The Higgs boson – its discovery and what we have learnt since

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CCE Lecture Quarks to the Cosmos

14th November, 2019





Back in July 2012 there was lot's of media interest

The Sydney Morning Herald

Another year of pain for Blues



New twist in DJs sag

Uggs get the boo

Wandering boy died in mar

pool – is this manslaug



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In that other big hit-up,

science finds Higgs boson



In that other big hit-up, science finds Higgs boson

Deborah Smith

IT EXISTS. In a discovery that throws light on the very fabric of space and time, a new subatomic particle has been found that is very likely the long-sought Higgs boson.

Making one of the most anticipated and exciting announcements in modern science last night, two teams of researchers using the world's biggest atom smasher, the Large Hadron Collider near Geneva, Switzerland, announced they had observed the new particle in collisions in the giant instrument. "We have reached a milestone in our understanding of nature," the directorgeneral of CERN, Rolf Heuer, said. "This is the physics version of the discovery of DNA," Sir Peter Knight, president of

the Institute of Physics said.²⁵ President of More studies, however, will be needed to pin down the exact nature of the boson, which is the most massive ever seen, scientists said. "This is indeed a new particle," Joe Incandela, spokesman for one of the discovery sigteams, said. "The implications are very sig-

nificant and it is precisely for this reason that we must be extremely diligent in all our studies and cross-checks." The Higgs boson is the last undiscovered

particle predicted to exist by the Standard Model of matter, and scientists have been hunting it for almost 50 years. It is thought to give all other particles their mass, and some have dubbed it the God parHOW IT IS DONE

 Deams of protons are accelerated at almost the speed of light around the 27-kilometre ring of the Large Hadron Collider.
 Two detectors, ATLAS and CMS, analyse millions of collisions per second.
 New boson is created in some of the collisions.

Excess decay into two photons detected. New boson has mass about 130 times that of a proton. Could be the Higgs boson or something even more exotic. Image: CER

ticle because of its importance, to the annoyance of scientists.

Researchers will now look to see if the new particle has the same properties as the Higgs boson predicted by the standard model, or whether it is an even more exotic particle. If this is the case, it would be a revolutionary find, possibly leading to the discovery of

more new particles and new dimensions in space, Professor Incandela said.

"It could be a gateway to the next phase of exploring the deepest parts of the fabric of the universe, which is pretty profound."

Researchers using the CMS and ATLAS detectors announced the results of their searches at a joint scientific seminar in Geneva and Melbourne, where the International Conference on High Energy Physics is being held.

The two teams had been blinded to each other's data, to avoid influencing their independent analyses. They each found a particle consistent with a Higgs boson with a mass of 125-126 gigaelectronvolts – about 130 times the mass of a proton.

"This is a milestone for human understanding of the fundamental laws that govern the universe," Geoff Taylor, of the University of Melbourne, said.

Peter Higgs, of the University of Edinburgh, who predicted the existence of the Higgs boson in 1964, congratulated the scientists on their achievement. "I am astounded at the amazing speed

"1 am astounded at the amazing speed with which these results have emerged. I never expected this to happen in my lifetime," Professor Higgs said.

Anthony Thomas, of the University of Adelaide, said it was a very exciting discovery. "There's more work yet to be done to prove that this is the Hirgs boson, but it certainly

looks like it," Professor Thomas said. Australians helped design and build parts of the ATLAS detector and analyse the results.

SMH 5th July 2012

ATLAS and CMS experiments

Seems such a long time ago ...

2

ICHEP Conference Melbourne July 4, 2012



Live webcast from CERN



CERN press conference

CERN Auditorium



Image: Associated Press

3

ICHEP conference Melbourne



Image: Laura Vanags



Image:http://particleadventure.org

Empedocles C 450 BC



Image:Science Photo Libray



Democritus c. 400 BC





http://www.aip.org/

Mendeleev 1834-1907



http://www.nndb.com/ 6



http://www.super-science-fair-projects.com/



http://www.nobelprize.org/

Rutherford 1871-1937

The very large to the very small



One definition of Particle (High Energy) Physics ...

Particle physics studies the fundamental constituents of matter and their interactions

... down to very very small dimensions (of order 0.0000000000000000001 metres or less)



Maxwell took a step along the path of unifying the forces of nature



We can probe matter with high energies

Because of this equivalence of mass and energy, (E=mc²) we can use high energies to create new, massive particles



High energy or momentum corresponds to high resolution allowing us to probe short distances

Wavelength
$$\lambda = \frac{h}{p}$$
 Planck's constant
Momentum

How to make new particles fruit analogy

This is a better analogy than colliding e.g. clocks and studying the clock bits that fly out



Image: http://particleadventure.org

A century of research since Rutherford arrived at a set of basic building blocks for matter, the particles of the Standard Model



We only need three of these fundamental particles (plus forces) to build everything we see around us



Image: Adapted from Fermilab Visual Media Services

There are a number of unanswered questions about the Standard Model

Why are there at least three "families" of quarks and leptons?

Why do the particles have the masses they do? (or mass at all?)



Image: Fermilab Visual Media Services

What is the origin of mass? Why do the particles have the masses that they do?



Image: https://scienceblogs.com/

What is the origin of mass? Why do particles have mass at all?

Unification of the electromagnetic and weak forces (late 1960s) - needed the Higgs field (1964)

Particles which would otherwise be mass-less, interacting with the Higgs field, get a mass

There is a particle associated with the Higgs field, called the Higgs boson





The Higgs Field



A particle in the Higgs Field



A disturbance



A Higgs Boson

One thing that we didn't know was the Higgs mass

It was expected to be in the range of approximately 100 -1000 times the proton mass

(based on things we did know and had measured already)



Image:http://particlezoo.net/individual_pages/shop_higgsboson.html

A very sophisticated machine was needed to search for the Higgs



Some machine!

		-
LHC Machine Parameters		
Beam energy	E	7.0 TeV
Dipole magnetic field	В	8.4 T
Luminosity	L	10 ³⁴ cm ⁻² s ⁻¹
Injection energy	E _i	450 GeV
Circulating current/beam	I _{beam}	0.53 A
Number of bunches	k _b	2835
Time between bunches	τь	24.95 ns
Protons per bunch	nb	1.05×10 ¹¹
Stored beam energy	Es	334 MJ
r.m.s. beam radius at intersection point	σ*	l6 μm
Crossing angle	¢	200 µrad
Number of events per crossing	n _c	19
Beam lifetime	$\tau_{\rm beam}$	22 h
Luminosity lifetime	τ	10 h



Image: CERN

Each proton crosses the French-Swiss border 11,200 times per second

The 27km tunnel contains some 1200 superconducting bending magnets



Operates at 1.9K

Experimental collaborations are truly global



Image: https://atlas.cern/discover/collaboration

38 countries183 institutions> 3000 scientific authors

We need a method of observing the products of the collisions

CMS is similar



Mass 7000 tonnes

Different types of particle require different detection techniques



The LHC started up on 10th September 2008



Image:CERN

The LHC on 19th September 2008



Image:CERN

The LHC recommenced after a year of repairs

Albeit at 50% design energy



The first task was to rediscover the Standard Model that we know

 $Z^0 \rightarrow e^+e^-$



The first task was to rediscover the Standard Model that we know



It's not easy to sort the Higgs out from the rest



Here is an example of what a Higgs boson candidate looks like in ATLAS



The evidence that there really are Higgs bosons



Higgs candidate decaying to a pair of photons



Image: ATLAS@CERN 2012

ATLAS result of search for Higgs decaying to 2 photons, July 2012



CMS had a similar result



François Englert and Peter 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"

With the Higgs discovery, the set of fundamental building blocks is expanded by one

The particles of the Standard Model



Image: Fermilab Visual Media Services

In 2019 we know much more about the Higgs



Image: https://msneubauer.github.io/projects/4_project/



ATLAS Preliminary	Stat	. 👝 🤅	Syst.	I SM
$V_S = 13 \text{ [eV, } 24.5 - 79.8 \text{ [b]}$				
$p_{SM} = 71\%$		Total	Stat.	Svst.
	0.96	+ 0.14 (+ 0.11	+0.09
	1 04	+0.14 (+0.14	-0.08 /
	1.04	-0.15	+ 0.14	+0.15)
	0.06	+0.59 /	± 0.11, + 0.37	± 0.15) + 0.45 \
	1.04	-0.52	- 0.36 ,	-0.38/
	1.04	+ 0.40	+ 0.31	+ 0.26
	0.00	-0.35	- 0.30 × + 0.94	-0.19/ +0.27 \
	2.00	- 0.83 (+ 0.36 /	- 0.81 , + 0.29	-0.20)
	0.59	0.35 (+0.58 /	0.27 + 0.42	± 0.21) + 0.40
	1.10	- 0.53 (- 0.40 , + 1.63	-0.35) +0.39
	3.01	- 1.61 (- 1.57 •	- 0.36)
	1.21	-0.22 (-0.17 *	-0.13)
	1.09	- 0.54 (- 0.49 *	-0.22)
VH ZZ	0.68	+1.20 -0.78	+ 1.18	+0.18
VH bb	1.19	+0.27 -0.25 (+ 0.18	+0.20 -0.18)
VH comb.	1.15	+0.24 -0.22 (±0.16,	+0.17 -0.16)
ttH+tH γγ	1.10	+0.41 -0.35 (+0.36 -0.33 •	+0.19 -0.14)
ttH+tH VV	1.50	+ 0.59 - 0.57 (+0.43 -0.42,	+0.41 -0.38)
ttH+tH TT F	1.38	+1.13 -0.96 (+0.84 -0.76 •	+0.75 -0.59)
ttH+tH bb	0.79	+0.60 -0.59 (±0.29,	±0.52)
<i>ttH+tH</i> comb. ⊨	1.21	+ 0.26 - 0.24 ($\pm \; 0.17$,	+0.20 -0.18
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Parameter normaliz	ed	to S	SM ·	value

It also has the expected spin

Image: https://cosmicglimpses.blog/

The Standard Model works – too, too well



But the Standard Model can't be the whole story

All known Standard Model particles

We still don't understand the pattern of masses



Image: https://scienceblogs.com/

Indeed, if the Standard Model is all that there is, then we actually have a very big mystery

The Higgs mass would be expected to be more like 10,000,000,000,000,000 times the mass of a proton, or even greater ...

... rather than about 135 times larger



Also, what is dark matter?

Pink – Hot gas Blue – Dark Matter



Could Supersymmetry (SUSY) be the answer?

A symmetry between fermions and bosons



Image: https://arstechnica.com/

SUSY could potentially unify the forces of nature



Image: CERN

SUSY has not appeared – not for lack of searching

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Lorg-Ived particles	Denot $S_{1,27}^{+}$ prod., long-load J Denot $S_{1,27}^{+}$ prod., long-load J State subpact 3 Arbackon States J_{2} Brockon Mena subs ℓ Prhadron GMSB: bischer, $S_{1}^{-} \rightarrow \ell \ell$, long-lived J_{1}^{+} $\xi \in T_{1}^{+} \rightarrow \delta l$ under J_{1}^{+} $\xi \in S_{1}^{+} \rightarrow \delta l$ and $J_{1}^{+} \rightarrow \delta \ell$	$\begin{array}{lll} & \text{Dsapp. trk} \\ & \text{cE/dx trk} \\ & \text{tk} \\ & \text{cE/dx trk} \\ & \text{cE/dx trk} \\ & \text{cE/dx trk} \\ & \text{r(e, \mu)} & 1{\text{-}}2{\mu} \\ & 2{\gamma} \\ & \text{crspl. } {\alpha}/{\mu}/{\mu} \\ & \text{crspl. } {vtx} + \text{jet} \end{array}$	1 jet 1-5 jers - - - - - - - - - - - - - - - - - - -	Yes Yes Yes - - Yes -	20.3 18.4 27.9 3.2 3.2 3.2 3.2 3.2 20.3 20.3 20.3	3* 270 GeV 31 495 GeV 7 860 GeV 8 7 7 537 GeV 7 537 GeV 7 446 GeV 7 1.0 TeV 7 1.0 TeV	$\begin{array}{c} m(\vec{r}_1^*) + n(\vec{r}_1^*) + 164 \ \text{MeV}, v(\vec{r}_1^*) - 1.2 \ \text{ns} \\ m(\vec{r}_1^*) + 164 \ \text{MeV}, v(\vec{r}_1^*) - 1.5 \ \text{ns} \\ m(\vec{r}_1^*) + 104 \ \text{MeV}, (0 \ \text{ps} - v(\vec{k} - 1.00 \ \text{s} \\ \textbf{1.57 TeV} \\ \textbf{1.57 TeV} \\ \textbf{1.57 TeV} \\ m(\vec{r}_1^*) + 104 \ \text{GeV}, r > 10 \ \text{ns} \\ 104 \ \text{m}(\vec{r}_2^*) - 50 \ \text{ns} \\ 104 \ \text{m}(\vec{r}_2^*) - 50 \ \text{ns} \\ 104 \ \text{m}(\vec{r}_2^*) - 50 \ \text{ms} \\ 104 \ \text{ms} \ \text{ms} \\ 104 \ \text{ms} \ \text{ms} \ 104 $	1310.3675 -503.0533 1310.6554 -603.0523 -604.0522 1411.6755 14(9.5542 -504.05162 -504.05162
NdB	$ \begin{array}{c} L(2^{n},p) & \in \{+,3,0\}, \rightarrow ap/(n),p\\ \textbf{Dinear FP}, CMSSM\\ & \uparrow_{1}, f_{1}^{n}, f_{2}^{n} + (nf_{1}^{n}, f_{2}^{n}) \rightarrow arrap, \\ & \uparrow_{1}, f_{1}^{n}, f_{2}^{n} + (nf_{1}^{n}, f_{2}^{n}) \rightarrow arrap, \\ & f_{1}, f_{1}^{n}, f_{2}^{n} + (nf_{1}^{n}, f_{2}^{n}) \rightarrow arg, \\ & f_{2}, f_{1}^{n}, f_{2}^{n} + agg, \\ & f_{2}, f_{1}^{n}, f_{1}^{n} \rightarrow agg, \\ & f_{2}, f_{1}^{n}, f_{1}^{n} \rightarrow agg, \\ & f_{2}, f_{1}^{n}, f_{1}^{n} \rightarrow agg, \\ & f_{3}, f_{1}, f_{1}^{n} \rightarrow bg, \\ & h, f_{3}, d, \end{array} $	т уч. ет. рт 2 е., р (\$\$) дан 4 е., р 1 е., т 3 1 е. р 1 е. р 3 2 е. р	0-3 i 5 lan e-R je 5 lan e-R je -10 jets/0-4 -10 jets/0-4 2 jets + 2 i 2 b	- Visa Visa Visa ts ts b b -	3.2 20.3 13.3 20.3 14.8 14.8 14.8 14.8 15.4 20.3	C C 2 C 3 C 3 C 453 GeV C 1.: 4 Tr C 453 GeV C 1.00 TeV C 450 S10 GeV C 450 S10 S10 S10 S10 S10 S10 S10 S10 S10 S1	1.0 TeV H ₁ =111. A _{25,126,000} =0.07 1.45 TeV m(²) ₁ >40,007, μ _{20,0} =0.07 m ² (²) ₁ >40,007, μ _{20,0} =0.5 m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ , μ ₂₀ , e0.5 = 1, 5) m ² (²) ₁ >6.25m(²) ₁ >1, 0.25m(²	- 667.06079 14(4.5500 ATLAS CONF 30(4.774 14(5.506) ATLAS CONF 30(4.577 ATLAS CONF 30(4.577 ATLAS-CONF.20(4.594 ATLAS-CONF.20(4.594 ATLAS-CONF.20(4.594 ATLAS-CONF.20(4.594 ATLAS-CONF.20(4.594)
Other	Scalarchorn, $i \rightarrow \partial \hat{e}_1^{\oplus}$	J	$Z \in$	Yes	20.3	¢ 510 GeV	m(t ² ₁₁)<200 GeV	- 501 JU 2025
	"Only a selection of the states or phenomena	e available ru sia shown	ess iinds	un nei	^{or} 1	0-' 1	Mass scale [TeV]	<u>.</u>

So there is a long way to go towards our ultimate aim, to understand all of this ...

And of course things might be quite different to what we currently think ...





Image: CERN