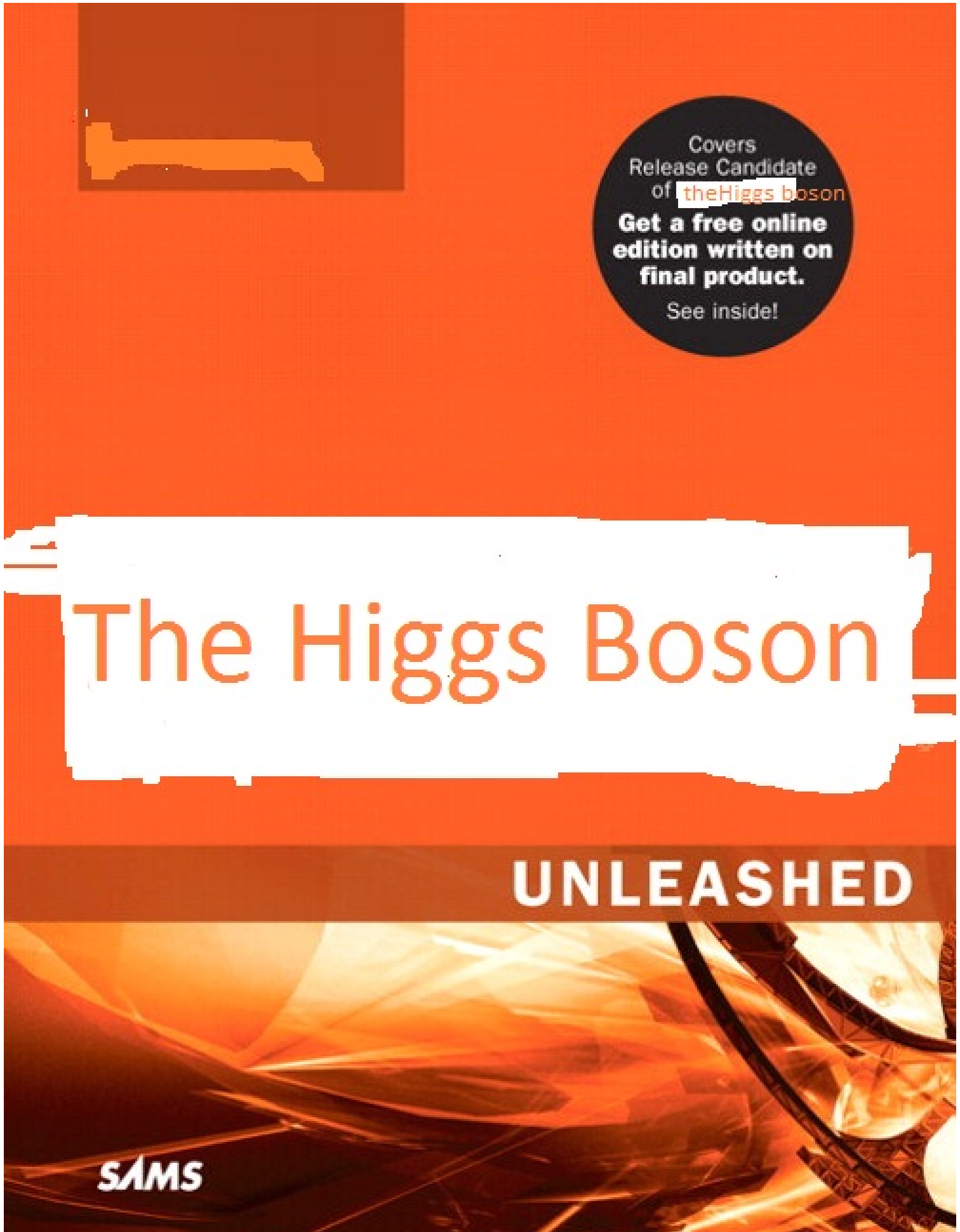


Howard E. Haber
Colloquium at UCSC
November 29, 2012

Outline

- **The Higgs boson explained in 60 seconds**
- **The Higgs boson explained in 30 minutes**
    1. The Standard Model of particle physics
    2. How do gauge bosons get their mass?
    3. Electroweak symmetry breaking and the Higgs boson
    4. Theoretical properties of the Higgs boson
    5. Expectations for the Higgs boson mass
- **Discovery of the Higgs boson at the Large Hadron Collider (LHC)**
- **Coming attractions**
- **Beyond the Standard Model Higgs boson**

symmetry dimensions of particle physics

volume 03 issue 06 august 06

explain it in 60 seconds

The Higgs boson, a fundamental particle predicted by theorist Peter Higgs, may be the key to understanding why elementary particles have mass. Explaining the connection, I am reminded of the puzzler, "If sound cannot travel in a vacuum, why are vacuum cleaners so noisy?" This riddle actually touches on a profound insight of modern physics: the vacuum—or empty space—is far from empty. It is indeed "noisy" and full of virtual particles and force fields. The origin of mass seems to be related to this phenomenon.

In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do massive particles arise? Higgs proposed that the vacuum contains an omnipresent field that can slow down some (otherwise massless) elementary particles—like a vat of molasses slowing down a high-speed bullet. Such particles would behave like massive particles traveling at less than light speed. Other particles—such as the photons of light—are immune to the field: they do not slow down and remain massless.

Although the Higgs field is not directly measurable, accelerators can excite this field and "shake loose" detectable particles called Higgs bosons. So far, experiments using the world's most powerful accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that particle physicists are poised for a profound discovery.

Howard E. Haber, University of California, Santa Cruz

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 $\hbar$, 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 = 1.67×10^{-27} kg.

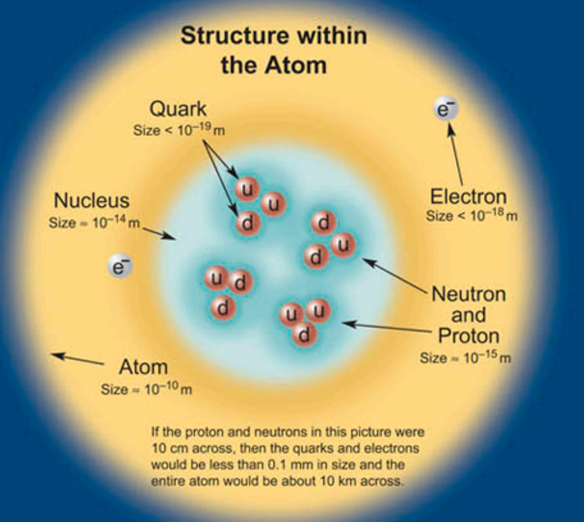
Neutrinos

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 (Electroweak)	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
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

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

ParticleAdventure.org

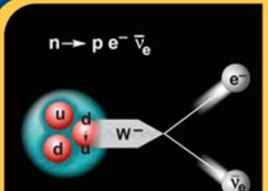
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory

CPEPweb.org

Particle Processes

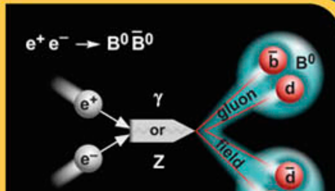
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

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



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?

Particle content of the Standard Model

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

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
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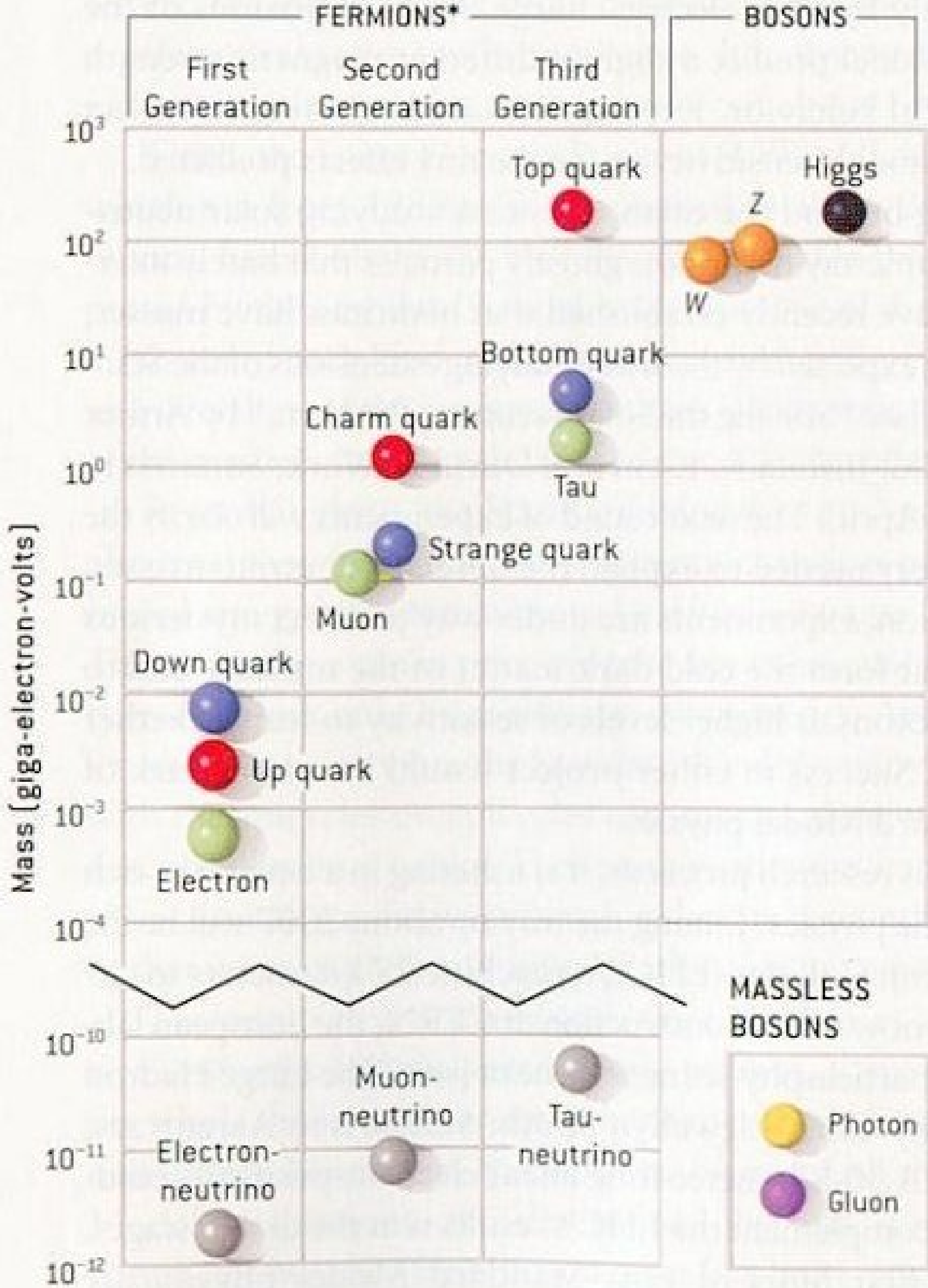
Strong (color) spin =1

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

Something is missing...



FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-10
10^-11
10^-12
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

Ingredients of the Standard Model of Particle Physics

- Quantum field theory (marriage of quantum mechanics and special relativity)

- Elementary spin-1/2 fermions (the quarks and leptons)

- Forces (electromagnetic, weak and strong) mediated by spin-1 gauge bosons

Mathematical consistency seems to require massless gauge bosons (e.g., the photon and the gluons)

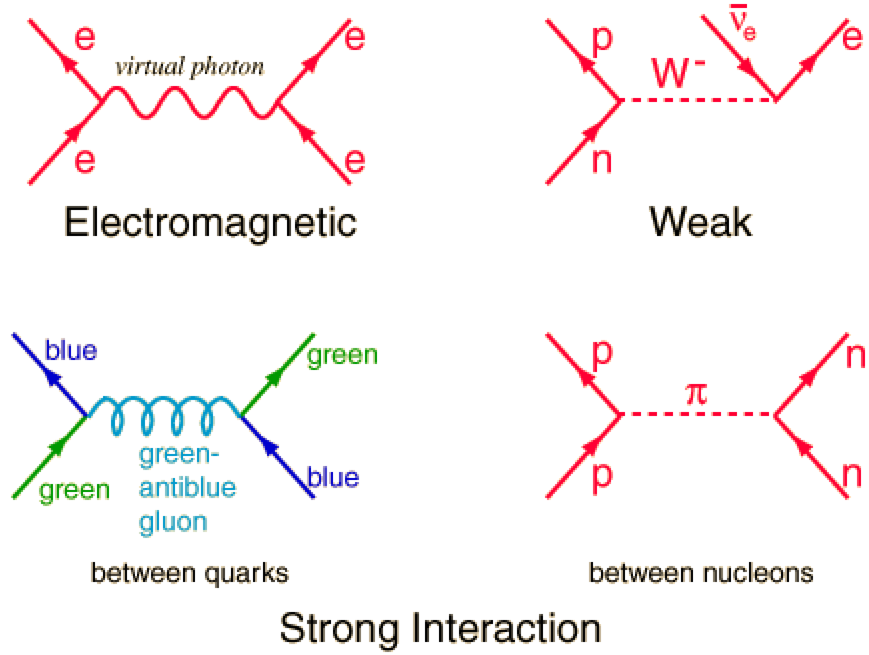
Contrast between massless and massive bosons

The potential energy between interacting particles is the Fourier transform of the quantum mechanical amplitude for "particle exchange."

$$\frac{1}{E^2 - |\vec{\boldsymbol{p}}|^2 - m^2}$$

$$\updownarrow \text{F.T.}$$

$$V(\vec{\boldsymbol{r}}) \sim \frac{e^{-mcr/\hbar}}{r}$$



m=0: yields long-range 1/r Coulomb potential

m>0: yields short-range Yukawa potential

Gauge invariance in quantum mechanics

The time-dependent Schrodinger equation in an external electromagnetic field:

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\vec{\nabla}^2\psi + \frac{ie\hbar}{mc}\vec{A}\cdot\vec{\nabla}\psi + \frac{ie\hbar}{mc}\psi(\vec{\nabla}\cdot\vec{A}) + \frac{e^2}{2mc^2}\vec{A}^2\psi + e\phi\psi$$

where the magnetic and electric fields are defined in terms of the vector and scalar potentials:

$$\vec{B} = \vec{\nabla}\times\vec{A}\,, \qquad \vec{E} = -\vec{\nabla}\phi - \frac{1}{c}\frac{\partial\vec{A}}{\partial t}\,.$$

The Schrodinger equation is invariant under the gauge transformation:

$$\vec{A} \longrightarrow \vec{A} + \vec{\nabla}X(\vec{r},t)\,, \quad \phi \longrightarrow \phi - \frac{1}{c}\frac{\partial X(\vec{r},t)}{\partial t}\,, \quad \psi \longrightarrow \exp\left(\frac{ieX(\vec{r},t)}{\hbar c}\right)\psi$$

Gauge invariance in quantum field theory

In relativity, introduce four-vectors:

$$A_\mu = (\phi\,;\,-\vec{\boldsymbol{A}})\,, \qquad \partial_\mu = \left(\tfrac{1}{c}\tfrac{\partial}{\partial t}\,;\,\vec{\boldsymbol{\nabla}}\right)\,, \qquad (\mu = 0, 1, 2, 3)$$

U(1)-gauge invariance (electromagnetism):

$$A_\mu \longrightarrow A_\mu - \partial_\mu X\,, \qquad \psi \longrightarrow \exp\left(\frac{ieX}{\hbar c}\right)\psi$$

<u>Non-abelian (Yang-Mills) theory:</u>

A_μ and U are $n \times n$ matrices, ψ is an n-component "vector"
with invariance under generalized gauge transformations:

$$A_\mu \longrightarrow U A_\mu U^{-1} - \frac{i\hbar c}{g} U \partial_\mu U^{-1}\,, \qquad \psi \longrightarrow U\psi$$

Implications of gauge symmetry

- Mathematically consistent theories containing charged (self-interacting) spin-one particles MUST be gauge theories

- Gauge invariance forbids an explicit mass term in the Lagrangian of a spin-one gauge boson

- But, the gauge symmetry of the Lagrangian may not be respected by the vacuum

- Gauge boson masses can potentially be generated by quantum corrections (due to the interactions with other sectors of the theory)

Constructing a theory of the weak interactions

- Use a non-abelian gauge theory to describe the photon and the gauge bosons that mediate the weak interactions (W^+, W^-, Z^0).

- Particles that feel the electromagnetic force possess electric charge. Particles that feel the weak force possess a "weak" charge.

- The combined electroweak theory is invariant under generalized gauge transformations that reflect the underlying electroweak symmetry.

  Mathematically , the electroweak symmetry is called SU(2) x U(1), corresponding to the matrices involved in the generalized gauge transformation [S means determinant=1 and U means unitary].

- The gauge symmetry leads to massless gauge bosons, in conflict with the observed massive W^+, W^-, Z^0. So, the electroweak symmetry must be broken.

How to break the electroweak symmetry?

- Explicit breaking (add masses “by hand” for the W^+, W^-, Z^0)

  Not viable: leads to mathematical inconsistencies (infinities,…)

- Spontaneous breaking
  - The fundamental laws respect the symmetry
  - The ground state (a.k.a. the “vacuum”) violates the symmetry

Example: the type-1 superconducting ground state

Cooper pairs (e^-e^- bound states) condense in the vacuum. The vacuum is therefore charged, and the electromagnetic symmetry of the vacuum is broken. Thus, photons propagating in this vacuum behave as if they are massive. The electromagnetic force is no longer long-range but exponentially damped. This is called the Meissner effect (static magnetic fields are screened from the interior of the bulk superconductor).

To break the electroweak symmetry, we must find some quantity that possesses “weak” charge that can condense in the vacuum. Since the vacuum of the universe is Lorentz-invariant, the quantity we seek must be a scalar (which is invariant with respect to Lorentz transformations).

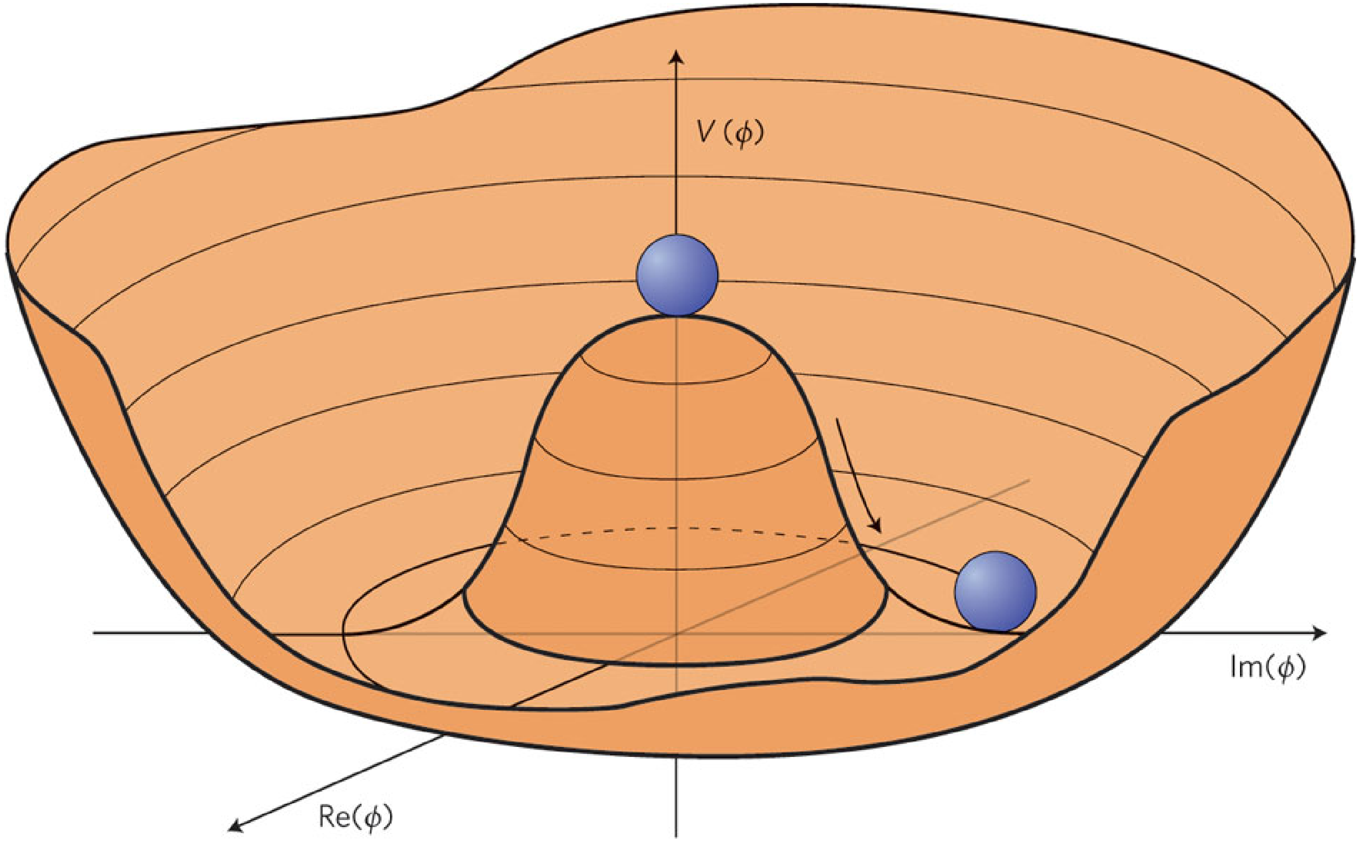
<u>Possible choices for the condensate</u>:

- An elementary spin-0 (scalar) field that possesses a weak charge
- A bound state of known particles that possesses a weak charge
  (example: a bound state of a top quark and anti-top quark)
- A bound state of unknown particles that possess a weak charge

Steven Weinberg proposed a theory of electroweak interactions in 1967 that employed a new elementary spin-0 field to break the electroweak symmetry. Later this theory became known as the Weinberg-Salam model.

Weinberg was inspired by the 1964 paper of Peter Higgs, who suggested that scalar fields could be used to break gauge symmetries. This idea was also suggested around the same time by Robert Brout and Francois Englert, and soon afterwards by Gerald Guralnik, C.R. Hagen and Tom Kibble.

If the potential energy density V(ϕ) of the scalar fields is arranged so that the lowest energy state corresponds to a non-zero value of the field, then the vacuum will possess a non-zero weak charge (condensation), and the electroweak symmetry is broken.



But excitations around the bottom of the “Mexican hat” do not cost energy, and correspond to the excitation of a new massless spin 0 particle---the Goldstone boson.

The Goldstone boson puzzle and the gauge boson mass problem: RESOLVED

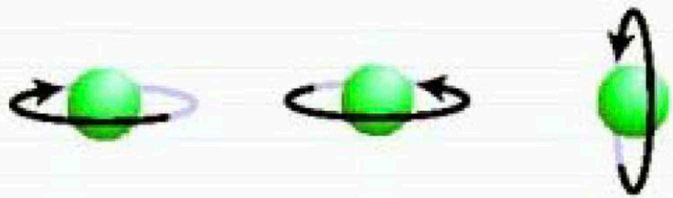
In the early 1960s, theorists were very troubled by the mechanism of spontaneous symmetry breaking, as it seemed to lead to the prediction of a new massless spin-0 particle. No evidence for such a particle has ever been seen in nature.

The remarkable discovery of Brout, Englert, Higgs, Guralnik, Hagen and Kibble was that when the symmetry-breaking mechanism was incorporated into gauge theories, the would-be Goldstone boson no longer appears as a physical particle. Instead, it provides the longitudinal polarization for the massive gauge boson. This is now unfairly called the "Higgs mechanism."

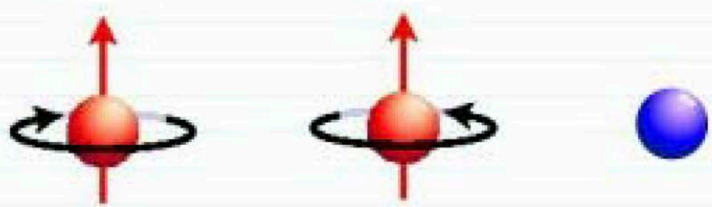
Massless and heavy

spin 1 particles

Heavy spin 1 particles can spin in 3 directions:



Massless particles must have their spin-axis
either parallel or anti-parallel to their direction of motion:



They can only spin in 2 directions.

That is, a gauge boson that is originally massless (due to the gauge symmetry) “swallows up” the Goldstone boson, thereby providing a mathematically consistent Lorentz-invariant mechanism for generating mass.

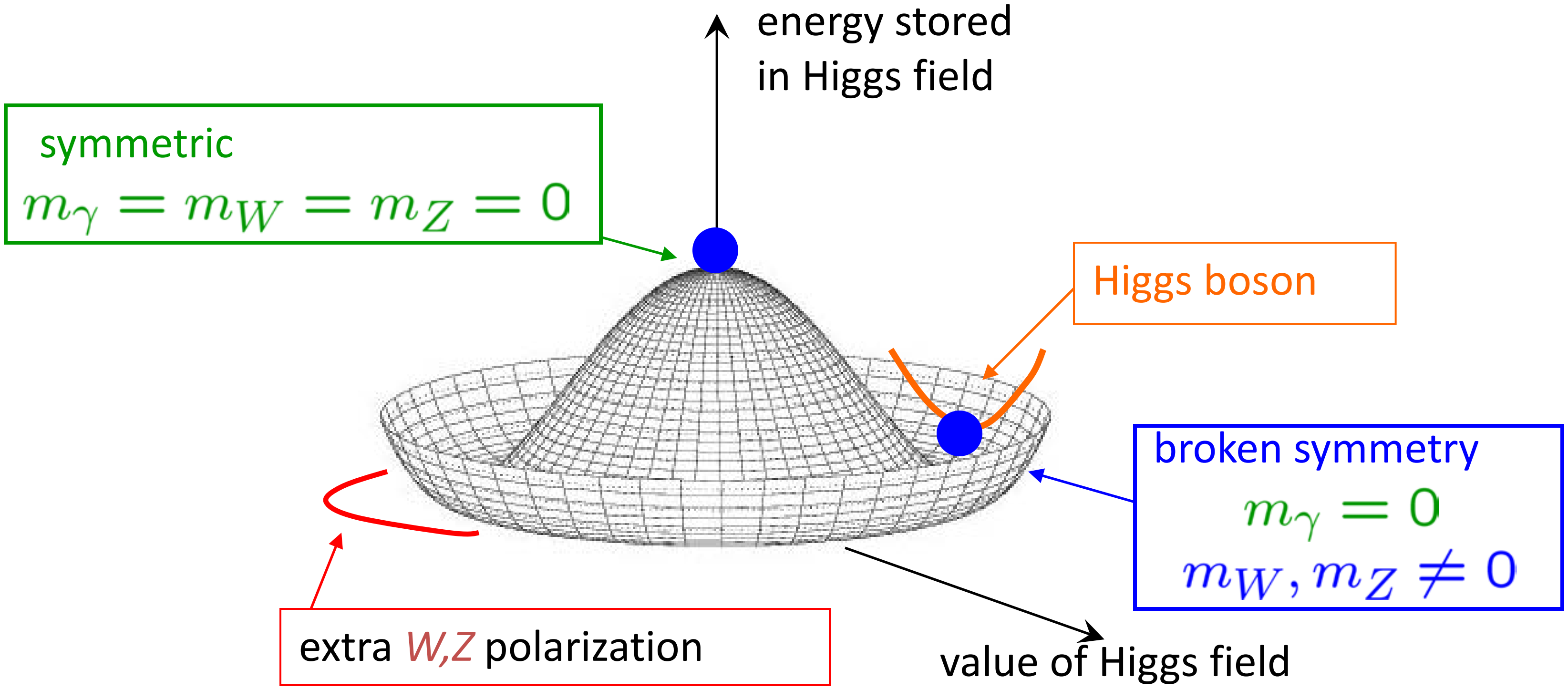
In 1964, Peter Higgs also noticed that the mechanism of spontaneous symmetry breaking by scalar fields can also produce excitations that are orthogonal to the Goldstone direction.   These excitations cost energy and correspond to a new massive spin-0 particle, which now bears the name of its inventor---the Higgs boson.

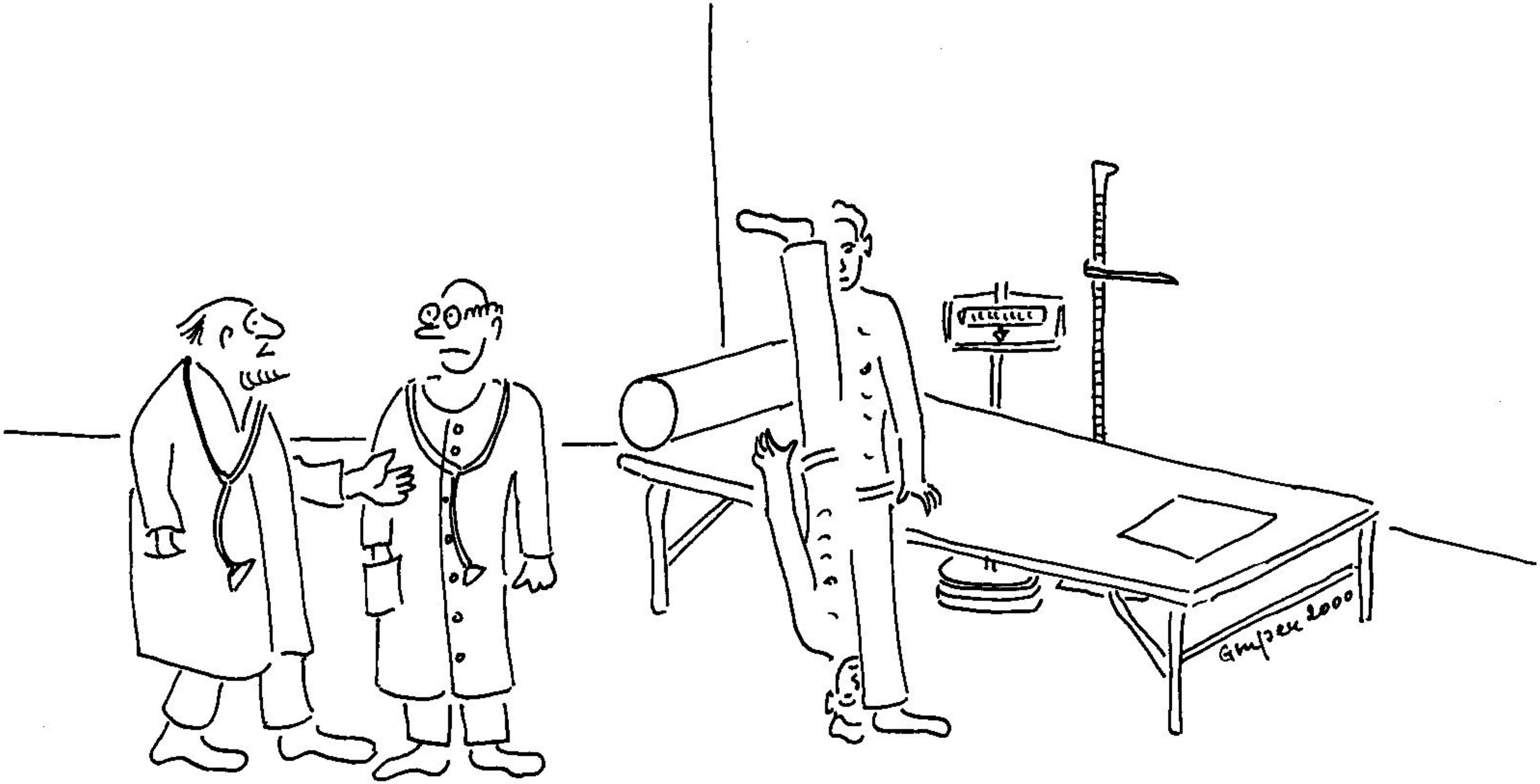
$$M^2_{ij} = \frac{\partial^2 V(\Phi)}{\partial\Phi_i \partial\Phi_j}$$

The scalar squared masses are eigenvalues of M^2; these are related to the curvatures of the scalar potential at its minimum.

Breaking the Electroweak Symmetry

Higgs imagined a field filling all of space, with a "weak charge".
Energy forces it to be **nonzero** at bottom of the "Mexican hat".





“A severe case of symmetry breaking!”

Timeline for the confirmation of electroweak theory

- 1964: the invention of the “Higgs mechanism” and the “Higgs boson.”
- 1967: Weinberg incorporates the Higgs boson into a theory of the electroweak force.
- 1971: Gerard `t Hooft proves the renormalizability of spontaneously broken gauge theories, thereby confirming the mathematical consistency of such theories.
- 1978: The structure of the weak force mediated by the Z^0 is confirmed at SLAC.
- 1983: Discovery of the W^+, W^-, Z^0 at CERN.
- 1995: Discovery of the top quark at the Fermilab Tevatron.
- 1989—2000: Precision tests of electroweak theory at CERN, Fermilab and SLAC.
- 2001—2011: Further precision tests at the Fermilab Tevatron.

But, where is the Higgs boson?

Nuclear Physics B106 (1976) 292–340

1976: The first comprehensive study of how to search for the Higgs boson

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

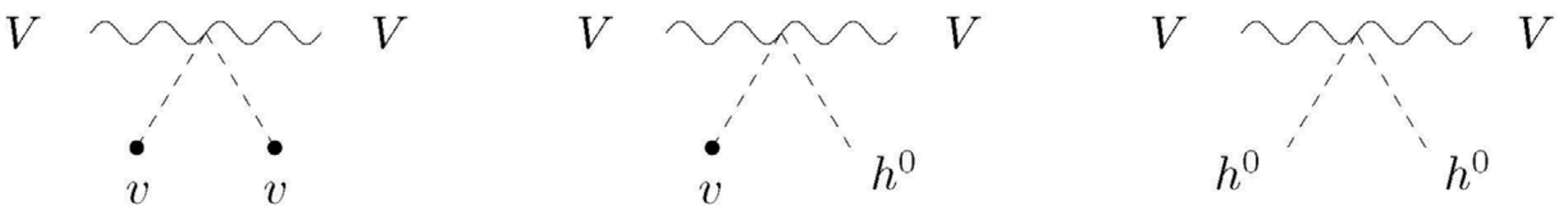
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

Michael Peskin (from SLAC) peruses the *Higgs Hunter's Guide,* published in 1990.

Standard Model masses and Higgs couplings

Gauge bosons ($V = W^{\pm}$ or Z) acquire mass via interaction with the Higgs vacuum condensate.



Thus,

$$g_{hVV} = 2m_V^2/v\,, \qquad \text{and} \qquad g_{hhVV} = 2m_V^2/v^2\,,$$

i.e., the Higgs couplings to vector bosons are proportional to the corresponding boson squared-mass.

Likewise, by replacing V with the Higgs field h^0 in the above diagrams, the Higgs self-couplings are also proportional to the square of the Higgs mass:

$$g_{hhh} = \tfrac{3}{2}\lambda v = \frac{3m_h^2}{v}\,, \qquad \text{and} \qquad g_{hhhh} = \tfrac{3}{2}\lambda = \frac{3m_h^2}{v^2}\,.$$

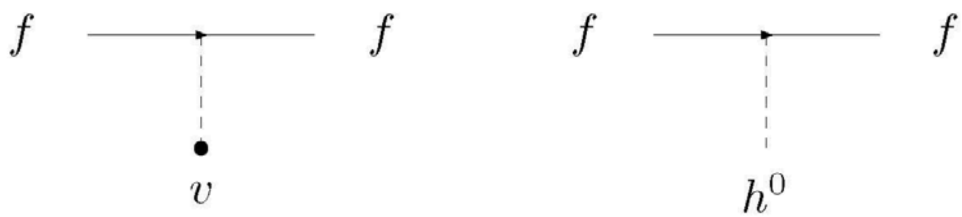
Fermions in the Standard Model

Under the electroweak gauge group, the right and left-handed components of each fermion has different SU(2)×U(1)$_{\rm Y}$ quantum numbers:

fermions	SU(2)	U(1)$_{\rm Y}$
$(\nu\,,\,e^-)_L$	2	-1
e^-_R	1	-2
$(u\,,\,d)_L$	2	$1/3$
u_R	1	$4/3$
d_R	1	$-2/3$

The electric charge is related to the U(1)$_{\rm Y}$ hypercharge by $Q = T_3 + \frac{1}{2}Y$.

Before electroweak symmetry breaking, Standard Model fermions are massless, since the fermion mass term is not gauge invariant. The quark and charged lepton masses are generated by virtue of their interactions with the Higgs boson.



Thus,

$$g_{hf\bar{f}} = m_f/v\,,$$

i.e., Higgs–fermion couplings are proportional to the corresponding fermion mass.

The bottom line

- Higgs bosons couple to other bosons with strength proportional to the boson squared mass
- Higgs bosons couple to fermions with strength proportional to the fermion mass
- The Higgs mass itself is the only undetermined parameter.

Theoretical expectations for the Higgs boson

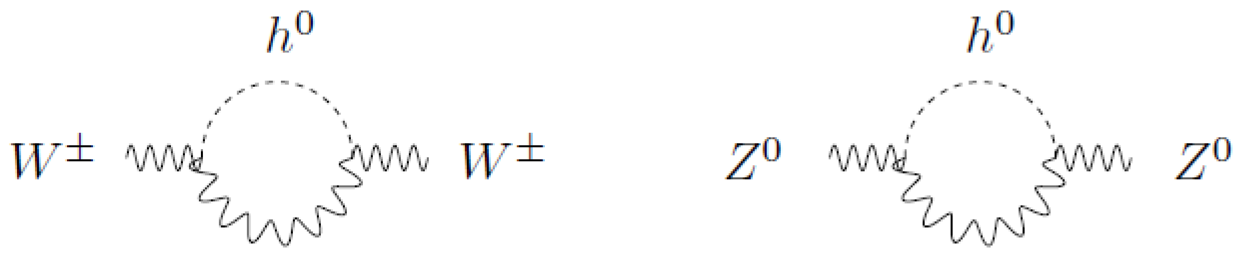
The interactions of the Higgs *field* with the gauge bosons, quarks and charged leptons generate masses for all these fundamental particles. As a result, the strengths of the interaction of these particles with the Higgs *boson* is proportional to the corresponding particle masses.

That is, the Higgs boson prefers to couple to the heaviest fundamental objects of the Standard Model. Thus, the Higgs boson couples strongest to the W^+, W^-, Z^0 and top quark.

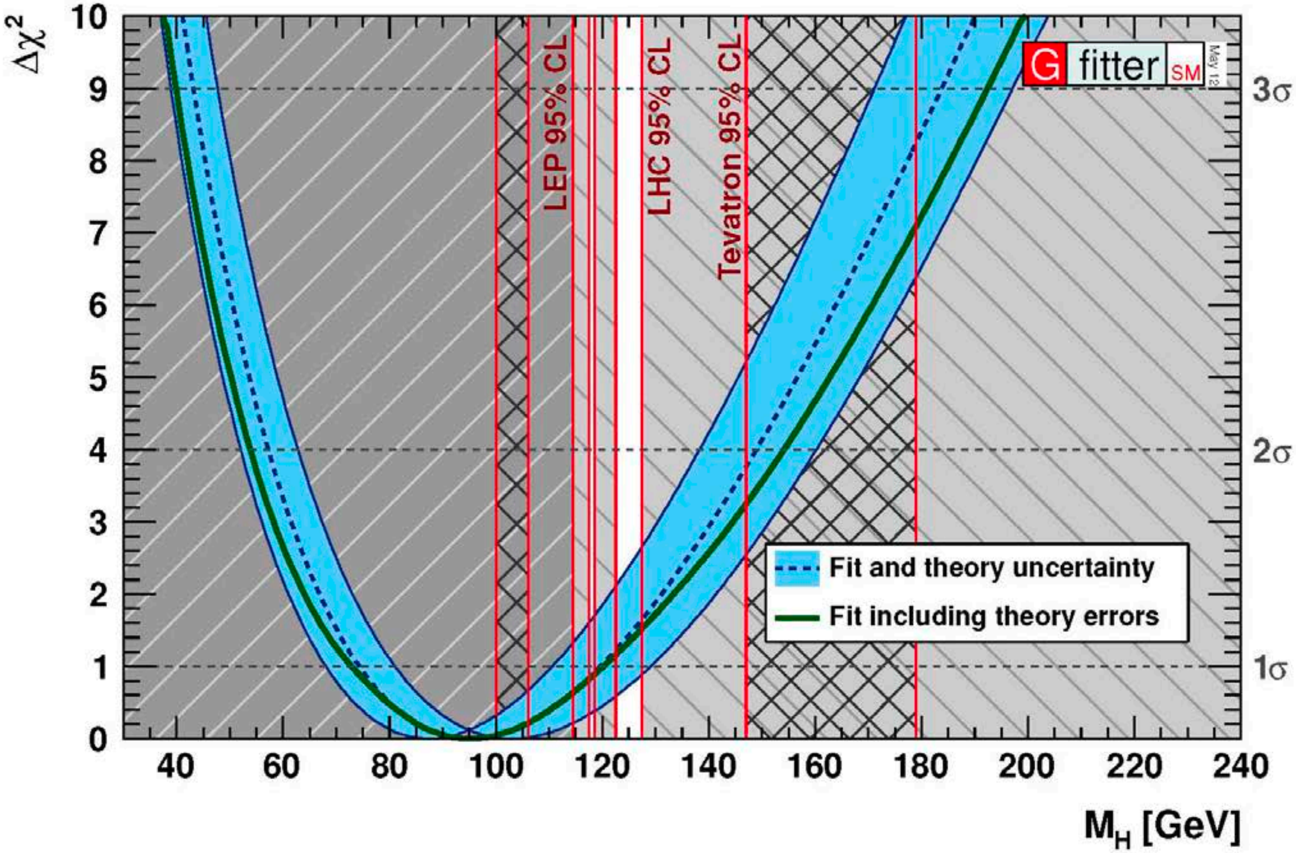
The mass of the Higgs boson (M_H) is NOT predicted by the theory. However, for a given Higgs mass, one can predict the production rate for Higgs bosons at colliders and the rates for Higgs boson decays to various Standard Model particles.

The LEP Collider at CERN spent ten years searching for the Higgs boson. Since no Higgs bosons were observed, experimenters at LEP concluded that its mass must be larger than 114 GeV.

Meanwhile, the analysis of precision electroweak data provides an indirect determination of the Higgs mass, assuming that the Standard Model is correct. In particular, the "virtual" emission and reabsorption of Higgs bosons by the W^+, W^-, Z^0 affects the mass and interactions of these gauge bosons.



Window of opportunity: 114 GeV < M_H < 153 GeV



The blue band, which does *not* employ the direct Higgs search limits, corresponds to a upper bound of $m_h < 153$ GeV at 95% CL. A similar result of the LEP Electroweak Working group quotes $m_h < 152$ GeV at 95% CL.

Higgs production at hadron colliders

At hadron colliders, the relevant processes are

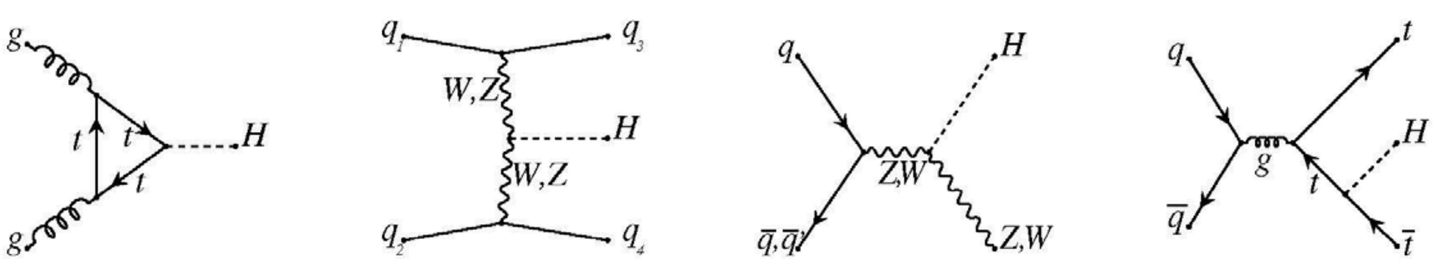
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

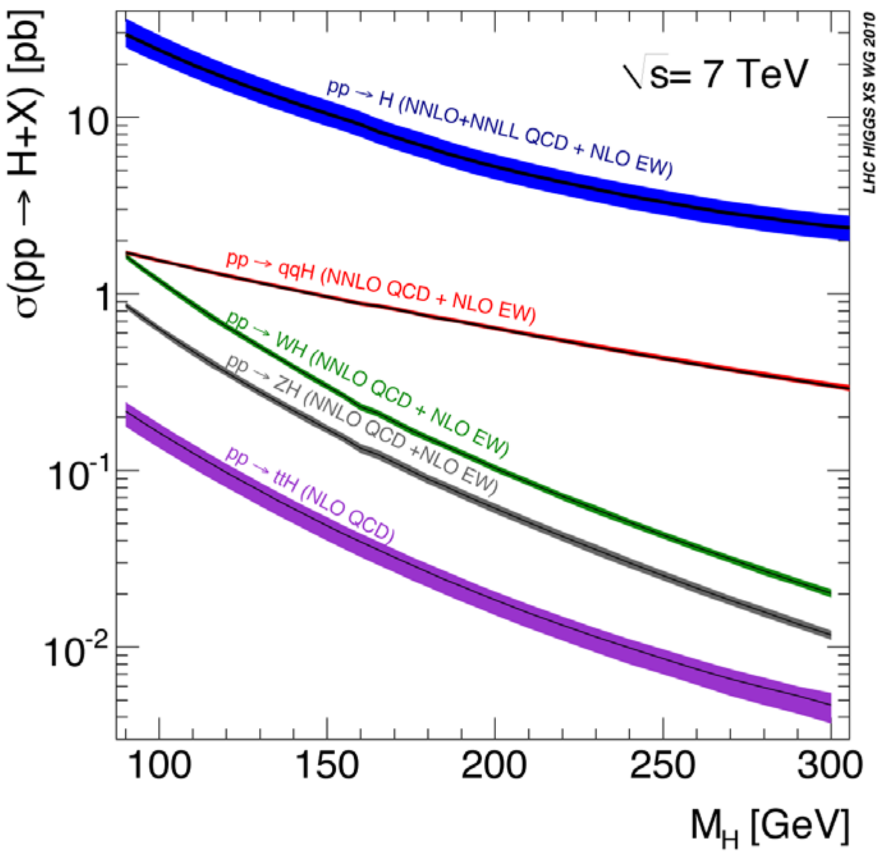
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

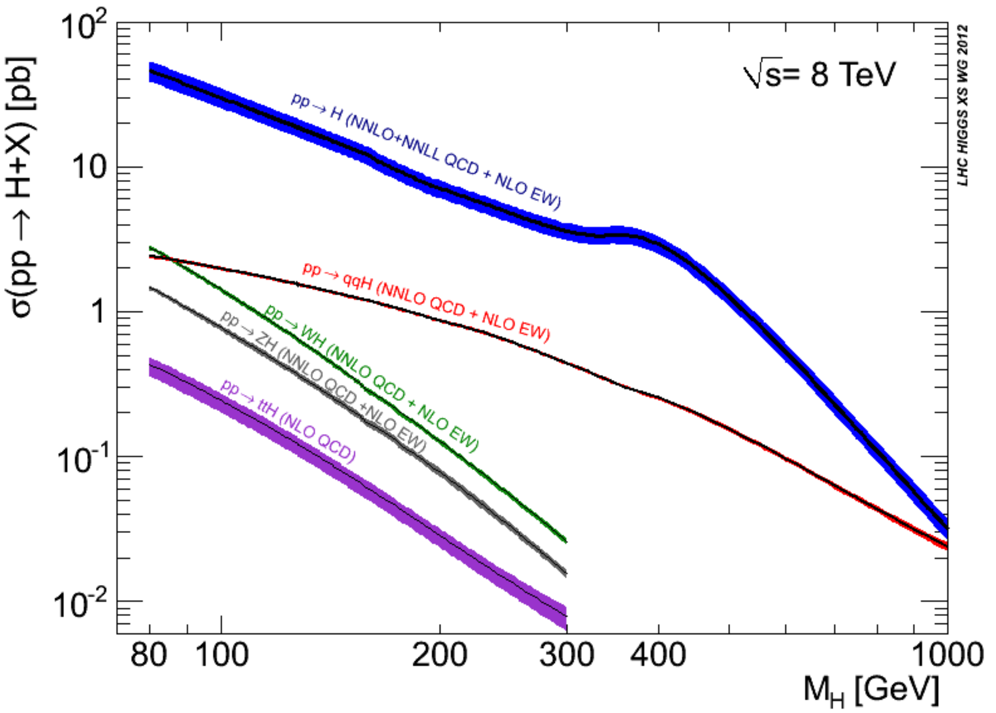
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.



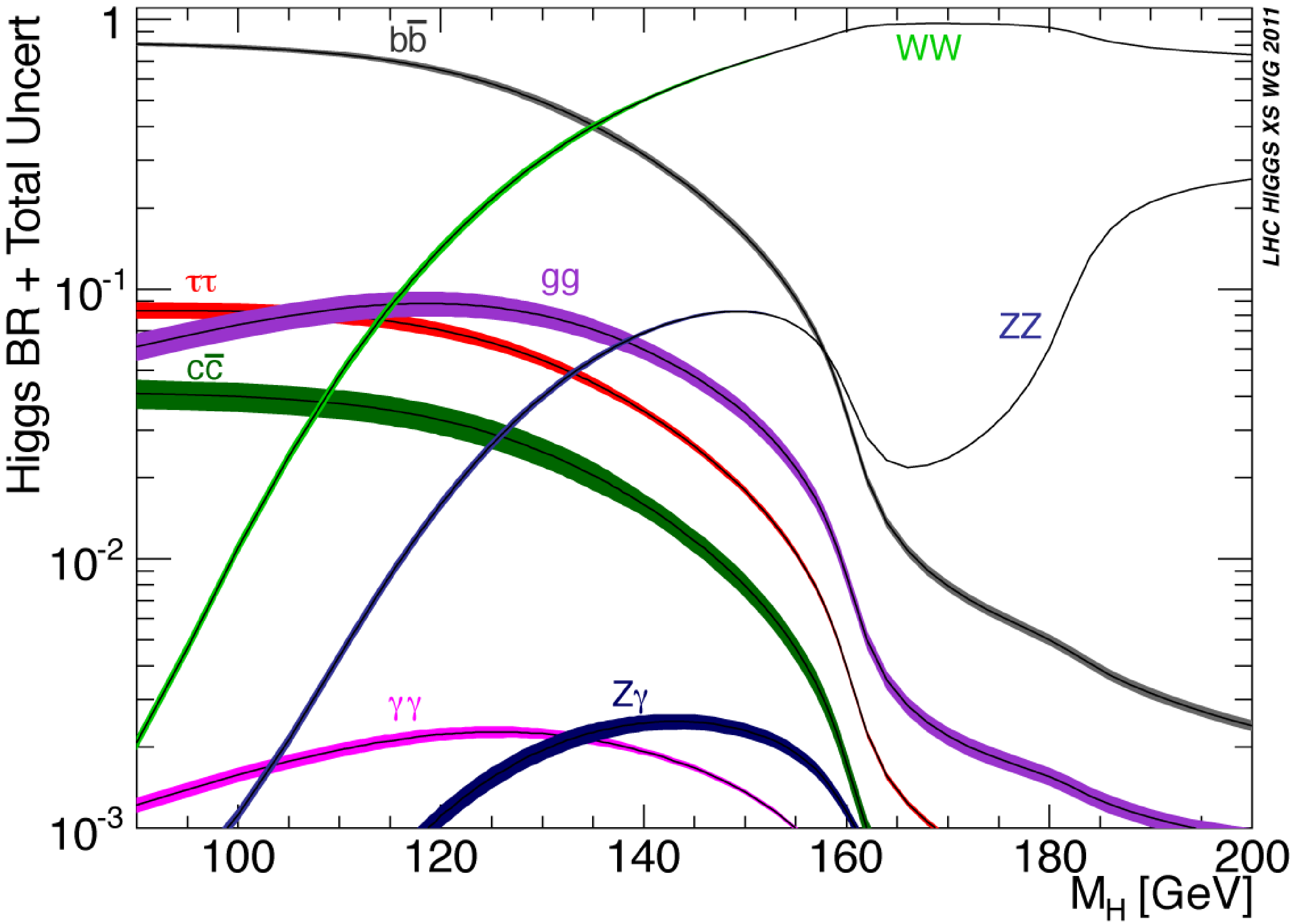
Higgs boson production cross sections at a pp collider





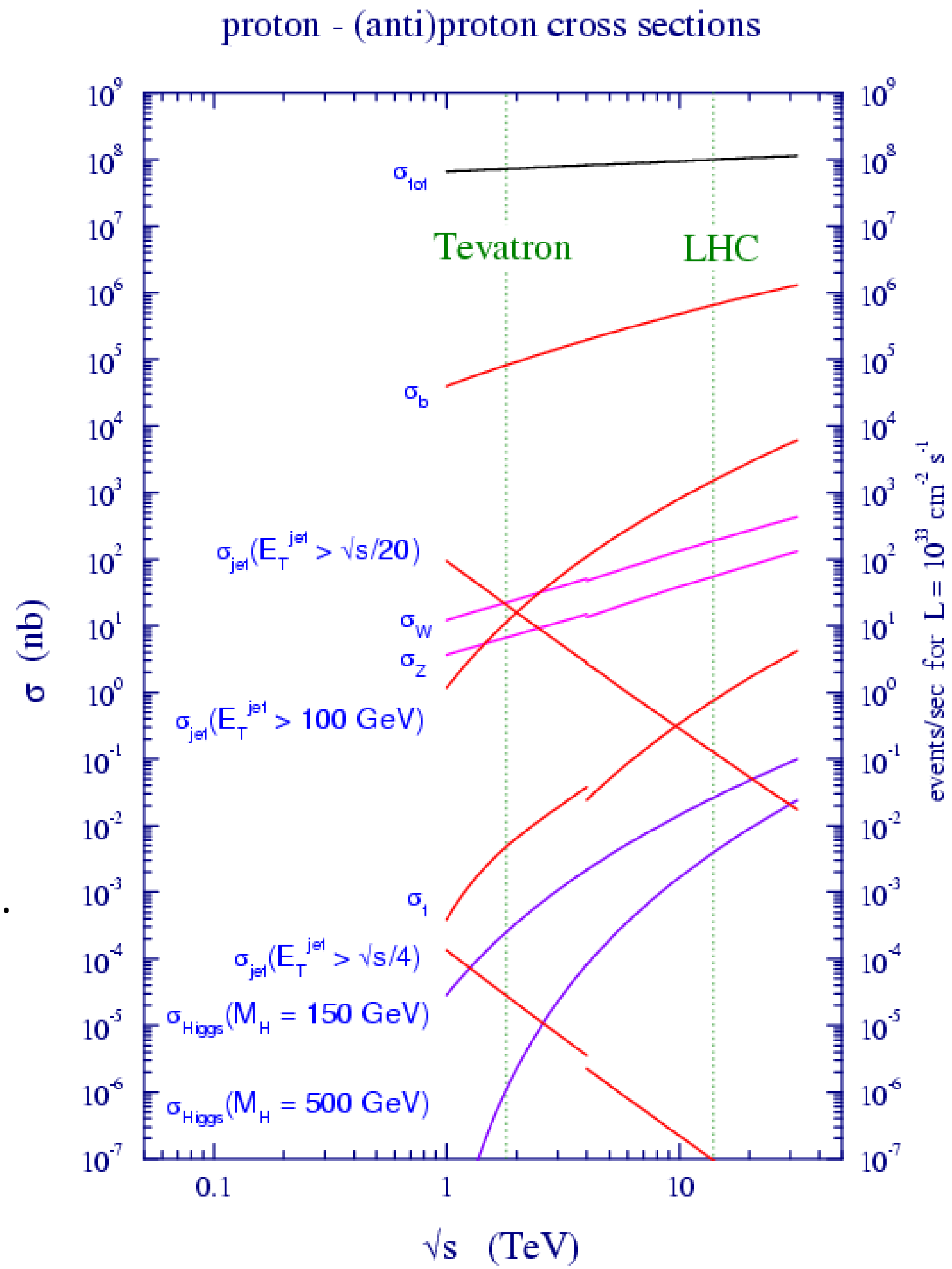
With 35 fb^{-1} of data, one would expect to produce roughly 500,000 Higgs bosons if the Higgs mass was, say, M_H = 125 GeV.

Probability of Higgs boson decay channels



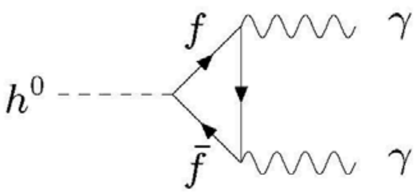
Question: why not search for Higgs bosons that decay into a pair of b-quarks?

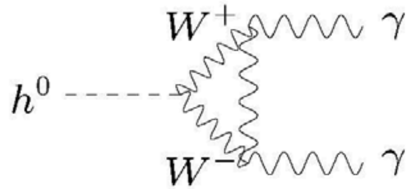
Answer: The Standard Model background is overwhelming. There are more than 10^7 times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

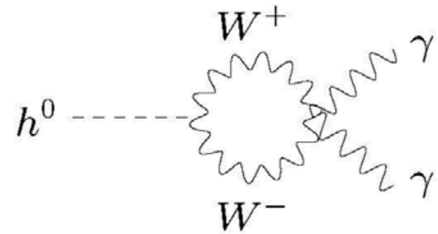


SM Higgs decays at the LHC for $m_h \sim 125$ GeV

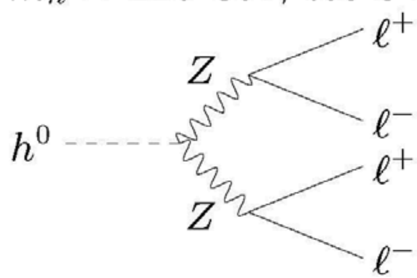
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



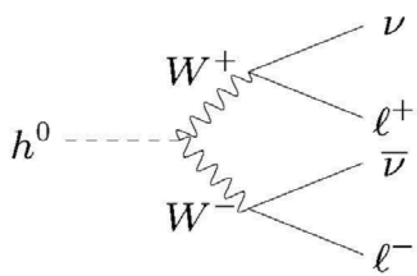




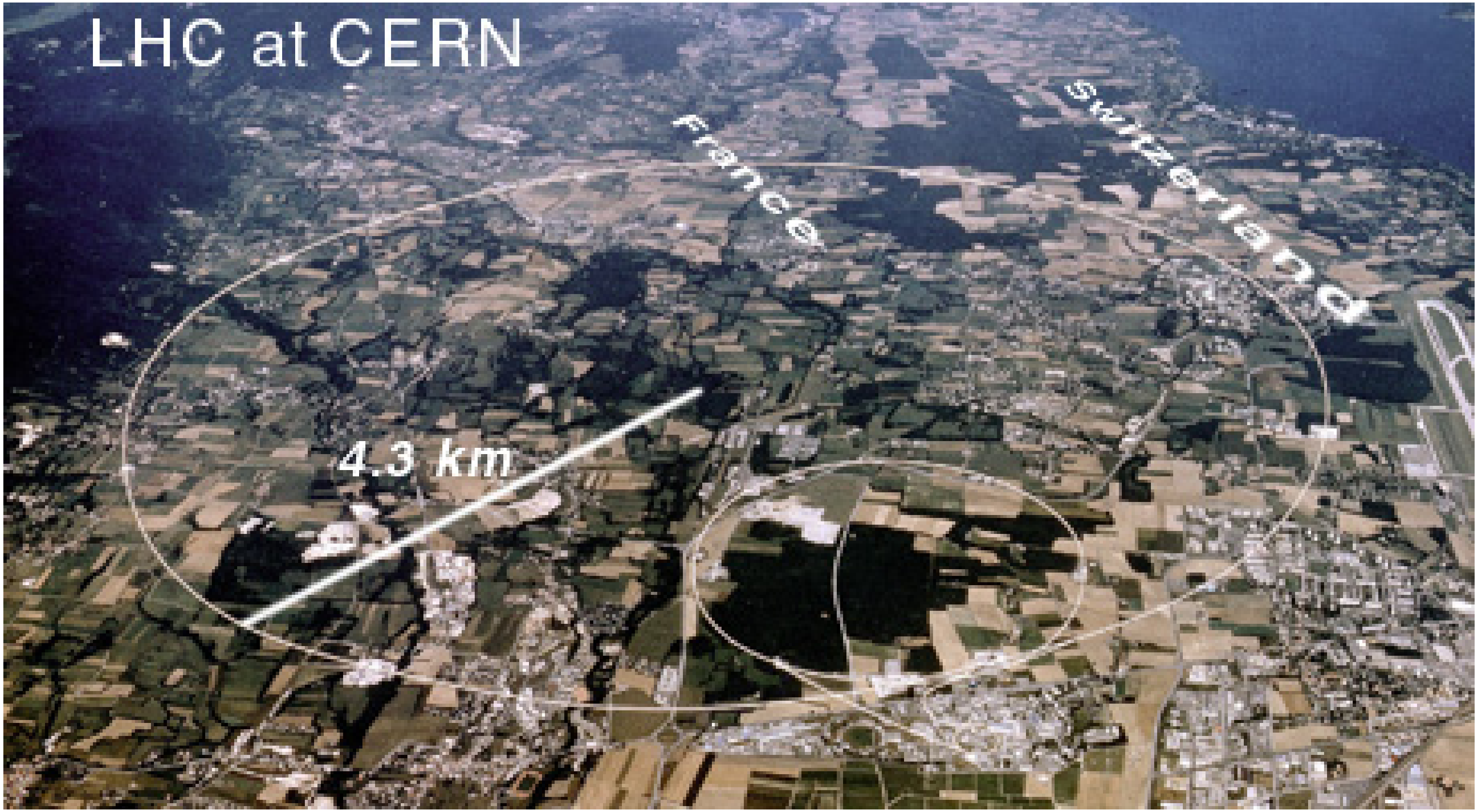
2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.



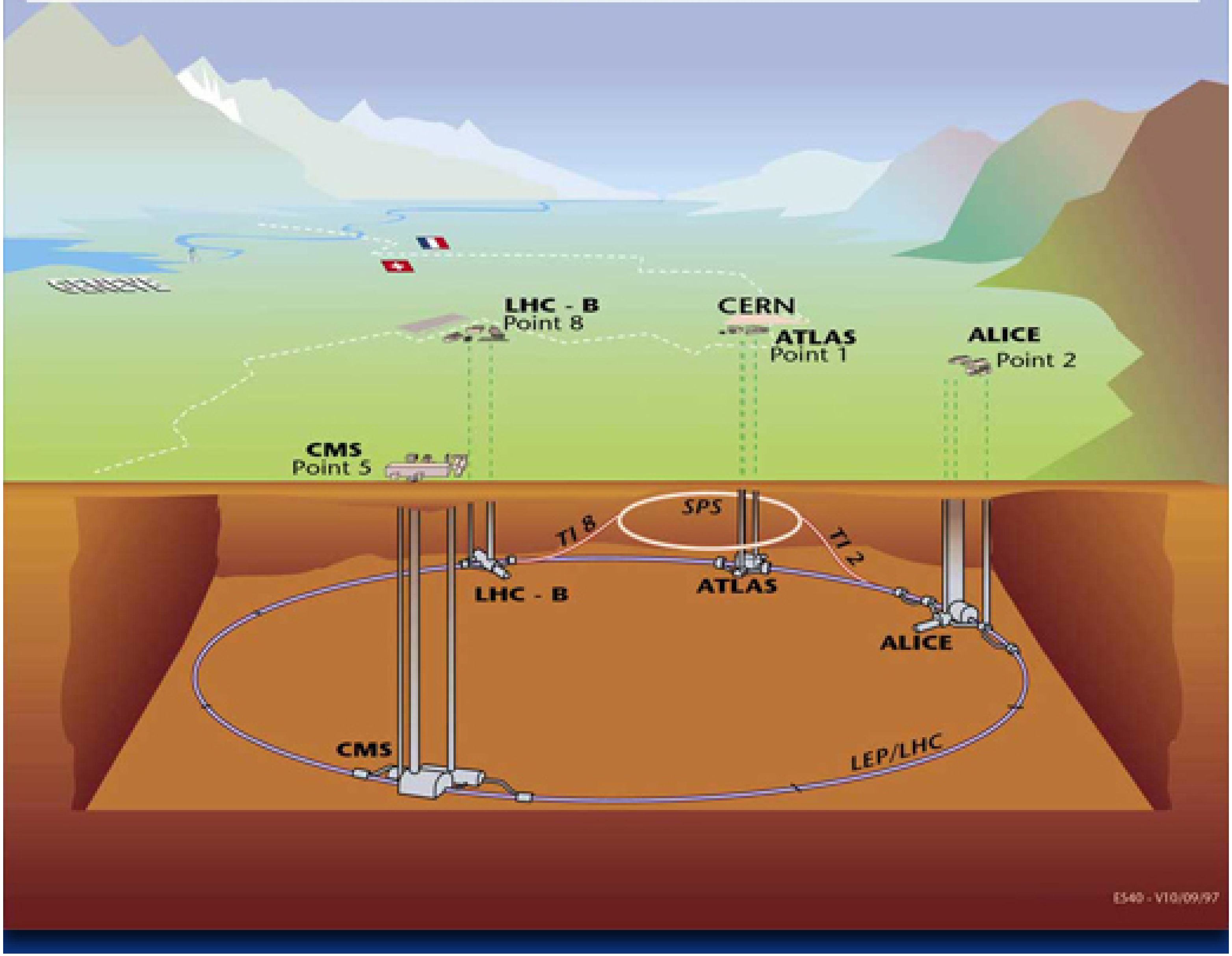
3. The channel, $h \to WW^* \to \ell^+\nu\ell^-\overline{\nu}$ is also useful, although it does not provide a good Higgs mass determination.



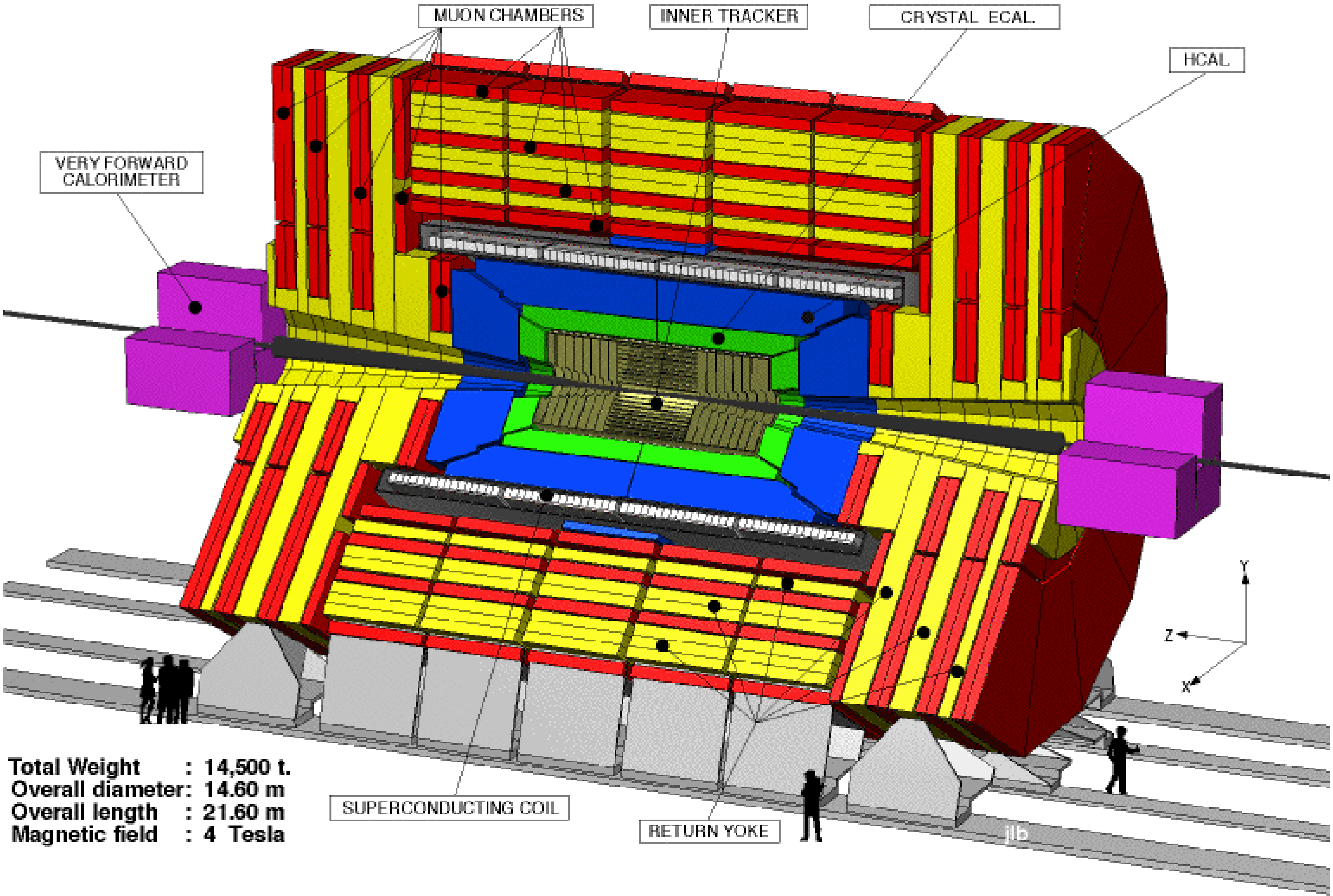
The Large Hadron Collider (LHC) at CERN



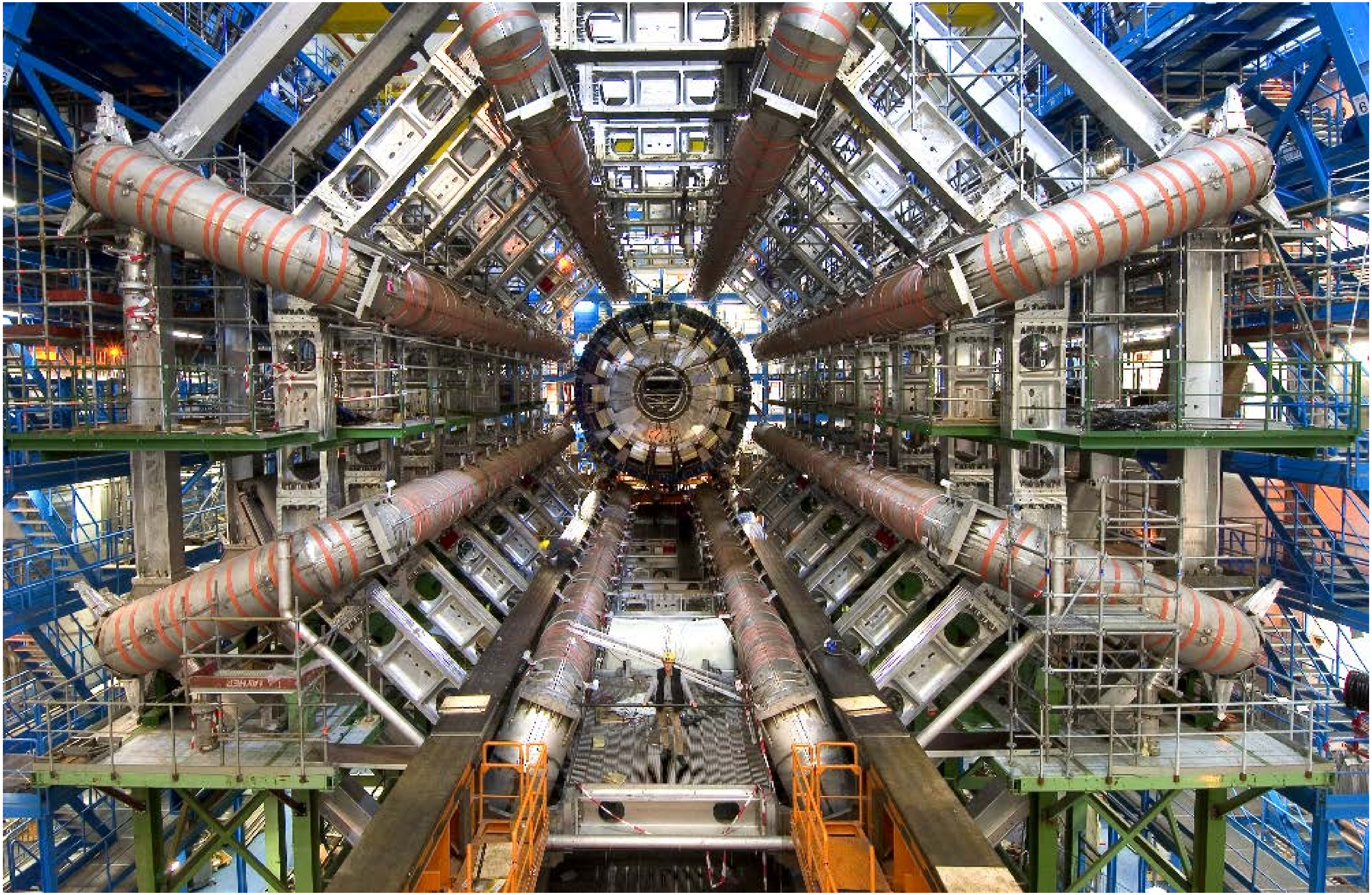
Overall view of the LHC experiments.



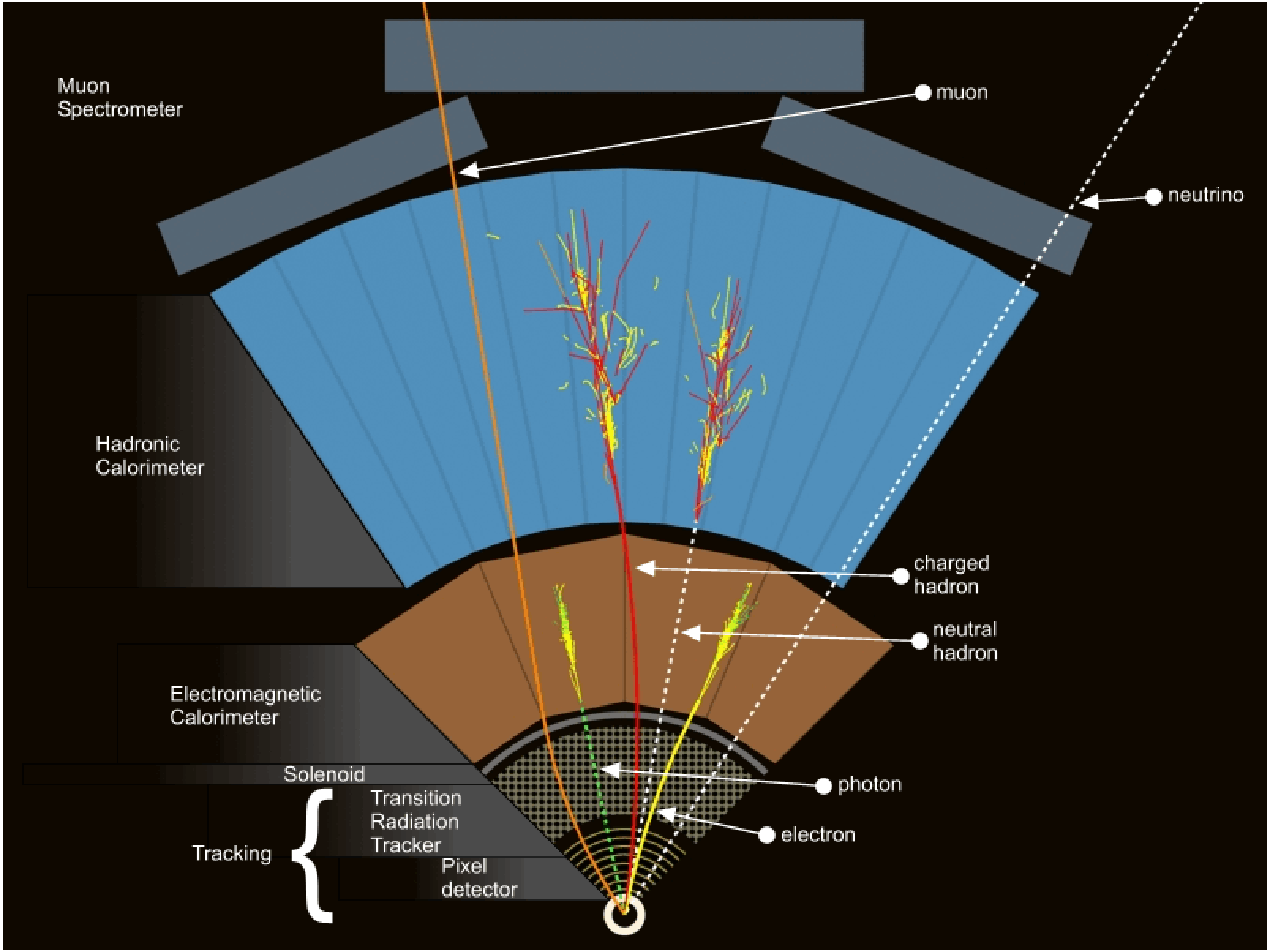
The CMS detector



The ATLAS detector



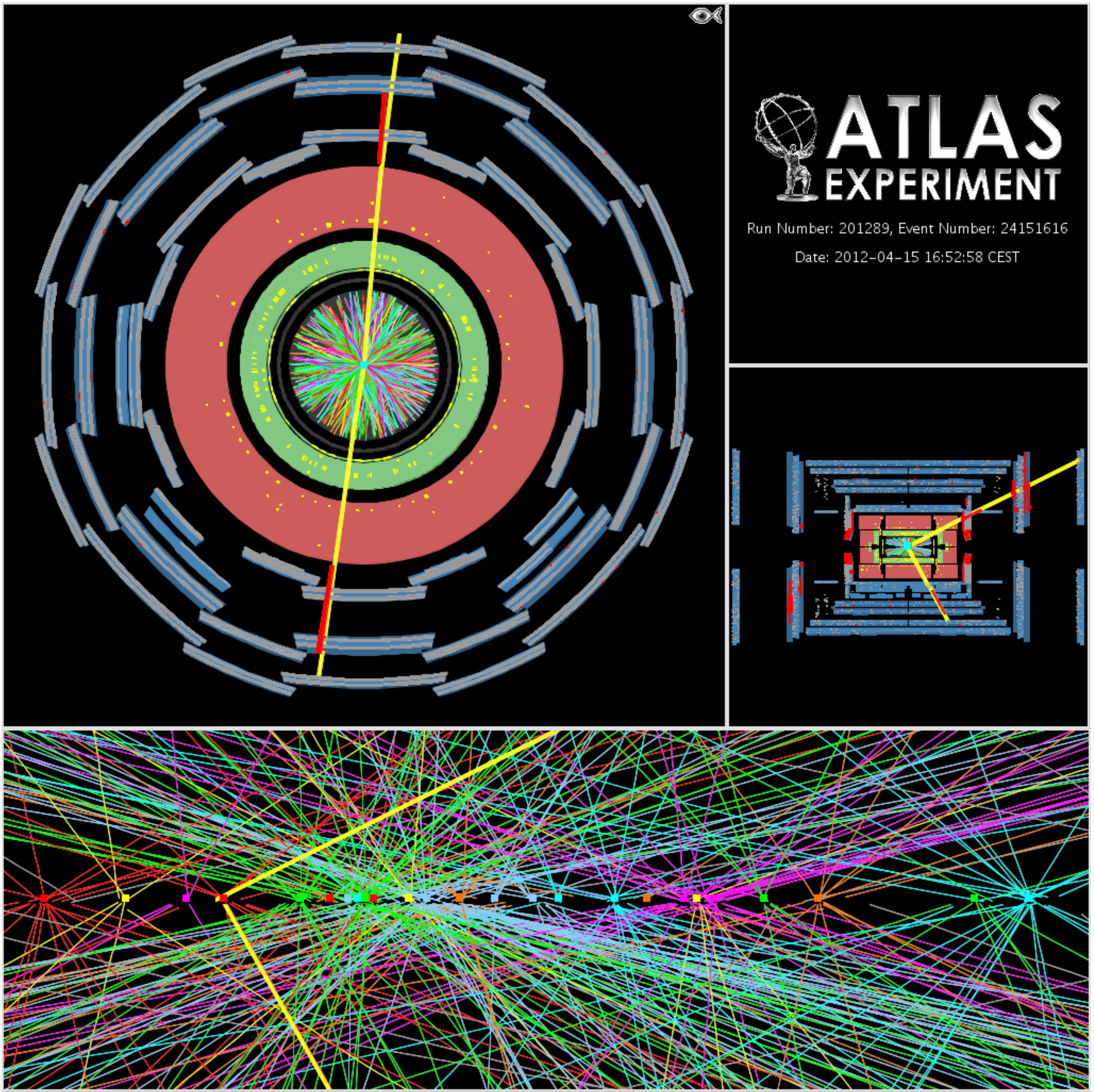
Different elements of the detector help to distinguish particles that are produced in the collision.



A challenging environment for analysis

A candidate Z boson event in the dimuon decay with 25 reconstructed vertices.

This event was recorded by the ATLAS collaboration on April 15th 2012 and demonstrates the high pileup environment in 2012 running. For this display the track p_T threshold is 0.4 GeV and all tracks are required to have at least 3 Pixel and 6 SCT hits. The vertices shown are reconstructed using tracks with p_T greater than 0.4 GeV, but with tighter requirements on the number of hits on the tracks than in the 2011 reconstruction.



The LHC Discovery of 4 July 2012

The CERN update of the search for the Higgs boson, simulcast at ICHEP-2012 in Melbourne, Australia

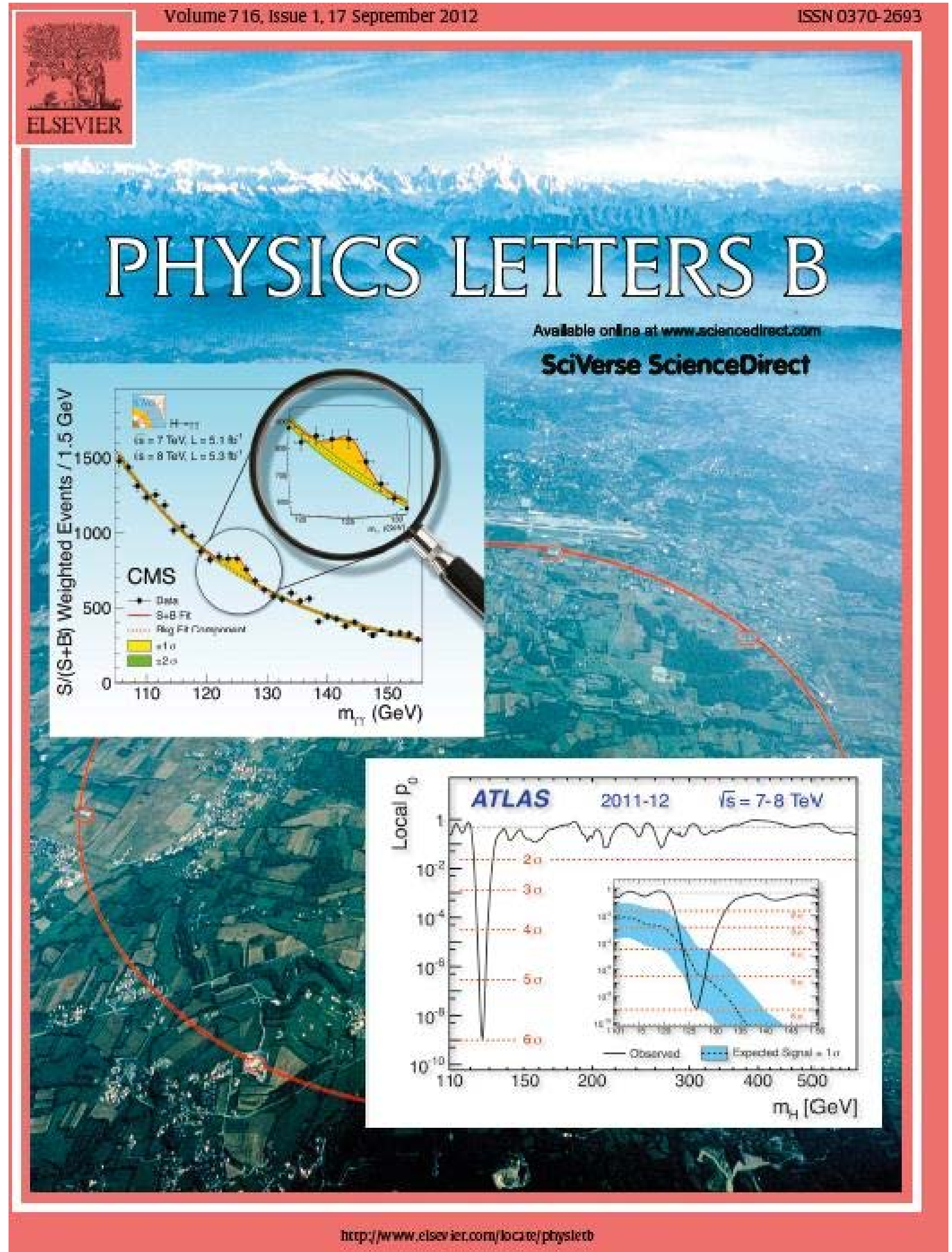
The discovery of the new boson is published in Physics Letters B.

ATLAS Collaboration:

Physics Letters B716 (2012) 1—29

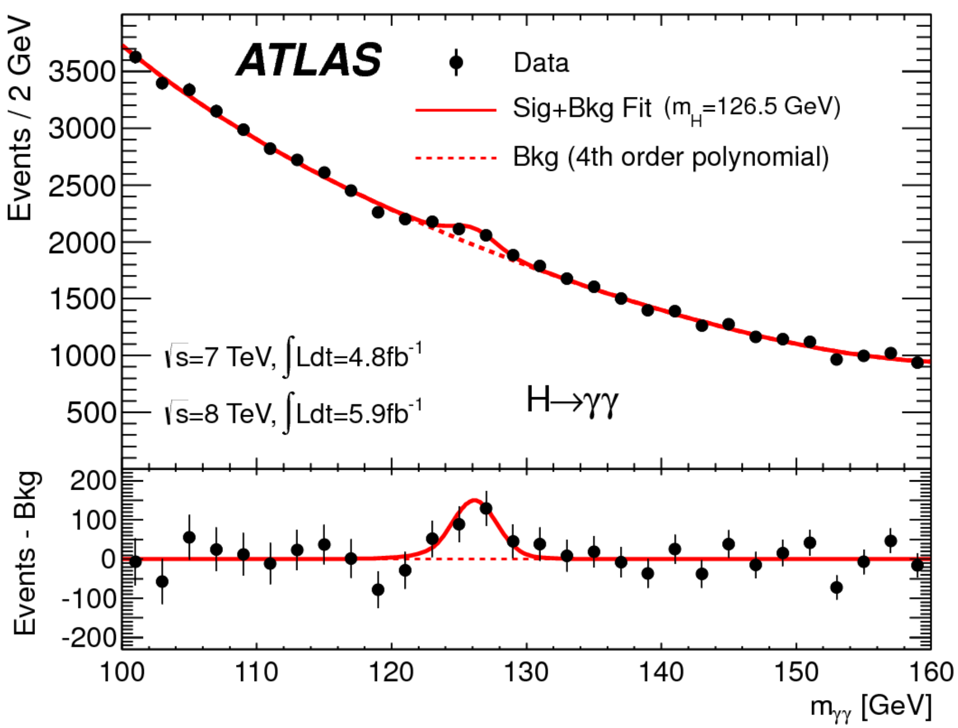
CMS Collaboration:

Physics Letters B716 (2012) 30—61

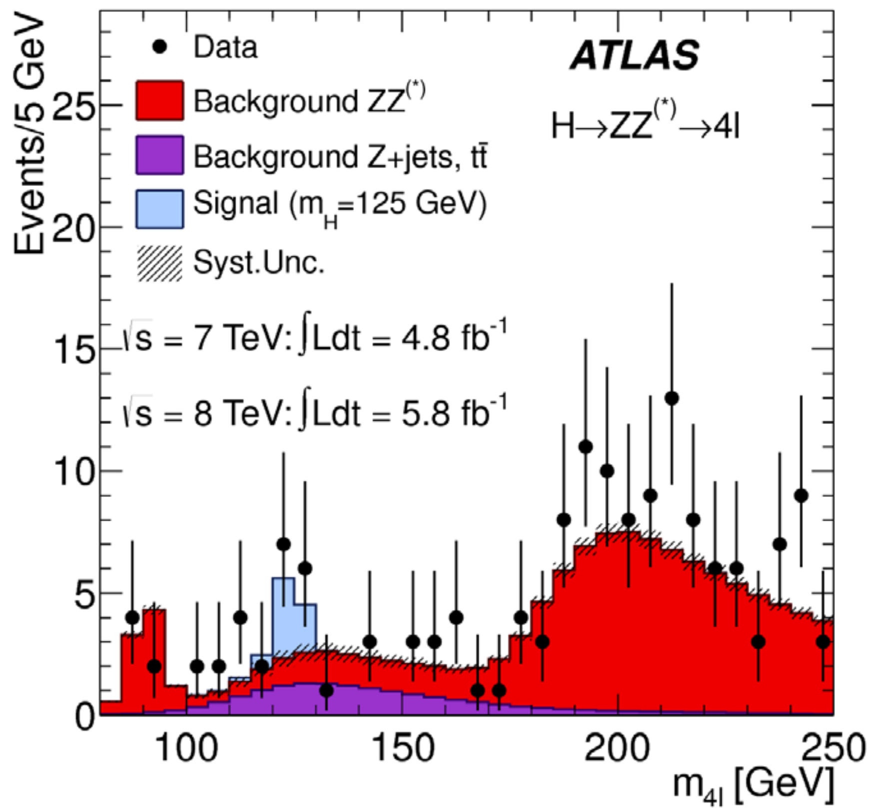



REACTIONS TO THE LATEST HIGGS BOSON ANNOUNCEMENT...
MAYBE WE WILL BEGIN TO UNDERSTAND HOW MATTER HOLDS TOGETHER!
MAYBE WE CAN DEVELOP A NEW GENERATION OF WEAPONS!
GOSH, I WONDER WHAT KIM KARDASHIAN IS DOING RIGHT NOW.
SCIENTISTS
MILITARY
THE PUBLIC

A boson is discovered at the LHC by the ATLAS Collaboration



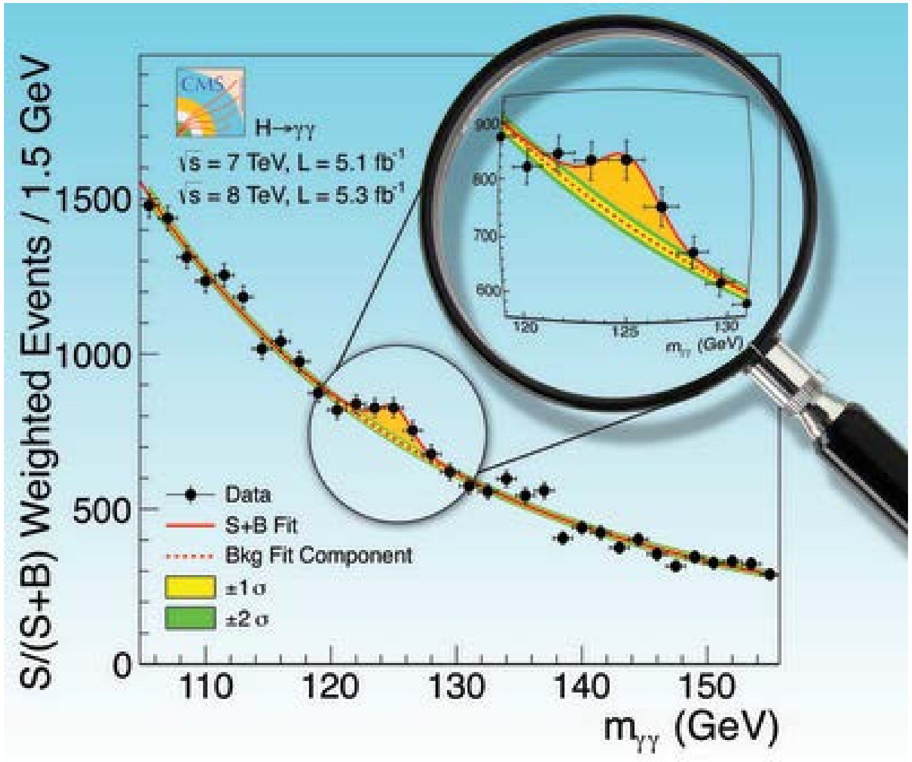
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component.



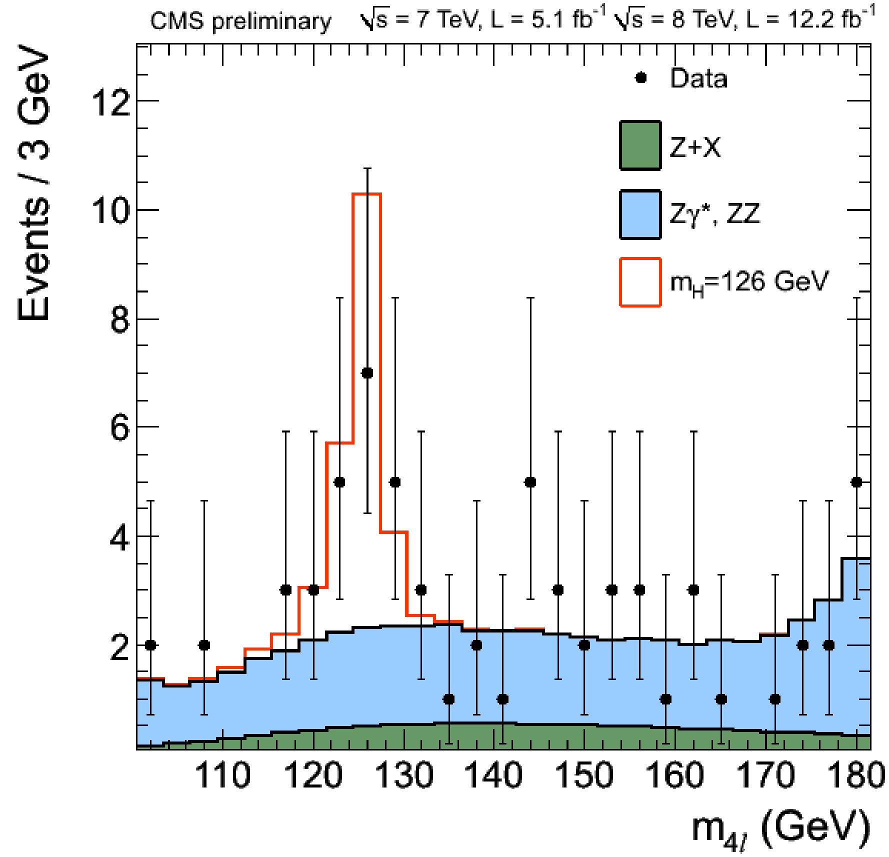
The distribution of the four-lepton invariant mass, m_{4l}, for the selected candidates, compared to the background expectation in the 80 to 250 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with m_H=125 GeV is also shown.

(Taken from Physics Letters B716 (2012) 1-29.)

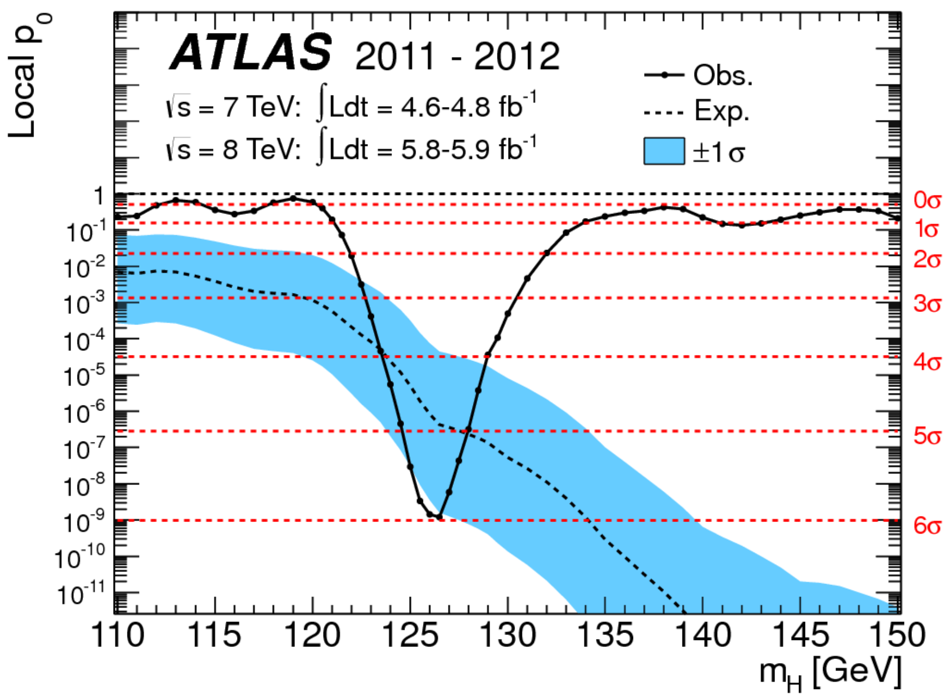
A boson is discovered at the LHC by the CMS Collaboration



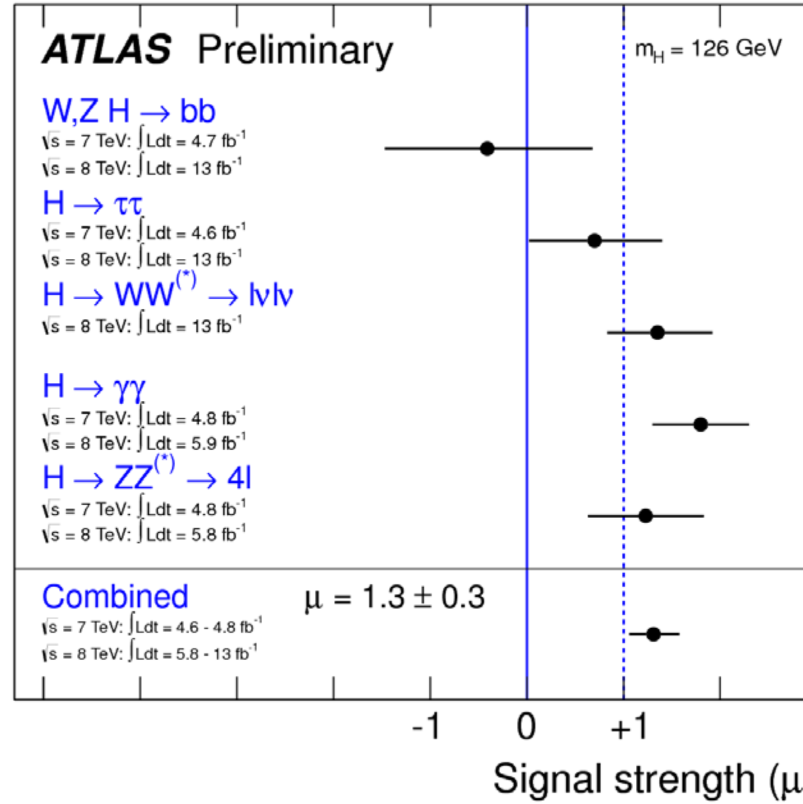
The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution. Taken from Physics Letters **B716** (2012) 30—61.



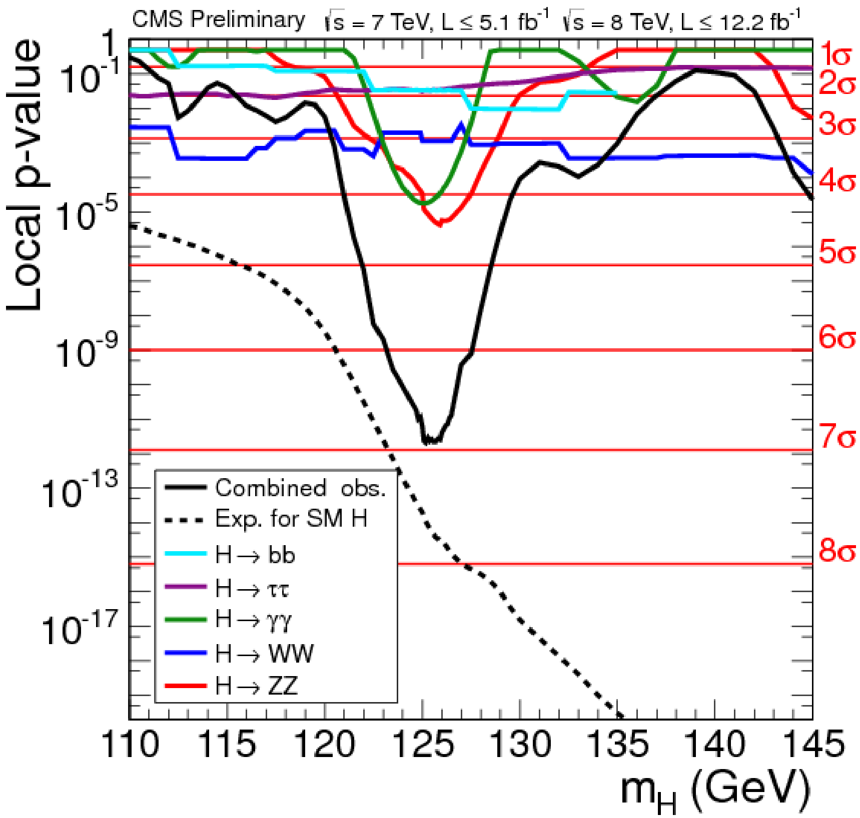
Distribution of the four-lepton invariant mass for the ZZ→4 leptons analysis. The points represent the data, the filled histograms represent the background, and the open histogram shows the signal expectation for a Higgs boson of mass m_H = 126 GeV, added to the background expectation. Taken from https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12041TWiki.

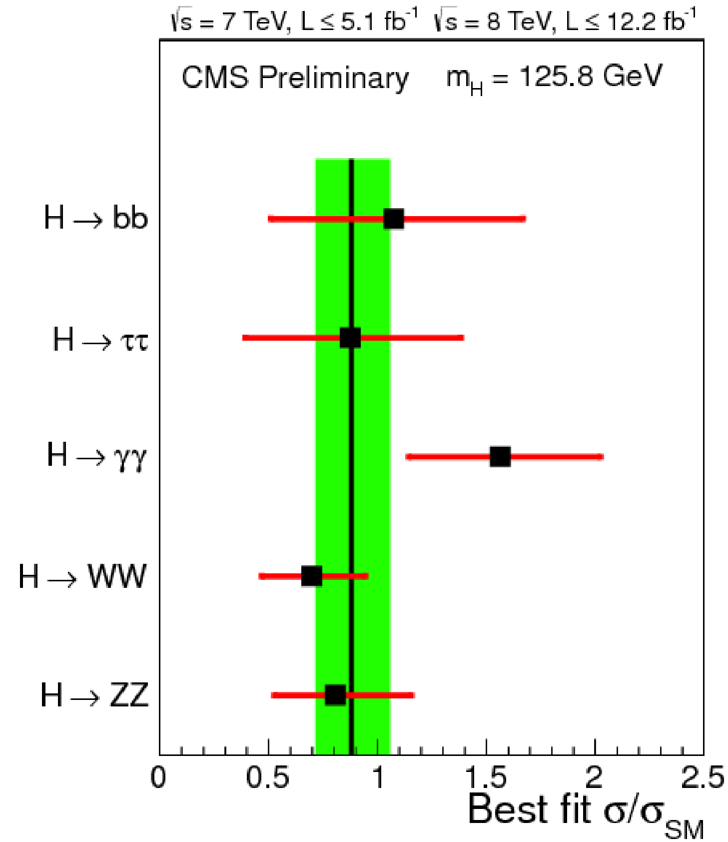


The local probability p_0 for a background-only experiment to be more signal-like than the observation in in the low mass range of this analysis as a function of m_H. The dashed curves show the median expected local p_0 under the hypothesis of a Standard Model Higgs boson production signal at that mass. The horizontal dashed lines indicate the p-values corresponding to significances of 1σ to 6σ. (Taken from Physics Letters B716 (2012) 1-29.)



Summary of the individual and combined best-fit values of the strength parameter for a Higgs boson mass hypothesis of 126 GeV. (Taken from ATLAS-CONF-2012-162, 13 November 2012.)



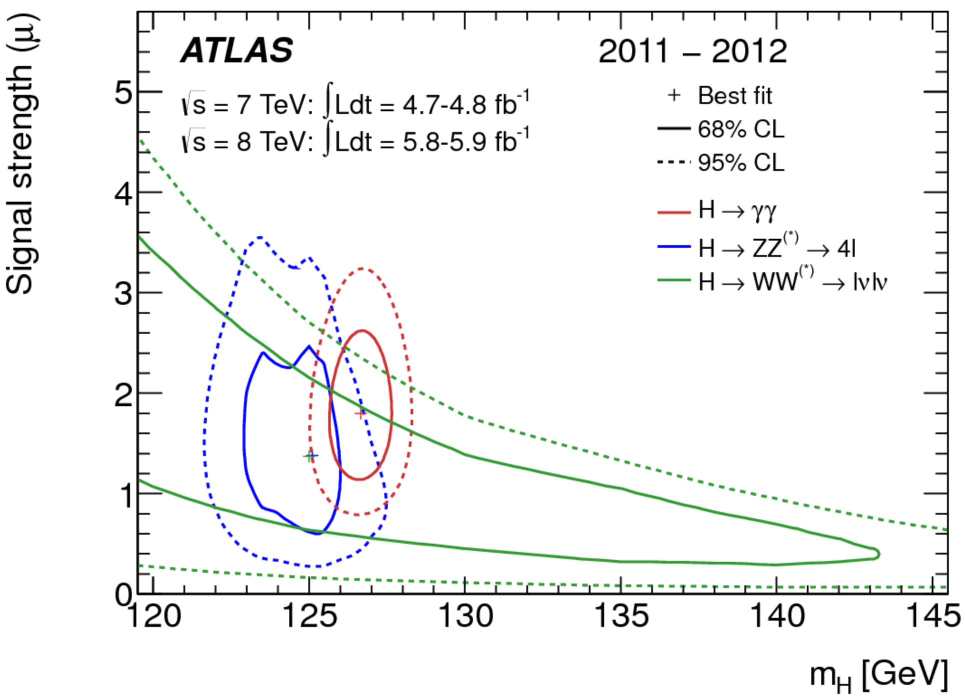


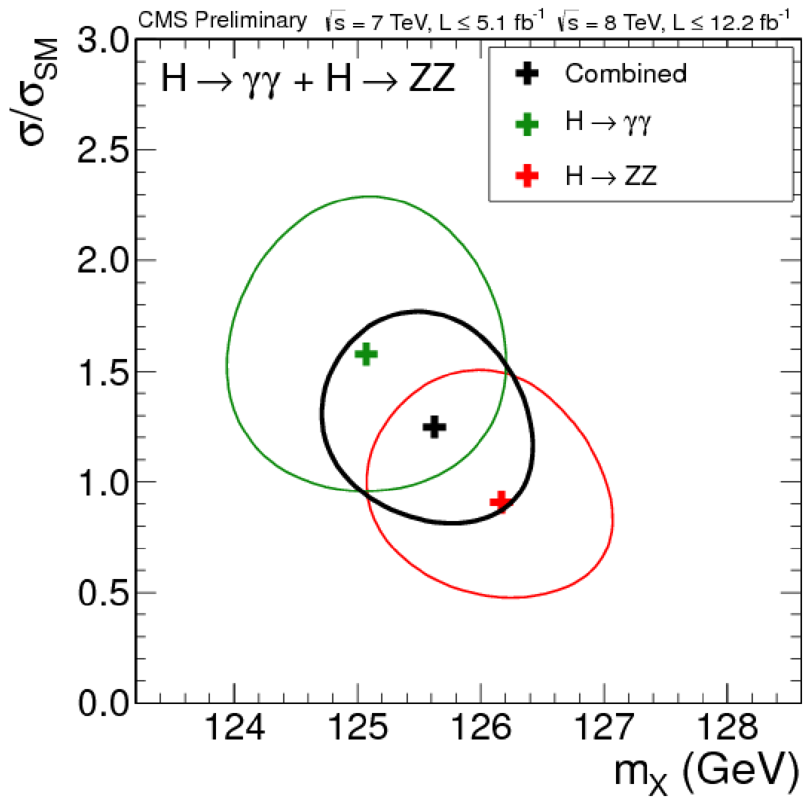
The observed local *p*-value p_0 for five subcombinations by decay mode and the overall combination as a function of the SM Higgs boson mass. The dashed lines show the expected local *p*-value $p_0(m_H)$, should a Higgs boson with a mass m_H exist.

Values of $\hat{\mu} = \sigma/\sigma_{SM}$ for the combination (solid vertical line) and for sub-combinations grouped by decay mode (points). The vertical band shows the overall $\hat{\mu}$ value 0.80 ± 0.22. The horizontal bars indicate the ±1σ uncertainties on the $\hat{\mu}$ values for individual channels; they include both statistical and systematic uncertainties.

Taken from https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12045TWiki

ATLAS and CMS mass determinations of the newly discovered boson

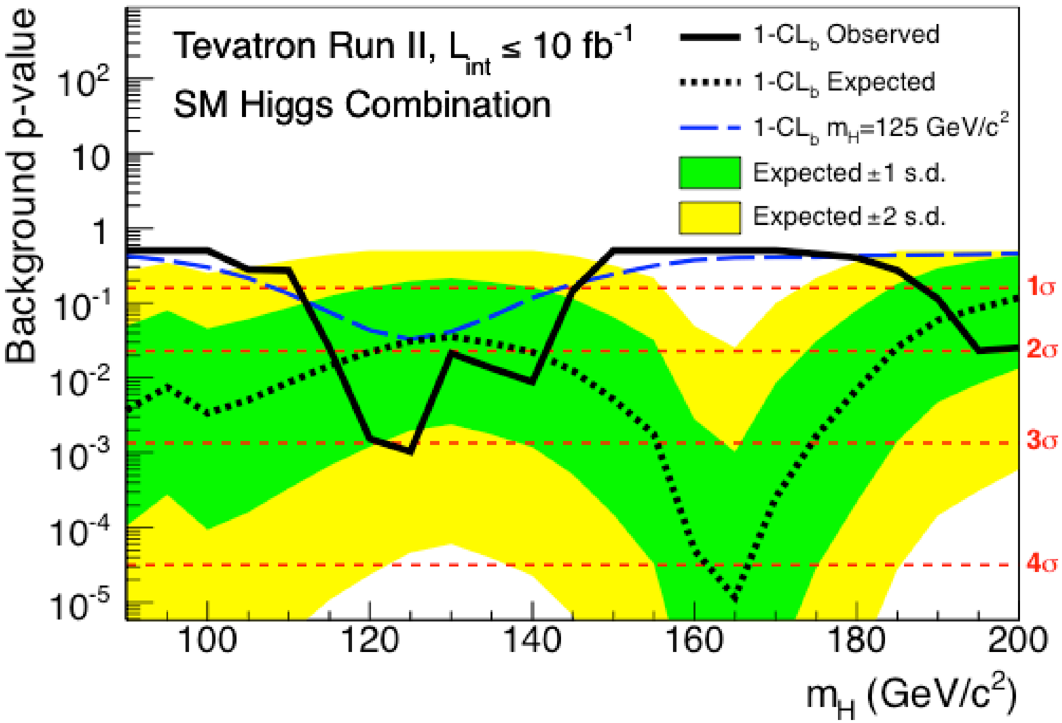




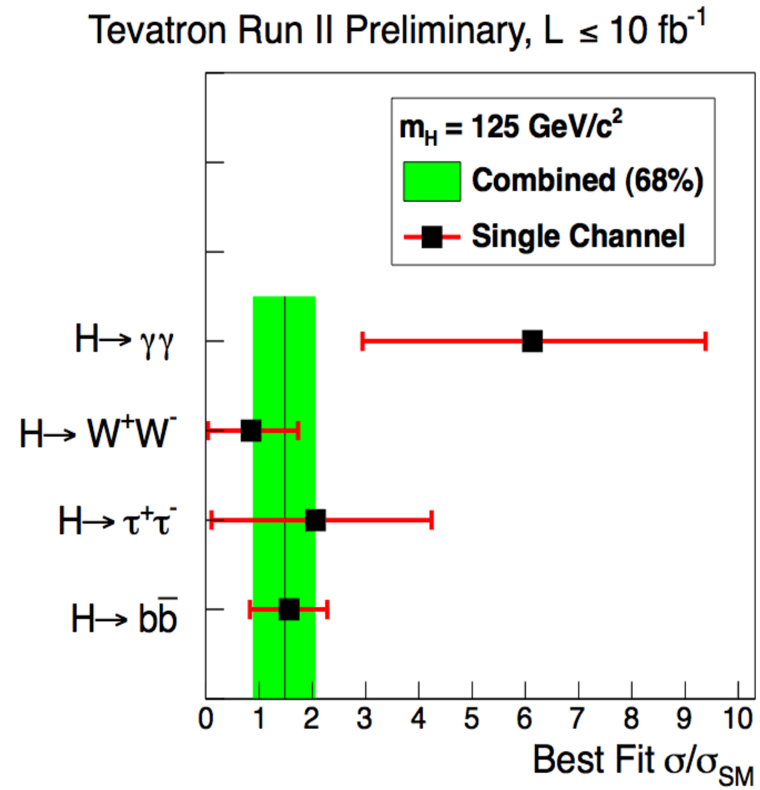
m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

m_H = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV

For m_h=125 GeV, Higgs bosons at the Tevatron decay primarily into bb.



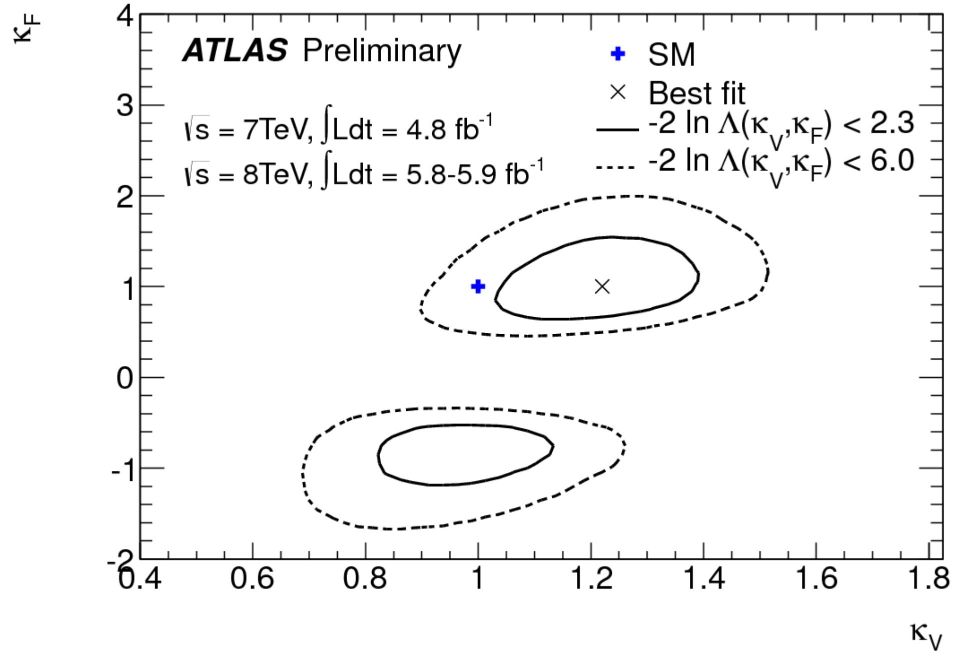
The local p-value distribution for background-only hypothesis, for the combination of the CDF and D0 analyses. The green and yellow bands correspond to the regions enclosing 1 σ and 2σ fluctuations around the median predicted value in the background-only hypothesis, respectively.



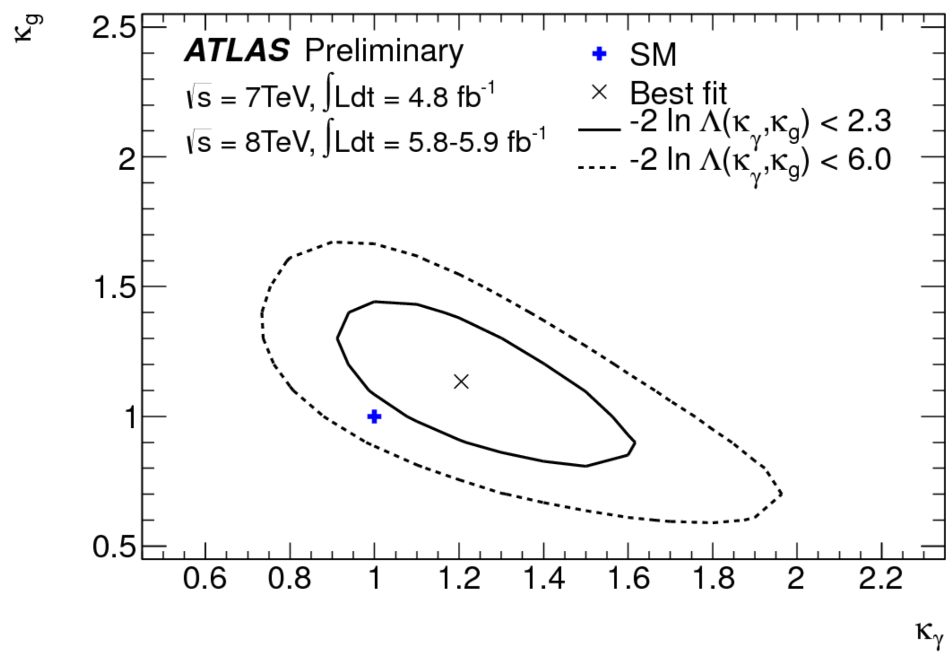
Best fit signal strength for a hypothesized Higgs boson mass of 125 GeV for the combination (black line) and for the three sub-combinations. The band corresponds to the ± 1σ uncertainties on the full combination.

Reference: Aurelio Juste, presentation at the HCP Symposium in Kyoto, Japan, November 15, 2012.

How well does ATLAS Higgs data fit the Standard Model expectations for Higgs couplings?



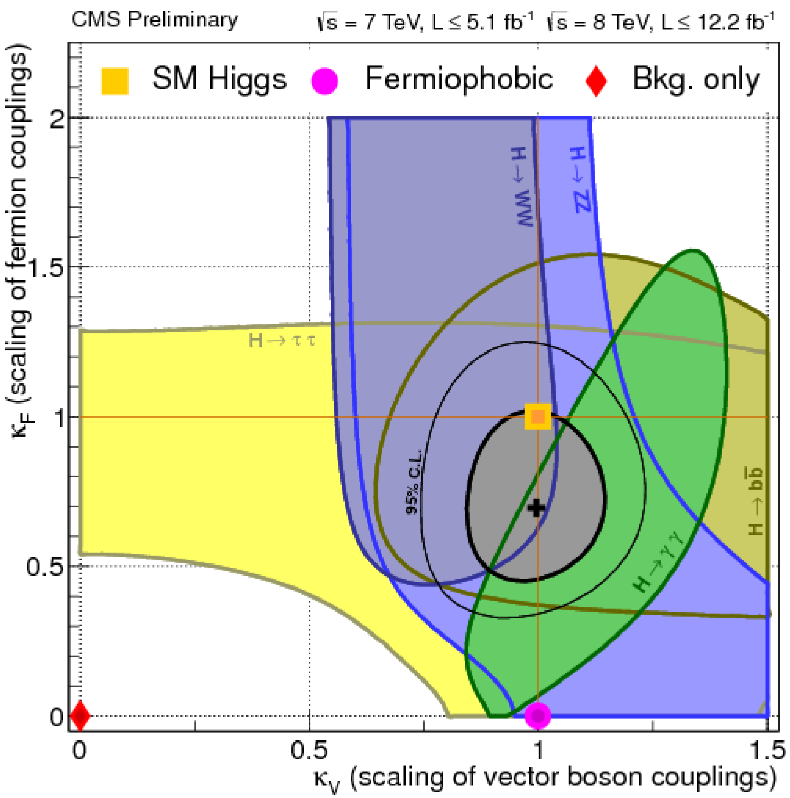
Top figure: Fits for 2-parameter benchmark models probing different Higgs coupling strength scale factors for fermions and vector bosons, under the assumption that there is a single coupling for all fermions t, b, τ (κ_F) and a single coupling for vector bosons (κ_V).



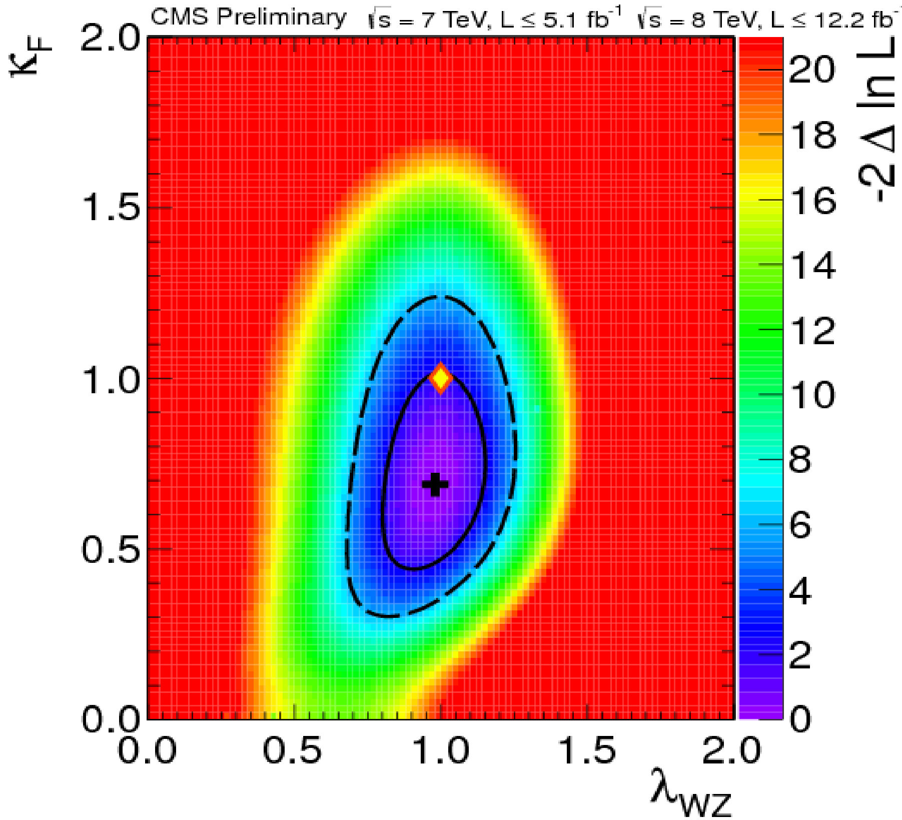
Bottom figure: Fits for benchmark models probing for contributions from non-Standard Model particles: probing only the gg → H and H→ γγ loops, assuming no sizable extra contribution to the total width. The magnitudes of the ggH and γγH couplings relative to their Standard Model values are denoted by κ_g and κ_γ.

Reference:
ATLAS-CONF-2012-127 (September 9, 2012)

How well does CMS Higgs data fit the Standard Model expectations for Higgs couplings?



Tests of fermion and vector boson couplings of the Higgs boson. The Standard Model (SM) expectation is $(\kappa_V, \kappa_F)=(1,1)$.



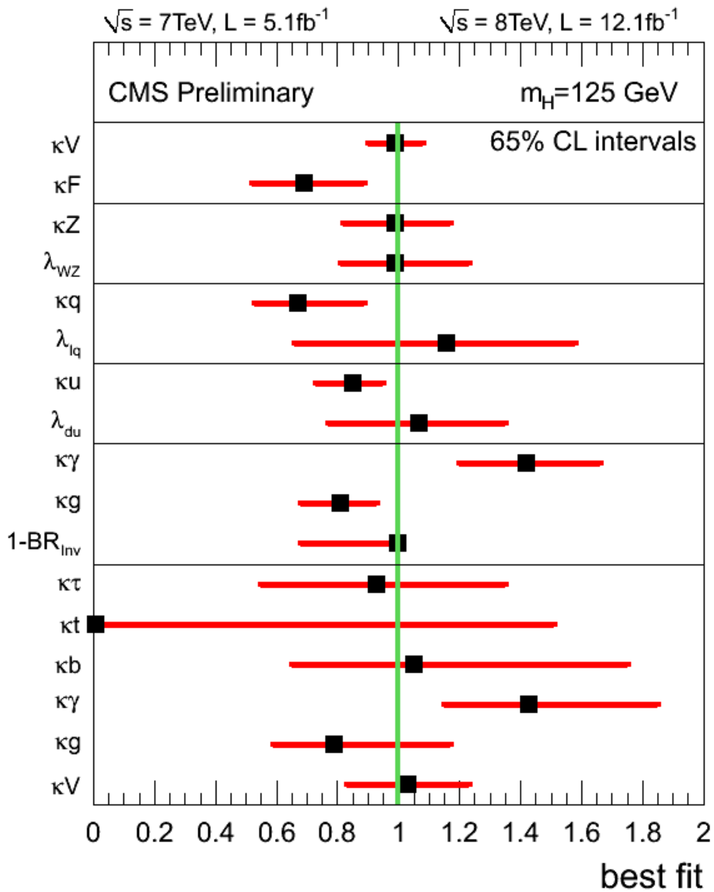
Test of custodial symmetry: the Standard Model expectation is $\lambda_{WZ} = \kappa_W / \kappa_Z = 1$.

Taken from: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12045TWiki

CMS Higgs couplings summary

- Overall good compatibility with SM predictions
- Still limited precision

Marco Zanetti, presentation at HCP 2012, Kyoto



Model parameters	Assessed scaling factors (95% CL intervals)	
λ_{WZ}, κ_Z	λ_{WZ}	[0.57–1.65]
$\lambda_{WZ}, \kappa_Z, \kappa_f$	λ_{WZ}	[0.67–1.55]
κ_V	κ_V	[0.78–1.19]
κ_f	κ_f	[0.40–1.12]
κ_γ, κ_g	κ_γ	[0.98–1.92]
	κ_g	[0.55–1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00–0.62]
$\lambda_{du}, \kappa_V, \kappa_u$	λ_{du}	[0.45–1.66]
$\lambda_{\ell q}, \kappa_V, \kappa_q$	$\lambda_{\ell q}$	[0.00–2.11]
$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_V	[0.58–1.41]
	κ_b	[not constrained]
	κ_τ	[0.00–1.80]
	κ_t	[not constrained]
	κ_g	[0.43–1.92]
	κ_γ	[0.81–2.27]

Coming Attractions

The reported data seems roughly consistent with Standard Model expectations. Nevertheless, there are a few intriguing (statistically insignificant) deviations:

- The $h \to \gamma\gamma$ signal appears to be enhanced beyond the Standard Model predictions by about 50%. This enhancement is seen by both ATLAS and CMS.

- A hint of a mass difference between the observed Higgs signals in the $\gamma\gamma$ and $ZZ^* \to 4$ lepton channels.

If these anomalies persist and become statistically significant, then it could portend the existence of new fundamental physics beyond the Standard Model!!

More information will be forthcoming from the LHC experiments when the full 2012 data set is reported at the March 2013 Winter conferences .

More Higgs data is on its way….

- The current data set includes 5 fb^{-1} at 7 TeV and 13 fb^{-1} at 8 TeV. (The latter includes an additional 7 fb^{-1} of data that was reported two weeks ago at the HCP Symposium in Kyoto, although only some analyses were updated based on the new data.)

- A further update of the Higgs data and analysis will be presented at the next CERN council meeting (12—14 December 2012). [ATLAS: "major updates" expected]

- At the Moriond Meeting (4—8 March 2013), an additional 10 fb^{-1} of data at 8 TeV will be presented, and all Higgs analyses will be updated.

The new data will provide improved analyses, updated coupling measurements, and first results on the spin and parity determinations (a Higgs boson of the Standard Model must be spin 0 and parity even).

- At the international Lepton-Photon conference in San Francisco (24—29 June 2013), one expects a statistical combination of the full 2011—2012 ATLAS and CMS data sets (corresponding to an effective total luminosity of 60 fb^{-1}).

Looking beyond 2012

- LHC shuts down in 2013—2014 to make repairs and improvements, and to upgrade the energy to the full design energy of 14 TeV.

- LHC resume running in 2015 at the full energy and an increased luminosity. Significant measurements of the Higgs boson properties, are anticipated.

- Meanwhile, serious discussions concerning a Higgs factory based on a high energy e^+e^- collider (called the International Linear Collider or ILC for short) may lead to a project in Japan. At such a facility, precision measurements of Higgs boson properties are possible (improving the precision of LHC measurements in some cases by an order of magnitude).

- Future directions for US high energy physics are now under discussion, with a critical planning meeting scheduled for the summer of 2013.

New physics beyond the Standard Model

- The dynamics responsible for breaking the electroweak gauge symmetry may be something other than the simplest Higgs model
  - more than one Higgs boson (some neutral and some charged)
  - composite Higgs bosons (bound states of new particles)
  - dynamical electroweak symmetry breaking (modeled after Cooper pair condensation in a superconductor)

- New symmetries beyond the Standard Model
  - new gauge forces
  - supersymmetry

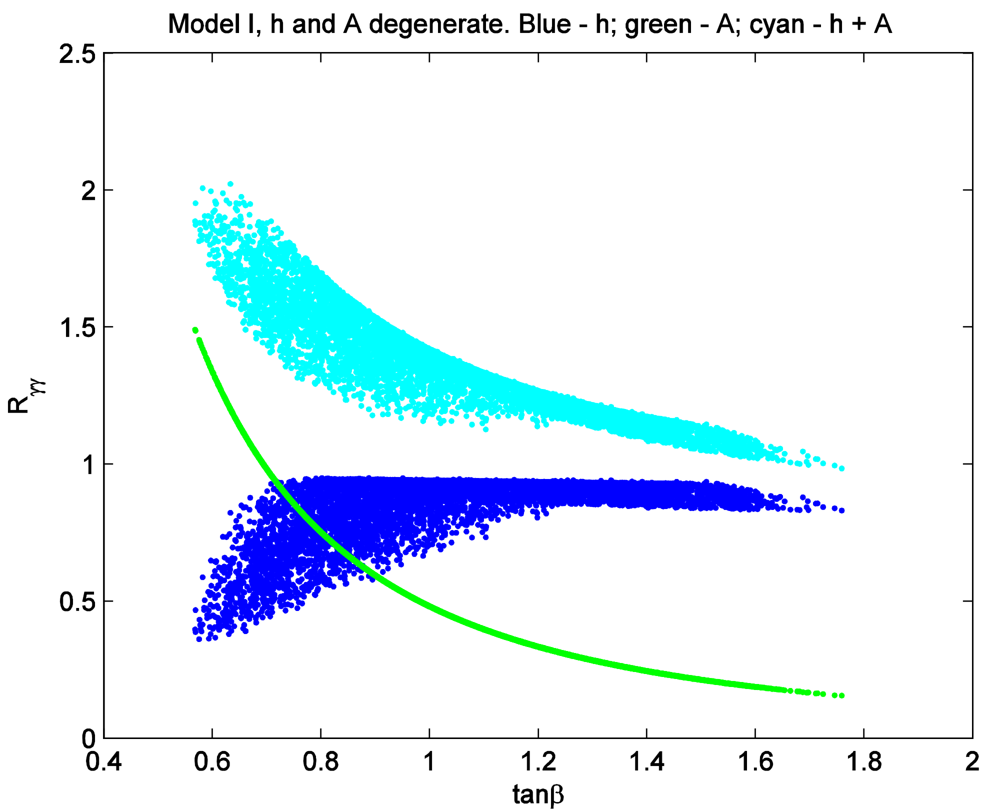
- Extra dimensions of space (beyond the 3 we know and love)

- Unexpected effects of gravity at the TeV energy scale

Beware of theorists who take statistically insignificant deviations too seriously

Is there a simple model of Higgs physics that can lead to enhanced $\gamma\gamma$ signal and a a difference in masses as measured via the $\gamma\gamma$ and $ZZ^* \to 4$ lepton channels?

In a two Higgs doublet model, suppose there are two neutral scalars that are nearly degenerate in mass. If one has approximately SM-like couplings to ZZ, then the other will be nearly decoupled from the ZZ channel. Yet, both scalars can be produced in gluon-gluon fusion, and both scalars can decay to $\gamma\gamma$.



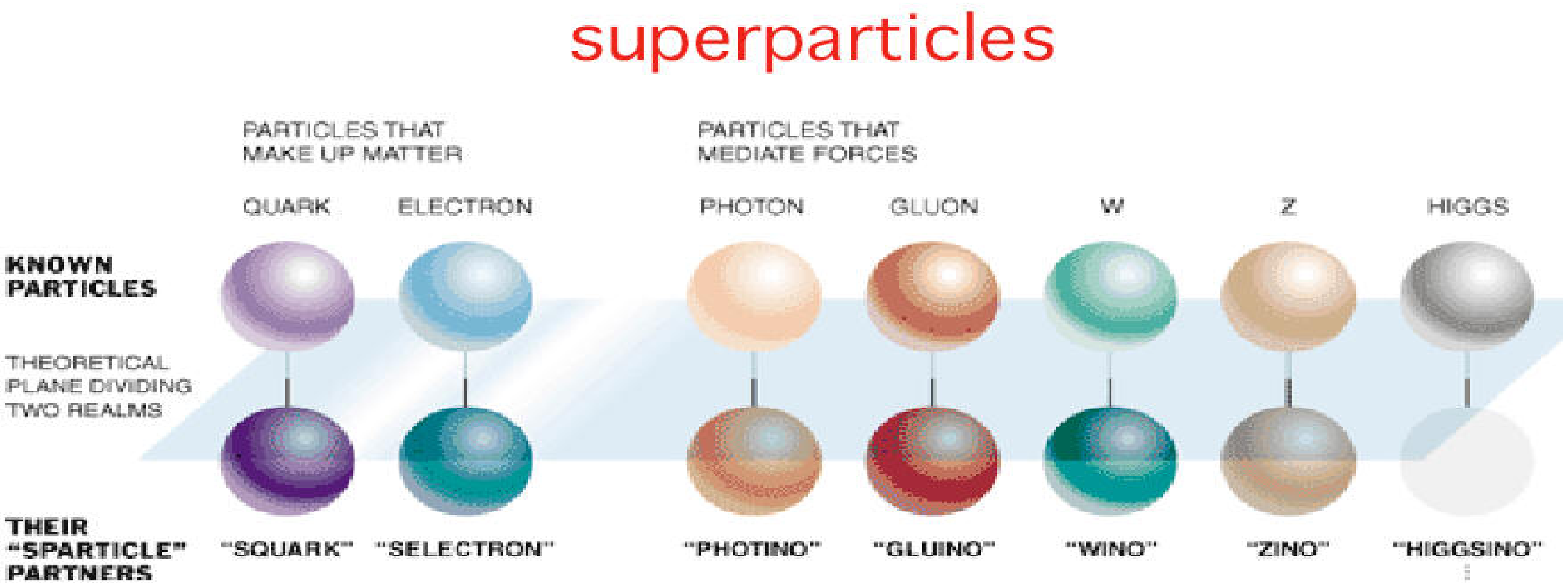
Result: Some regions of the parameter space yield an enhanced $\gamma\gamma$ signal and different Higgs mass measurements in the $\gamma\gamma$ and $ZZ^* \to 4$ lepton channels.

Prediction: an enhanced $\tau\tau$ signal.

Reference: P.M. Ferreira, Howard E. Haber, João P. Silva and Rui Santos, arXiv:1211.3131

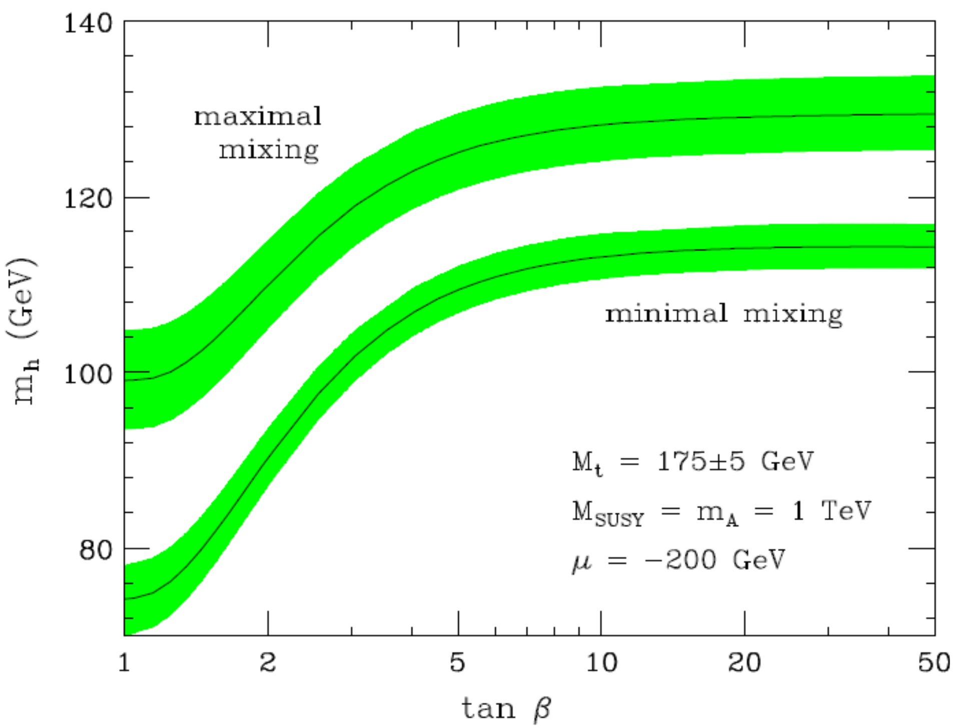
Supersymmetry

- A new kind of symmetry that relates fermions and bosons---all particles have a supersymmetric partner differing by half a unit of spin
- For **every** elementary particle already seen, **a new one** will show up at the LHC
- The lightest supersymmetric particle could be **dark matter**
- **Comes with at least 5 Higgs bosons (three neutral and a charged pair)**



In the minimal supersymmetric extension of the Standard Model (MSSM), the Higgs boson self-couplings are not free parameters but are related to the known gauge couplings. This led to the initial prediction of model, $m_H \leq m_Z$, in conflict with experimental observation.

In 1991, H.E. Haber and R. Hempfling discovered that the Higgs mass bound was significantly increased by including quantum corrections. In the years following more precise calculations were done, which raised the upper bound to about 135 GeV (assuming $M_{\rm SUSY} \lesssim 2\ {\rm TeV}$).



Taken from M. Carena and H.E. Haber, "Higgs boson theory and phenomenology,'' Prog. Part. Nucl. Phys. **50**, 63 (2003)

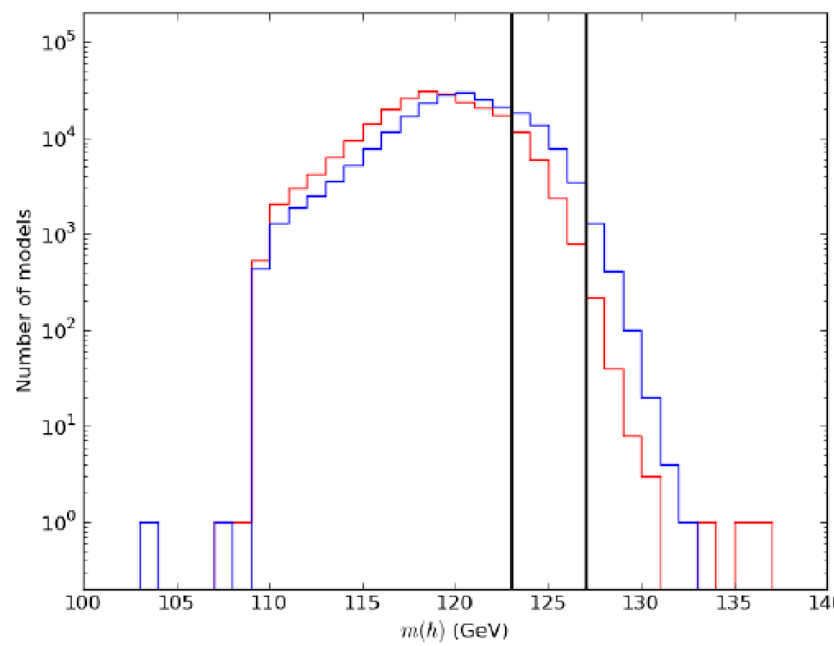


Figure 1: Distribution of the lightest CP-even Higgs mass for the neutralino (blue) and gravitino (red) LSP pMSSM model sets, highlighting the $m_h = 125 \pm 2$ GeV region.

Taken from M.W. Cahill-Rowley, J.L. Hewett, A. Ismail and T.G. Rizzo, "The Higgs Sector and Fine-Tuning in the pMSSM," Phys. Rev. **D86**, 075015 (2012)

Conclusions

• The discovery of the Higgs boson provides a profound confirmation of our theoretical understanding of mass.

• We are in the early stages of the discovery. It will be important to confirm that the newly discovered boson has spin 0.

• Have we discovered the Higgs boson of the Standard Model? One must check that the properties of the newly discovered boson are consistent with the predictions of the Standard Model.

• If deviations from Standard Model properties were to be confirmed, then the fun really begins!!

• Fundamental physics does not end with the Higgs boson. The LHC may be on the brink of even greater discoveries…