The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "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"
The Higgs Particle

- The Nobel prize for the Higgs mechanism
  - theoretical idea \(\sim 50\) years ago

- This idea became the reality with the Higgs particle
  - experimental discovery
How many Bosons did we know in 2012?

- We knew 12 bosons: photon, $Z^0$, $W^+$, $W^-$, 8 gluons

- Photons (γ) are massless vector (spin=$\hbar=1$) bosons

- $Z^0$ and $W^\pm$ are heavy $\rightarrow$ weak force

- Gauge bosons in unified electro-weak theory after spontaneous symmetry breaking

$$|\gamma\rangle = \cos \theta_W |B^0\rangle + \sin \theta_W |W^0\rangle \quad \text{light (massless)}$$

$$|Z^0\rangle = \sin \theta_W |B^0\rangle + \cos \theta_W |W^0\rangle \quad \text{heavy}$$

$\theta_W$ - Weak mixing (Weinberg) angle
• Early moments of the Universe
  - massless particles: $B^0$ and $W^0$, $W^+$, $W^-$, ...
  - all forces unify

• As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak ($Z^0$, $W^\pm$ mass)
  - Higgs field – possible mechanism
The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field \((\phi_1, \phi_2, \phi_3, \phi_4)\)

\[
V = \frac{1}{4} \lambda \left[ \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 \right]^2 + \frac{1}{2} \mu^2 \left[ \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 \right]
\]

- Higgs particle described by one component of the Higgs field

\[
h = \phi_1 - v
\]

- The other Higgs field components \(\phi_2, \phi_3, \phi_4\) couple to Weak bosons \(Z^0, W^-, W^+\) and generate mass, longitudinal polarization (not \(\gamma\))
Idea - the Higgs Field

- Empty space filled with invisible "force" – the Higgs field
Idea - the Higgs Field

- The Higgs field clusters around the particle – gives mass
Idea - the Higgs Field

- Pass energy into the **Higgs field** (no particle)
Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field
What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (boson)

- People sometimes confuse these phenomena
  - especially the last two

- We have hard evidence for two:
  - 1964 article by Peter Higgs in *Physics Review Letters*
  - 2012 discovery of a new *Boson* by CMS and ATLAS
More on the History of the Higgs Mechanism

• In fact, there are several names of the Higgs mechanism:
  – Brout-Englert-Higgs mechanism
  – Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  – Anderson-Higgs mechanism
  – Higgs mechanism is just simpler
  – all for authors of independent papers on the topic

• Partly due to ironic history with the paper by Higgs:
  – rejected from European Physics Letters
    “of no obvious relevance to physics”
  – added a reference to predicting a new particle
More on the History of the Higgs Mechanism

1950: Ginzburg- Landau model of superconductivity
1959-60: Nambu- Goldstone bosons in spontaneous symmetry breaking
1962: P. Anderson - nonrelativistic example
1964: R. Brout & F. Englert; P. Higgs; G. Guralnik & C. R. Hagen & T. Kibble
1967: Incorporated into Standard Model by S. Weinberg and A. Salam
All Elementary Particles get Mass from Higgs Field

- **Fermions** $S = \frac{\hbar}{2}$ (matter)
  - Leptons
    - $e^-$, $\nu_e$
    - $\mu^-$, $\nu_\mu$
    - $\tau^-$, $\nu_\tau$
  - Quarks
    - $u$, $d$
    - $c$, $s$
    - $t$, $b$

- **Bosons** $S = \hbar$ (force carries):
  - EM (massless)
  - Strong (weak force bosons mass)
  - CP (antisymmetry)
Mass of Matter

- Most of our mass is **protons and neutrons**

  - most mass is **energy** of quark-gluon soup: \( m_p c^2 = E \)

Mass from quark-gluon soup energy:
\[ m_p c^2 = 938 \text{ MeV} \approx 1.7 \times 10^{-27} \text{ kg} \]

Mass from the Higgs field:
\[ m_u c^2 \sim 3 \text{ MeV}, \quad m_d c^2 \sim 5 \text{ MeV} \]

but **Higgs field** is very important
Stability of the Vacuum

- Higgs self-coupling $\lambda < 0$ at higher scale
  - may tunnel thru ”potential barrier” ⇒ unstable Universe
  - tunneling time > Universe lifetime ⇒ metastable Universe
  - for $m_H \sim 126 \text{ GeV}/c^2$ and SM Higgs field ⇒ metastable

arXiv:1205.6497
The Large Hadron Collider

one of the coldest places (1.9 K, 96T He)
one of the hottest places (10^{16} °C)
vacuum emptier than outer space (10^{-10} Torr)
the fastest racetrack \(v_p = 0.999999991c\)
the largest electronic instrument (27 km)
Study of the $H^0$ boson

Produce

Detect

Andrei Gritsan, JHU 28 July 2017
Study of the $H^0$ boson

Produce

Detect

Andrei Gritsan, JHU 28 July 2017
Produce

\[ \psi_i \psi_j \phi + h.c. \]

\[ \psi_i \gamma_i \psi_j \phi + h.c. \]

\[ -V(\phi) \]

\[ \psi_i \psi_j \phi + h.c. \]

Detect

\[ |D_\mu \phi|^2 \]

\[ |D_\mu \phi|^2 \]

\[ |D_\mu \phi|^2 \]

Study of the $H^0$ boson

Andrei Gritsan, JHU

28 July 2017
LHC schedule: 10 year plan

- LHC $E_{pp}=13$ TeV, Phase-1 thru 2023/24

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- **Run-2**
  - ~80 fb$^{-1}$
  - ~120 fb$^{-1}$

- **Run-3** thru 2023/24
  - ~300 fb$^{-1}$

- Phase-2 with **Run-4** plan to start in 2026,
  Snowmass: ~3000 fb$^{-1}$

- Legacy: **Run-1** (2010-2012)
  - ~25 fb$^{-1}$ at 7 and 8 TeV

---

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28 July 2017
Particles $\rightarrow$ Resonances $\rightarrow$ “Bumps”

- We often see particles as “resonances”
  - most particles are not stable
  - reconstruct from their decay products
Higgs boson yield

$H(125)^0 \rightarrow 4\ell$

$Z \rightarrow 4\ell$

$ZZ \rightarrow 4\ell$

Events / 3 GeV

~80 events in Run-1 + Run-2
~20 events in Run-1 (2011+12)

$H(125)$

$\bar{q}q / gg \rightarrow ZZ, Z\gamma^*$

Z+X

$5.1 \text{ fb}^{-1} (7 \text{ TeV}) + 19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 38.6 \text{ fb}^{-1} (13 \text{ TeV})$

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Run-2 of LHC

ratios of LHC parton luminosities: 13 TeV / 8 TeV

gain x2.2

luminosity ratio

M_X (GeV)

2016

Projection 2016

2017

2011

2012

2015

13 TeV

8 TeV

7 TeV

2016

2017

2011

2012

2015

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24

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New Pixel Detector in CMS Now (“Phase-1”)

- first stable beams on May 23, 2017

66 million channels in 1440 modules → 124 million channels in 1856 modules
The Silicon Pixel Detector

1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \, \mu\text{m}$

Alignment: hardware and software
Study of the Higgs field $\varphi$

$\cdots$ 

$\psi_i \gamma_{ij} \psi_j \varphi + h.c.$

$-V(\varphi)$

$\varphi_1, \varphi_2, \ldots$

more Higgs bosons

$H(125)^0 \rightarrow VV$

$-|D_\mu \varphi|^2$

$H(125)^0 \rightarrow ff$

$\psi_i \gamma_{ij} \psi_j \varphi + h.c.$

$H(125)^0 \rightarrow H^0 H^0$

$V(\varphi)$
Study HVV or $|D_\mu \varphi|^2$

$H(125)^0 \to VV$

$|D_\mu \varphi|^2$

CMS (Run 2): $m_H = 125.26 \pm 0.20^{\text{(stat)}} \pm 0.08^{\text{(syst)}}$ GeV

Follow PDG check-list

- mass
- lifetime
- width
- quantum numbers
- coupling strength

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28 July 2017
Study $H_{ff}$ or $\psi_i \psi_j \phi$ + h.c.

$H(125)^0 \rightarrow ff$

All Elementary Particles get Mass from Higgs Field

- Fermions $S = \frac{h}{2}$ (matter) (anti-matter)
- Bosons $S = h$ (force carries)

Discovery of $H(125)^0 \rightarrow \tau\tau$
Study $H^0 \rightarrow ff$

$\psi_i\psi_j\phi + h.c.$

Strong evidence for $t\bar{t}H(125)^0$

<table>
<thead>
<tr>
<th>LHC Run1</th>
<th>$\mu = 2.3^{+0.7}_{-0.6}$, 4.4$\sigma$</th>
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<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>ATLAS, CMS 12.9 fb$^{-1}$</td>
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<tr>
<td>$t\bar{t}$</td>
<td>ATLAS, CMS 35.9 fb$^{-1}$ 3.3$\sigma$</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>ATLAS, CMS 35.9 fb$^{-1}$ 3.3$\sigma$</td>
</tr>
<tr>
<td>$4\ell$ CMS $\mu(t\bar{t}H)$</td>
<td>35.9 fb$^{-1}$ 1.4$\sigma$</td>
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Study HHH or $V(\varphi)$

$H(125)^0 \rightarrow H^0 H^0$

$V(\varphi)$

only limits so far need HL-LHC (3000 fb$^{-1}$) to find SM $H^0 H^0$ production

$HH \rightarrow (bb)^+ (bb/WW/ZZ/\tau\tau/\gamma\gamma)$

NOTE: ATLAS $bbbb$ limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses
Search for more Higgs bosons: $\phi_1, \phi_2 \ldots$

more involved Higgs field $\phi_1 \ldots \phi_2 \ldots$

more Higgs bosons, $H(125)^0, H, A, H^+, H^-$

nothing found yet

Events / 5 GeV

$\sigma(pp \to X \to ZZ) \ [pb]$
Study of the Higgs field $\varphi$

$\ldots$ $+|D_\mu \varphi|^2$
$+\psi_i y_{ij} \psi_j \varphi + h.c.$
$-V(\varphi)$
$\ldots \varphi_1 \ldots \varphi_2 \ldots$

- $H(125)^0 \rightarrow VV$
- $|D_\mu \varphi|^2$
- $H(125)^0 \rightarrow ff$
- $\psi_i y_{ij} \psi_j \varphi + h.c.$
- $H(125)^0 \rightarrow H^0 H^0$
- $V(\varphi)$

more Higgs bosons $H(125)^0, H, A, H^+, H^-$
Study of the Higgs field $\varphi$

- $H(125)^0$ is a completely new state of matter-energy

- the major LHC discovery so far

- yet it is just an extinct particle

- what remains in the Higgs field

- it is all around us

- gives mass to fermions, bosons

- its potential remains to be tested, implication for our existence