauge bosons with SSB.

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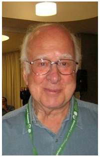

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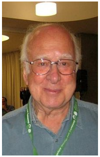


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The three 1964 papers

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

“Higgs mechanism” in one page

- There is Higgs field everywhere in the universe
- All Standard Model interactions obey a Gauge symmetry (Now known to be “$SU(3)_C \times SU(2)_L \times U(1)_Y$”). This means that all particles and Gauge bosons are massless.
- The vacuum of the universe breaks the Gauge symmetry spontaneously (SSB). Then Higgs field has a nonzero value even in vacuum.
- The original massless Gauge bosons “eat up” the Goldstone bosons from SSB, and get mass.
- All particles that interact with the Higgs field (like an electron) also get a mass, depending on how strongly they interact
- Particles that do not interact with the Higgs field remain massless
- There is a Higgs boson with a nonzero mass.

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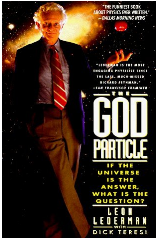
Higgs field, Higgs boson, and Particle masses

Outline

The Goddamn particle

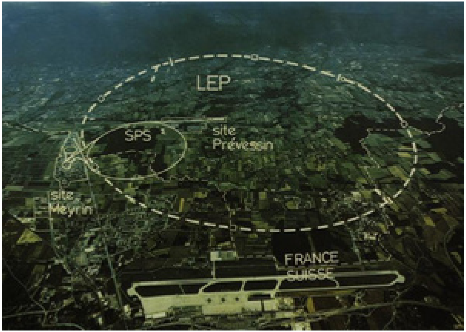
- Proposed in 1964, not found for $\sim$ 50 years
- Leon Lederman wrote “The Goddamn Particle” in 1992:

  “.. the publisher wouldn’t let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing.”

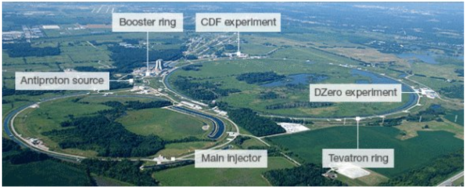


- The publisher changed the title to
- The book sold a lot of copies

Some major Higgs-searchers before the LHC



Large Electron Positron Collider (LEP), CERN, 1985–2000



Tevatron, Fermilab (proton-antiproton collider), 1983–2011

LHC accelerator and detectors

Some numbers

- Accelerator: 27 km circumference
- Proton-proton collision Energy: 8000 GeV
- Collisions per second: 20 Millions
- Total Number of Collisions: 10^{15} (a thousand trillion)

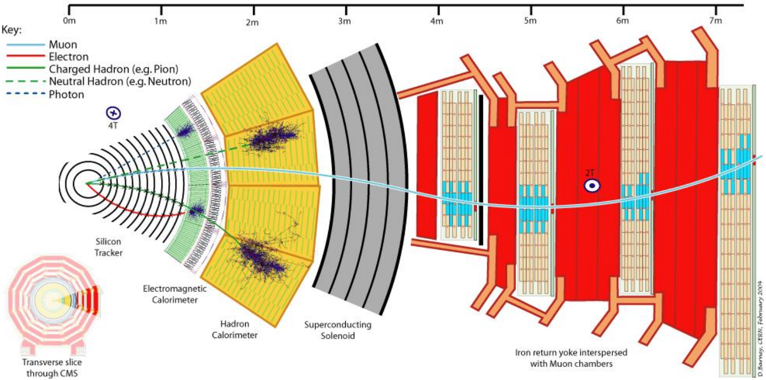
The CERN tunnel

The CMS collaboration (where India participates)

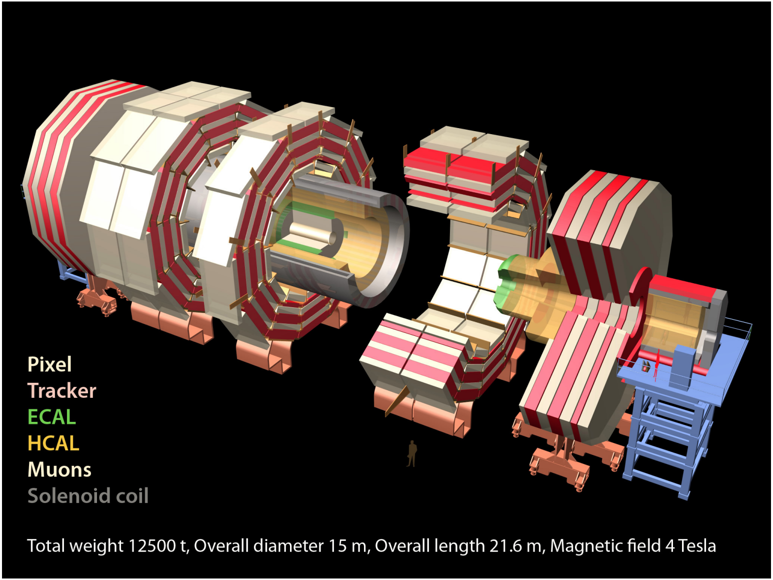
Some numbers

- 3600 physicists, engineers, students
- 183 institutes, 38 countries
- Detector weight: 12500 tons
- Diameter: 15 m, length: 22 m

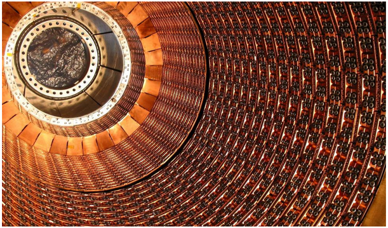
Detection of particles: CMS

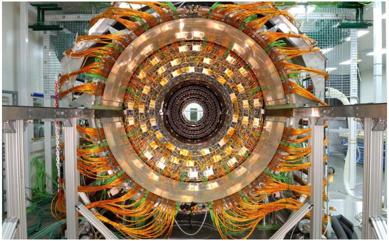


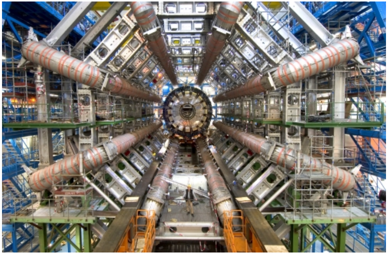
Assembly of the detector: CMS

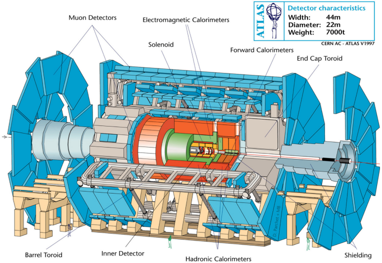


Inside the detector: ATLAS

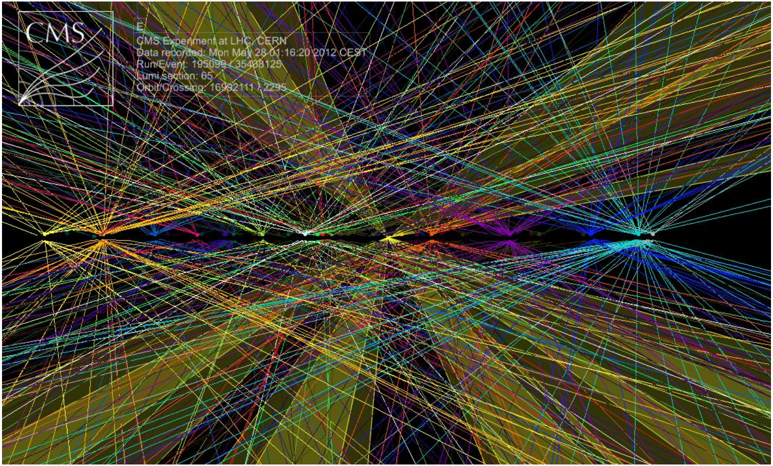






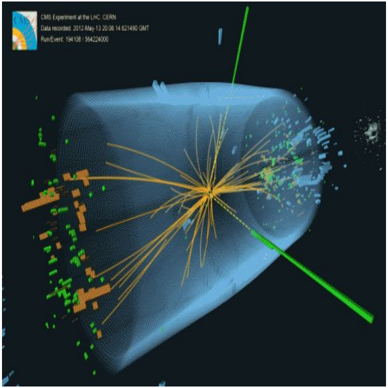


A typical proton-proton collision event

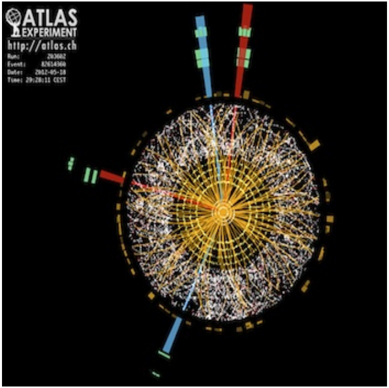


Detecting Higgs through its decays

$H \to \gamma\gamma$



$H \to ZZ^* \to \ell\ell\ell\ell$



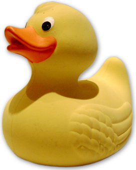
- Number of Higgs events: a few lakh
- Number of background events: 1000 trillions

July 4th, 2012

“I think we have it” – CERN Director General

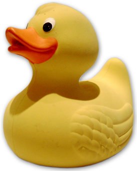
Do we really have it ?

- Looks and walks, but does it quack ?



- Is this the Higgs of the Standard Model ?
  (Properties: spin zero, interactions with other particles)
- Can it be a part of a new theory beyond the Standard Model, like Supersymmetry or Extra dimensions ?
- Only more experiments will give the answer.
  LHC may discover new particles from these new theories, or we may need new specialized experiments.

Do we really have it ?



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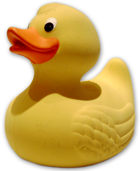
- Only more experiments will give the answer.
  LHC may discover new particles from these new theories, or we may need new specialized experiments.

Do we really have it ?

- Looks and walks, but does it quack ?



- Is this the Higgs of the Standard Model ?
  (Properties: spin zero, interactions with other particles)
- Can it be a part of a new theory beyond the Standard Model, like Supersymmetry or Extra dimensions ?
- Only more experiments will give the answer.
  LHC may discover new particles from these new theories, or we may need new specialized experiments.

Particle physics is far from being understood....

- Masses of neutrinos
- Matter-antimatter asymmetry
- Dark matter and dark energy: make 96% of the universe
- Grand Unification of all forces (including gravity)

A triumph of theory and experiment

- Theory: We can understand the world in mathematical terms, can make predictions That can be verified. Our interpretations of laws of nature are On the right track.
- Experiment: We can develop technology and tools to actually look for subtle effects and obtain physical evidence to test our understanding of the world.

Citation

"... for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles,

and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Another reason to celebrate the Nobel Prize

Triumph of the collaborative spirit of science: Thousands of people from more than 45 countries, many of whom would never meet each other in their lives, worked for more than 20 years towards a common goal and succeeded.

CERN did not get the Nobel Prize, but here is to all those thousands who made the discovery of Higgs boson possible.