Back to July 4th – Discovery of a Higgs boson at the Large Hadron Collider

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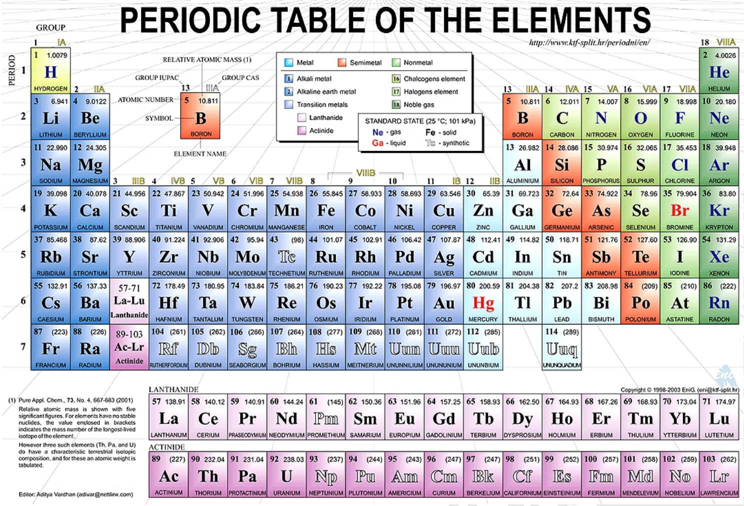
Outline

1. Recipe for a Universe

2. Searches for the Higgs boson at the LHC

The Universe from a chemist's point of view



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME
13 IIIA
5 10.811
B
BORON

- Metal
- Semimetal
- Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

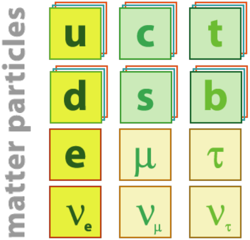
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001) Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@nettlinx.com)

The Universe from a physicist's point of view

All matter consists of 3 families of fermions, divided into quarks and leptons.



Six quarks:

- fractional electric charge: $-\frac{1}{3}$ for d, s, b and $+\frac{2}{3}$ for u, c, t.
- color charge (blue, green, red).

As only colorless objects can be observed, quarks stick together!

Six leptons:

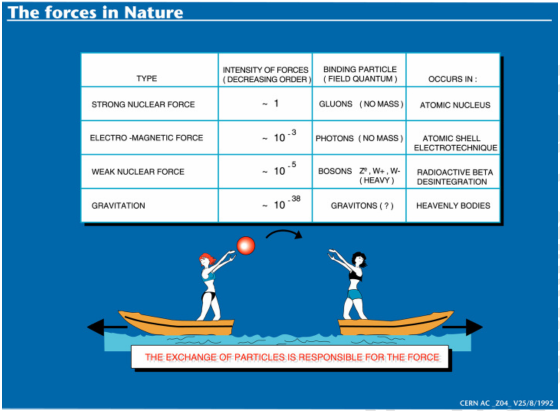
- three are charged: e^-, μ^-, τ^-.
- three neutrinos: very light, pass through everything and oscillate.

Stable matter (the world around us) mostly has fermions from the first family, the lighest one.

What holds matter together?

The Universe exists because fundamental particles interact. The four fundamental interactions include attractive/repulsive forces, decays and annihilations.

Each of them has its own force carrier (boson).



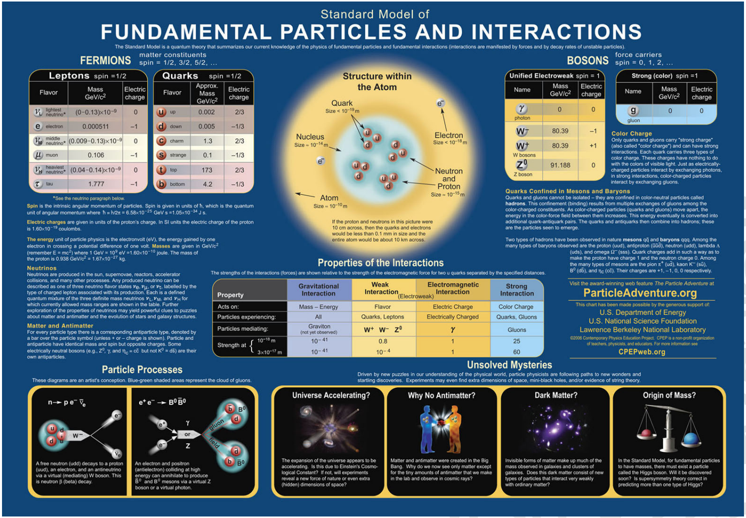
The forces in Nature

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, W+, W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

CERN AC _Z04_ V25/8/1992

The Standard Model (1)



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV $= 10^9$ eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.

Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, –1, 0, 0 respectively.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property		Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:		All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at	10^{-18} m	10^{-41}	0.8	1	25
	3×10^{-17} m	10^{-41}	10^{-4}	1	60

Visit the award-winning web feature *The Particle Adventure* at

ParticleAdventure.org

This chart has been made possible by the generous support of:
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Lawrence Berkeley National Laboratory

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Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^- \bar{\nu}_e$

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

The Standard Model (2)

The Standard Model is based on quantum field theory and, as such, must obey some rules (symmetries).

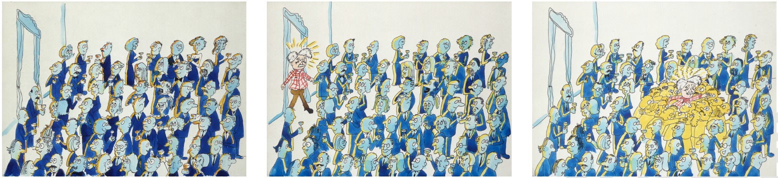
Unfortunately, any mass-like term breaks these rules: in its minimal version, the Standard Model can only have massless fermions and bosons!

In 1964, Higgs and Brout & Engler proposed to add a new scalar (spin 0) field into the Standard Model, which would give mass to fermions, as well as to the W and Z bosons, leaving the photon and gluon massless.

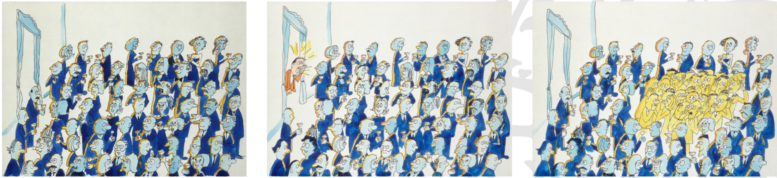
This Higgs mechanism predicts the existence of a new boson, with an unknown mass... It just took 48 years to discover it!

What is mass?

Mass is NOT an intrisic property of the fermions! It results from its coupling to a Higgs field that fills up vacuum.



What about the Higgs boson?



How to detect the Higgs boson?

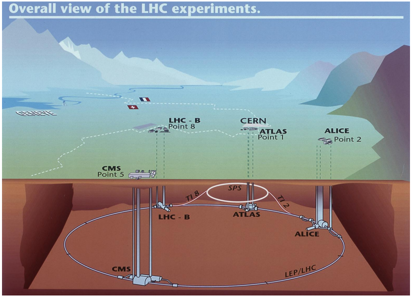
The Higgs boson, like most of the heavy fundamental particles, decays as soon as it is produced. So, one needs to look for the decay products:

- WW or ZZ, where each W/Z decays into quarks, electrons, muons and neutrinos,
- a pair of b-quarks, very difficult to detect (large background at hadron colliders),
- a pair of τ-leptons,
- a pair of photons.

To complicate things, we didn't know the Higgs boson mass, so we didn't know "where" to look for it!

Having identified the decay products of the Higgs boson, one normally has enough information to compute the mass of the mother particle.

The Large Hadron Collider in one slide



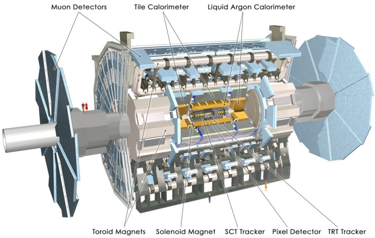
- Circumference = 27 km
- Proton revolutions per second = 11245.5
- Beam energy = 3.5 TeV in 2011, 4 TeV in 2012
- Delivered luminosity = 5.6/fb in 2011 and 10.5/fb (so far) in 2012, up to August 9th

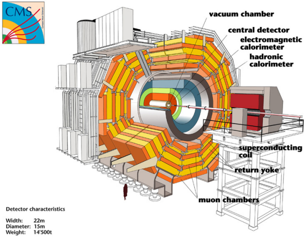
The LHC is colder than the outer space... but also the hottest spot in the galaxy (the proton-proton collisions generate temperatures more than 100,000 times hotter than in the heart of the Sun).

The LHC is also the emptiest space in the Solar System as the beams must travel in an ultra-high vacuum.

The LHC experiments

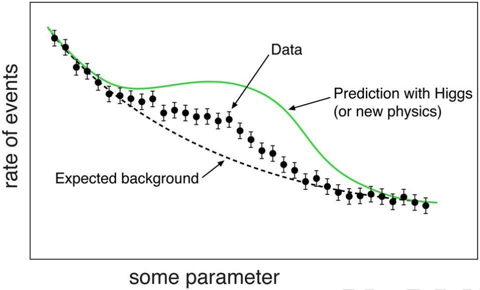
Two general purpose experiments (ATLAS and CMS), one dedicated to studies of *b*-quarks (LHCb) and one dedicated to studies of quark-gluon plasma (ALICE).





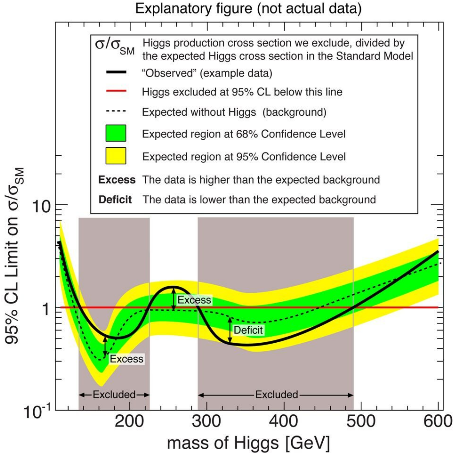
Data-analysis: signal and background

→ Compare the LHC data with the **predictions** of the Standard Model with or without the Higgs boson.



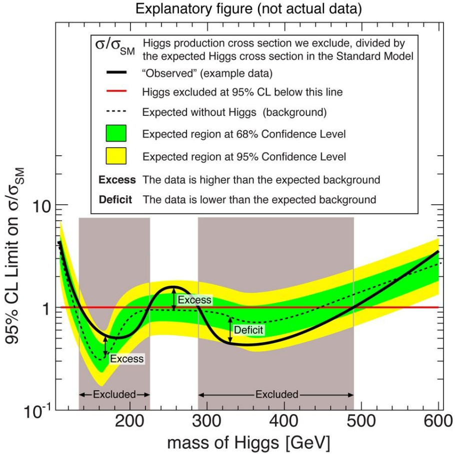
- black points close to the green curve: evidence for the Higgs boson (or new physics),
- black points on or below the dashed black curve (i.e. background): no evidence for a Higgs boson, which might be ruled out at the corresponding mass.

Data-analysis: exclusion plot



Cross section = likelihood of a collision event of a particular type to occur.

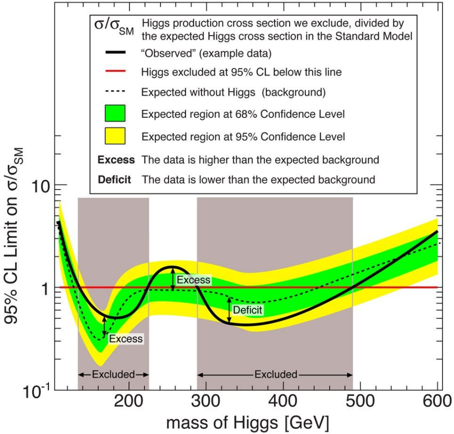
Data-analysis: exclusion plot



Vertical axis → Excluded Higgs boson cross section, divided by the one predicted by the Standard Model.

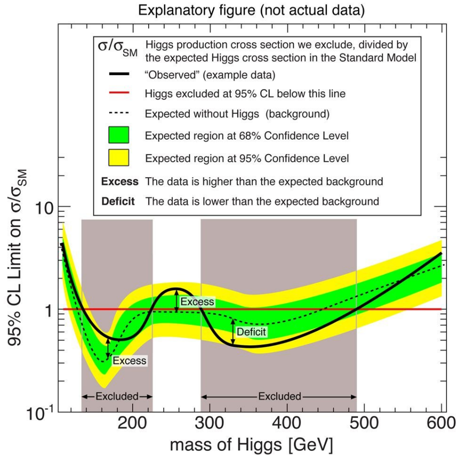
Data-analysis: exclusion plot

Explanatory figure (not actual data)



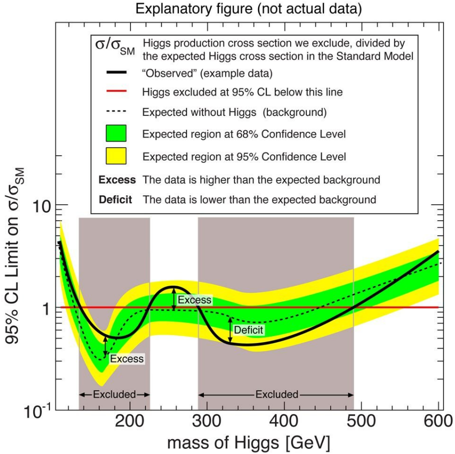
Solid black line → Exclusion with a 95% certainty that a Higgs boson with the given mass does not exist.

Data-analysis: exclusion plot



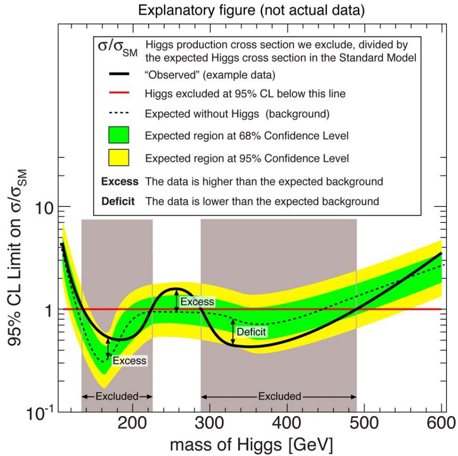
Dotted black line → Expected limit in the absence of a Higgs boson (derived from simulation).

Data-analysis: exclusion plot



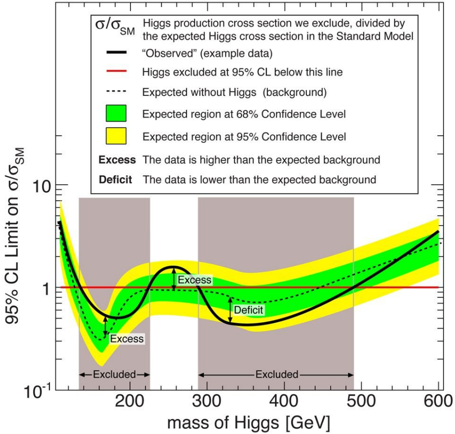
Green and yellow bands → 68% and 95% certainty on the value of the expected limit.

Data-analysis: exclusion plot



Deficit → Less data than the expected background. The observed limit is below the expected limit.

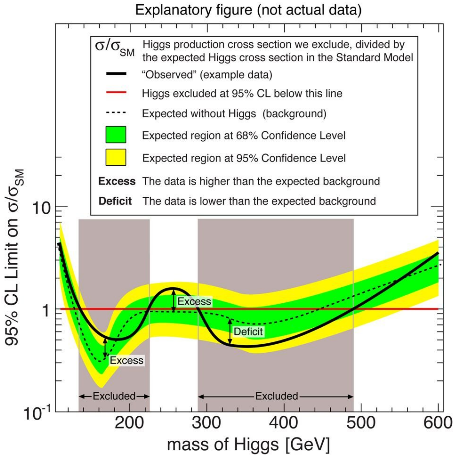
Data-analysis: exclusion plot



Explanatory figure (not actual data)

Excess → More data than the expected background. The observed limit is above the expected limit.

Data-analysis: exclusion plot



White vertical bands = non-excluded Higgs boson masses... but it does not mean discovery!

Recipe for a Higgs boson discovery

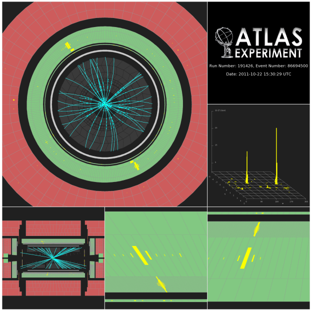
What is needed in order to discover a Higgs boson?

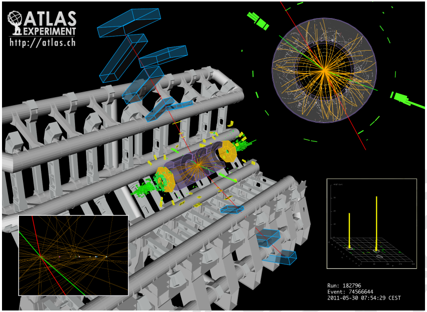
- the solid black line must be above 1.0 (no exclusion),
- the solid black line must be above the dotted black line (excess of data with respect to the background).

For a given mass, if the solid black line is at the upper edge of the yellow band, there is 95% certainty that the observed data exceed the background expectations. So, there is still a 5% chance that background processes or systematic errors in the detector are not well understood.

For a discovery, we want the chance that the observed data come from background fluctuations or systematic errors to be less than one in a million: 0.0001%!

ATLAS results (1)



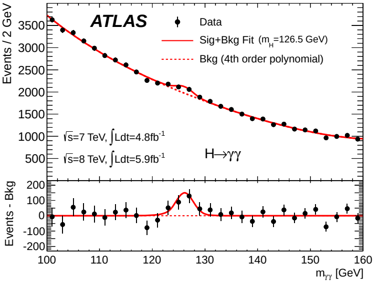


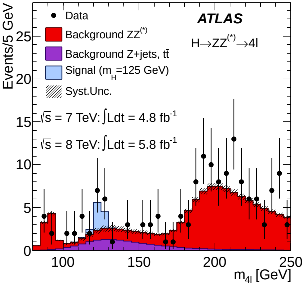
These two plots show **real** ATLAS events:

- two photons (left, mass = 126.6 GeV)
- 2 electrons + 2 muons (right, mass = 124.3 GeV).

ATLAS results (2)

Excess of events in the reconstructed mass spectra of the $\gamma\gamma$ and $ZZ \to 4\ell$ final states:

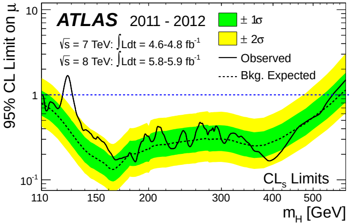


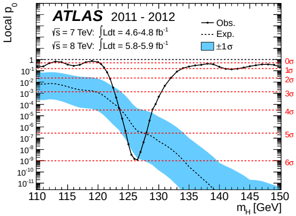


An excess of events is also observed in the *WW* $\to e\nu\mu\nu$ channel, but the direct reconstruction of the Higgs boson mass is not possible due to the escaping neutrinos.

ATLAS results (3)

The excess of events clearly appears in the exclusion plots and, in order to assess their compatibility with the background-only hypothesis, p0-values are computed:

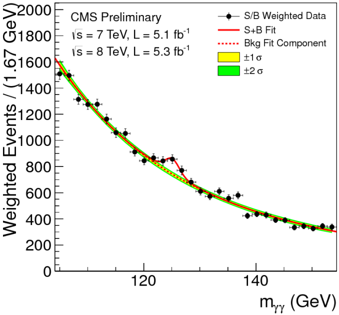


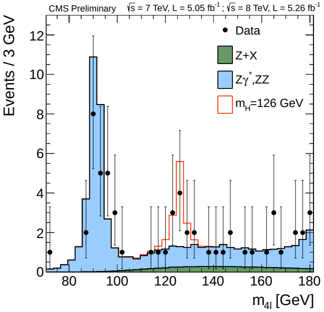


Clear evidence for the production of a new neutral boson with a measured mass of 126.0 GeV corresponding to a background fluctuation probability of 1.7×10^{-9} ($5.9\ \sigma$), compatible with a production and decay of the Standard Model Higgs boson.

CMS results (1)

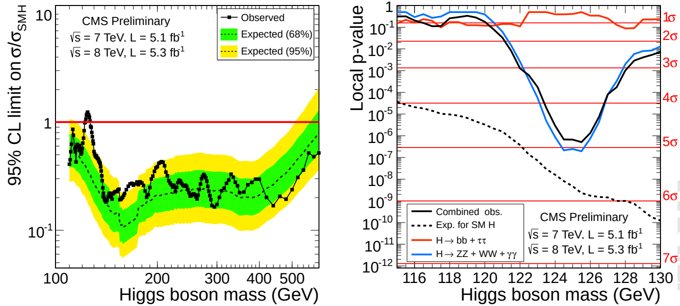
Excess of events in the reconstructed mass spectra of the $\gamma\gamma$ and *ZZ* $\rightarrow 4\ell$ final states:





Low mass resolution channels (*WW*, *ZZ* with neutrinos, $\tau\tau$, *bb* in association with *W* or *Z*) were also analyzed but they are much less sensitive...

CMS results (2)



Excess of events above the expected background, with a local significance of 4.9 σ for a Higgs boson mass around 125 GeV. The evidence is strongest in the two final states with the best mass resolution, giving a local significance of 5.0 σ.

Conclusion

The Standard Model of elementary particles has been confirmed by experimental data with great precision.

Up to a few weeks ago, the only missing piece of that puzzle was the Higgs boson, which is at the core of the mechanism providing mass to all particles.

A new neutral boson has been observed by both ATLAS and CMS at the LHC, with a mass of 125–126 GeV. The remaining mass range is meanwhile excluded with a high confidence level.

One should also investigate whether this is **THE** Standard Model Higgs boson, or **A** Higgs boson, e.g. by studying all decay channels (more data is needed).

Some theories beyond the Standard Model predict five Higgs bosons, three neutral and two charged.