Homing in on the Higgs Boson

Howard E. Haber

SPS Meeting at UCSC

June 7, 2012

References:

H.E. Haber, *Viewpoint: Homing in on the Higgs Boson,* Physics 5, 32 (2012).

For additional links, see my webpage:
http://scipp.ucsc.edu/~haber/


FRONTIERS IN PHYSICS
The Higgs Hunter's Guide
John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson
The Higgs Hunter's Guide

Outline

- **The Higgs boson explained in 60 seconds**
- **The Higgs boson explained in 7 minutes and 44 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
- **Hints of the Higgs boson at the Large Hadron Collider (LHC)**
- **Coming attractions**

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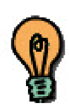

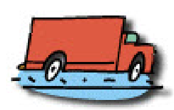

What Dr. Science stuff can I buy?

The Question of the Day: Ask Dr. Science

...He knows more than you do!

Q

If sound can't travel in a vacuum, how come vacuum cleaners make so much noise?

Submitted by Tom Leopold from Detroit, MI

A

Vacuum cleaners are, in themselves, silent. What makes the noise you find so offensive are the actual particles of dirt and pollution in the space being cleaned. If your living room were clean when you vacuumed, then your vacuum cleaner would make no noise at all. The flaw in all this, of course, is that if your living room were clean you wouldn't be vacuuming. Since there is no such thing as a perfectly clean living room in this less-than-best-of-all-possible-worlds, scientists had to prove this hypothesis by vacuuming in outer space, itself a perfect vacuum. Space is also incredibly clean. Astronauts reported that even the most powerful, poorly maintained vacuum cleaners made absolutely no noise in space. Millions of your tax dollars went toward proving this.

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Table of Contents volume 03 issue 06 august 06

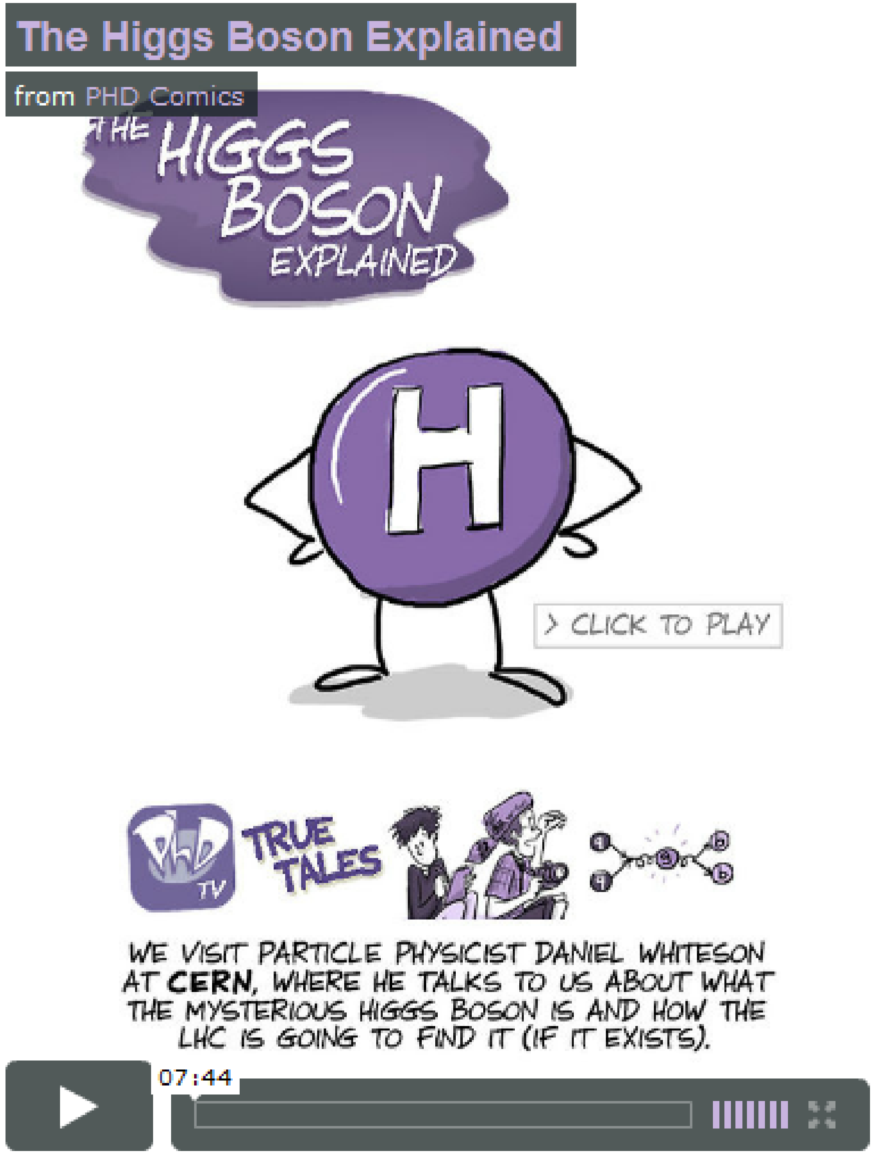
explain it in 60 seconds

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



[The Higgs Boson Explained]() from [PHD Comics]() on [Vimeo]().

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.

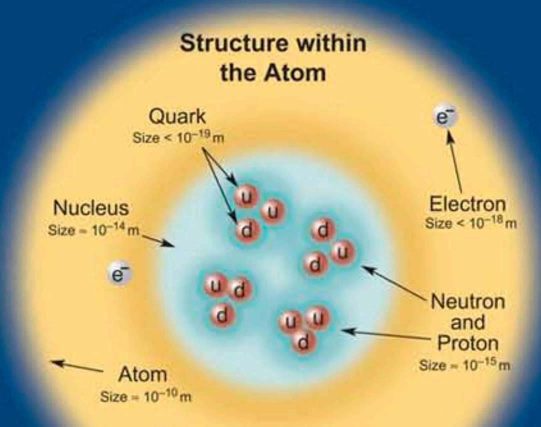
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27}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



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^- W bosons	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
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

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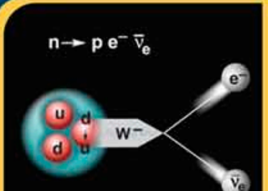
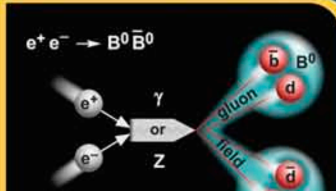
Particle Processes

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



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.



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

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matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

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W bosons		
Z^0 Z boson	91.188	0

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Something is missing…

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)

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):

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

Non-abelian (Yang-Mills) theory:

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)

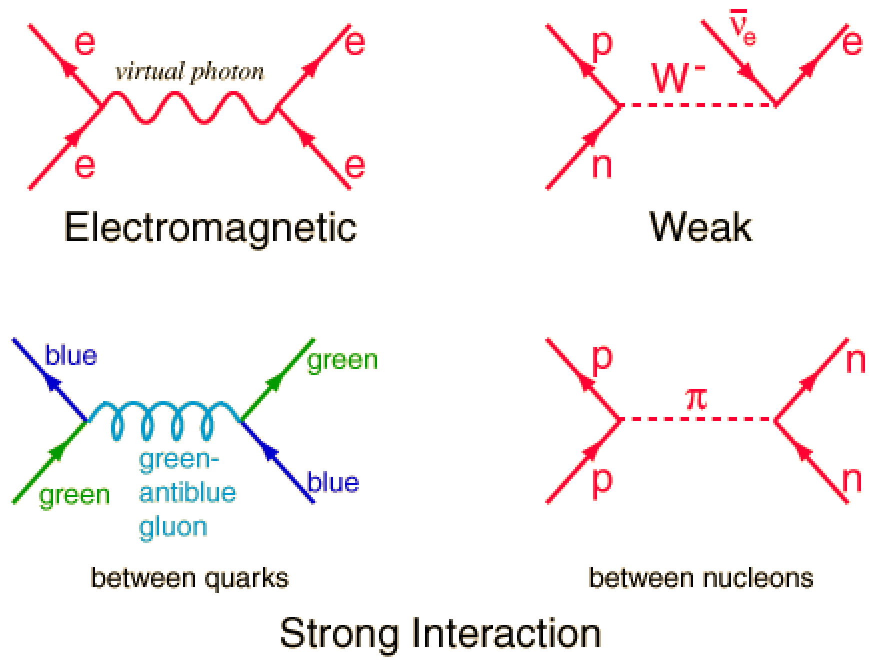
Contrast between massless and massive bosons

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

$$\frac{1}{p^2 - m^2} \quad \leftrightsquigarrow \quad V(\vec{r}) \sim \frac{e^{-mcr/\hbar}}{r}$$

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

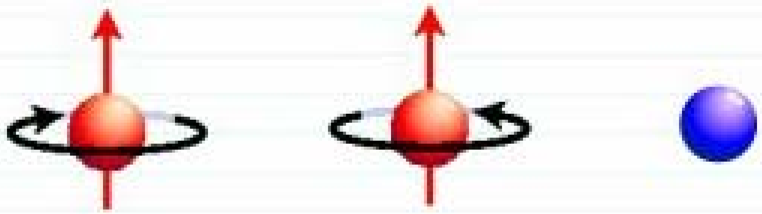
m>0: yields short-range Yukawa potential



Massless and heavy
spin 1 particles

Heavy spin 1 particles can spin in 3 directions:

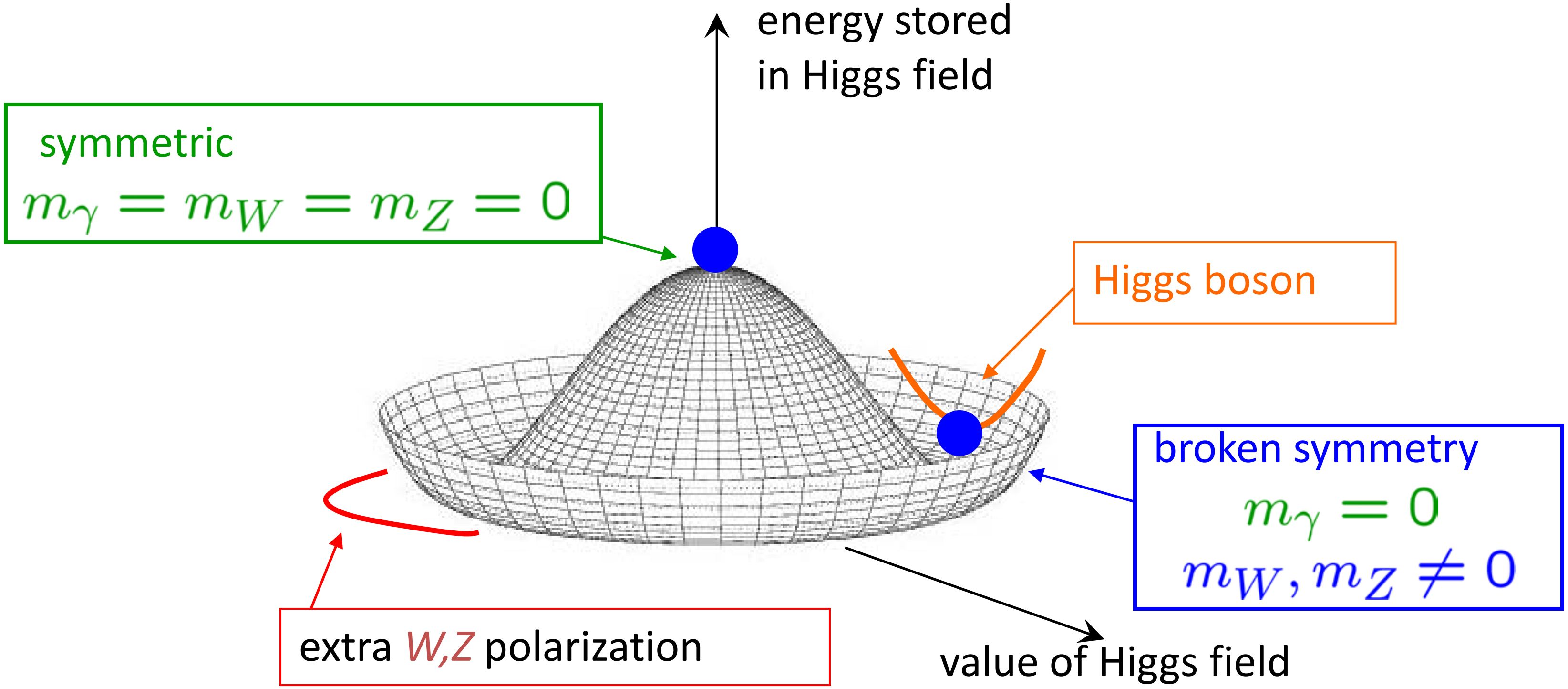
Massless particles must have their spin-axis
either parallel or anti-parallel to their direction of motion:

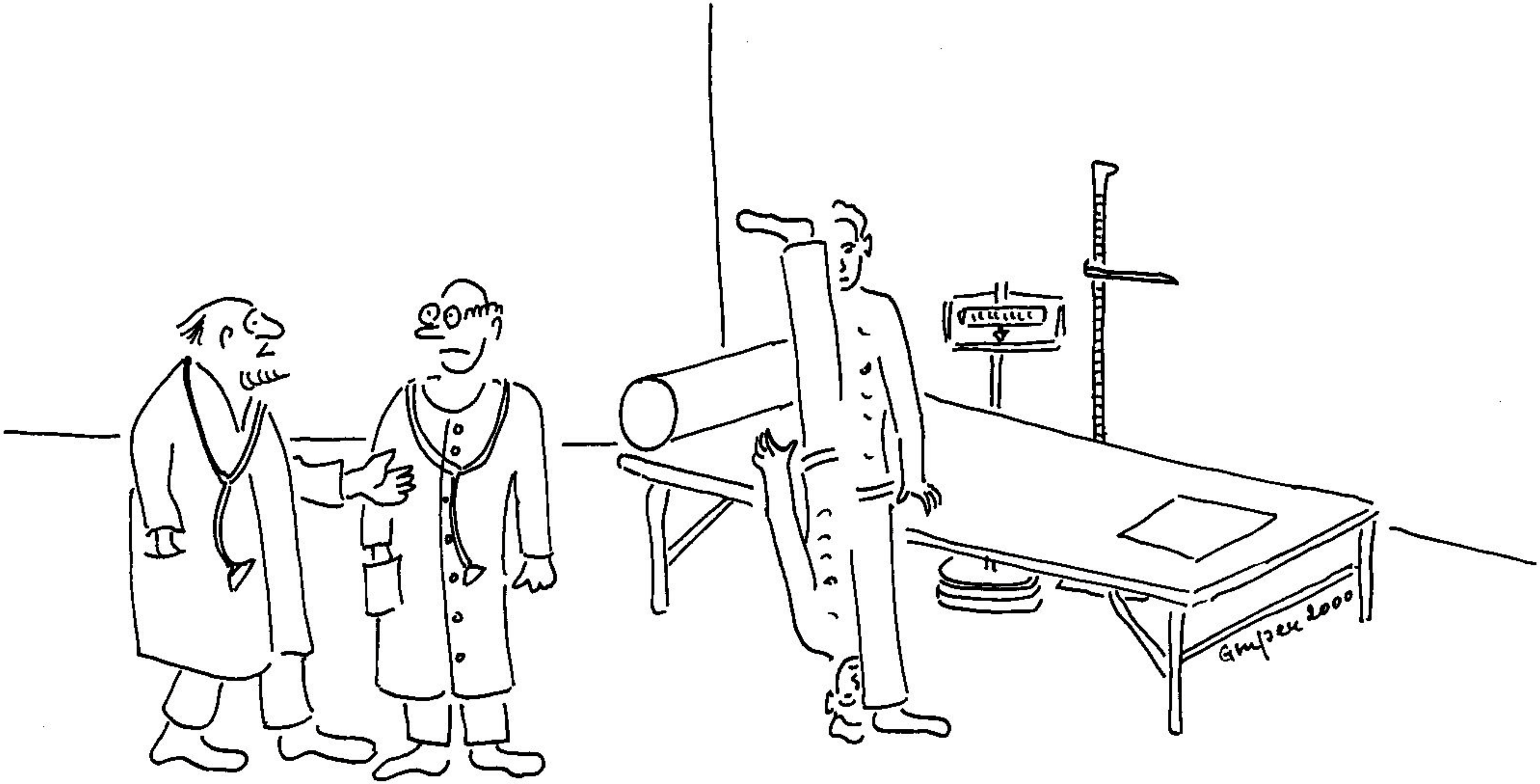


They can only spin in 2 directions.

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”.

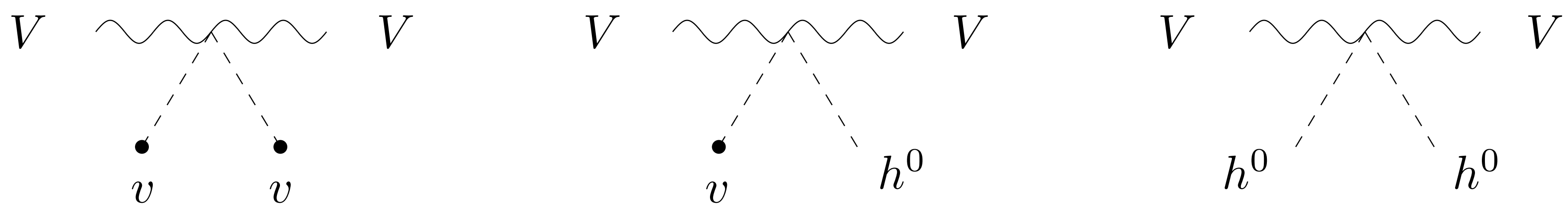




“A severe case of symmetry breaking!”

Standard Model masses and Higgs couplings

Gauge bosons ($V = W^\pm$ or Z) acquire mass via interaction with the Higgs vacuum condensate, $\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV.



Thus,

$$m_V^2 = \tfrac{1}{4} g_V^2 v^2 \,, \qquad g_{hVV} = 2m_V^2/v \,, \qquad g_{hhVV} = 2m_V^2/v^2 \,,$$

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:

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

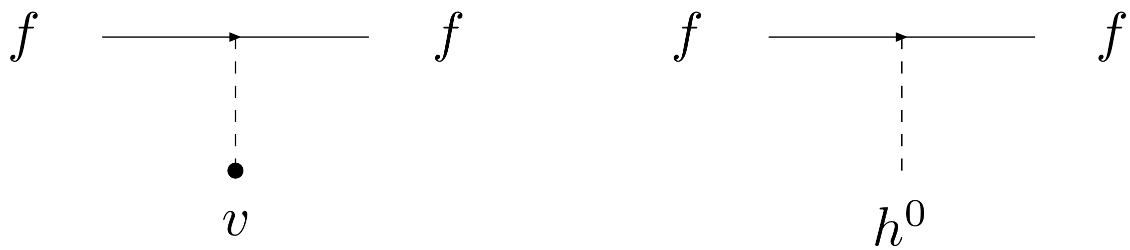
Fermions in the Standard Model

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 (or equivalently, the self-coupling parameter λ, is the only undetermined parameter.

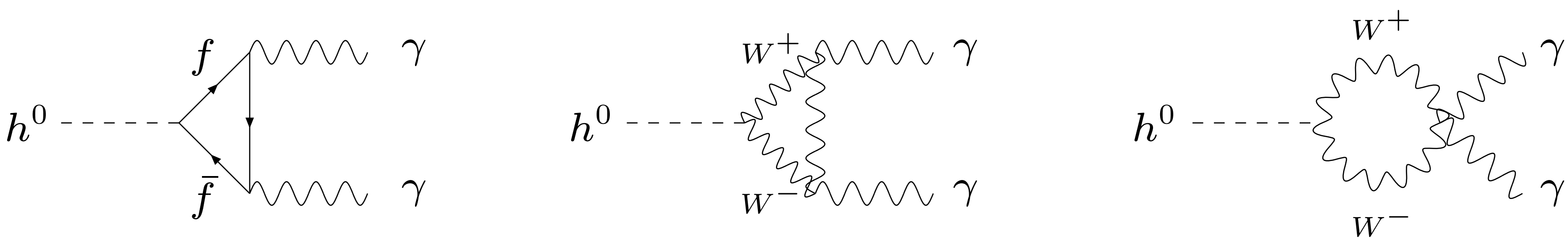
Importance of the loop-induced Higgs couplings for the LHC Higgs program

1. Dominant LHC Higgs production mechanism: gluon-gluon fusion. At leading order,

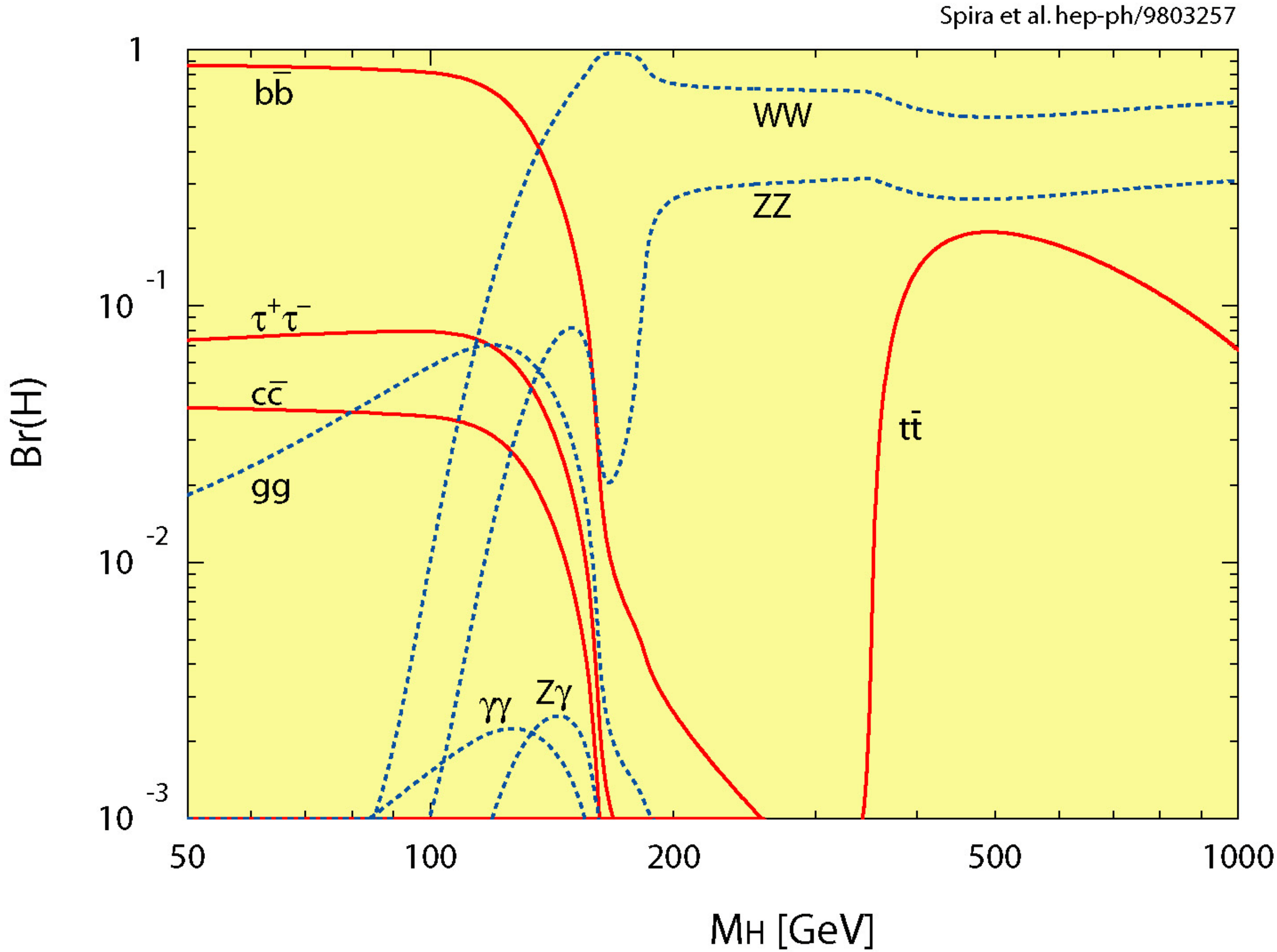
$$\frac{d\sigma}{dy}(pp \to h^0 + X) = \frac{\pi^2 \Gamma(h^0 \to gg)}{8m_h^3} g(x_+, m_h^2) g(x_-, m_h^2)\,,$$

where $g(x, Q^2)$ is the gluon distribution function at the scale Q^2 and $x_\pm \equiv m_h e^{\pm y}/\sqrt{s}$, $y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$.

2. For $m_h \simeq 125$ GeV, the main discovery channel for the Higgs boson at the LHC is via the rare decay $h^0 \to \gamma\gamma$. The Higgs boson couples to photons via a loop of charged particles:



Probability of various Higgs boson decays



Present Status of the Higgs boson—Part I

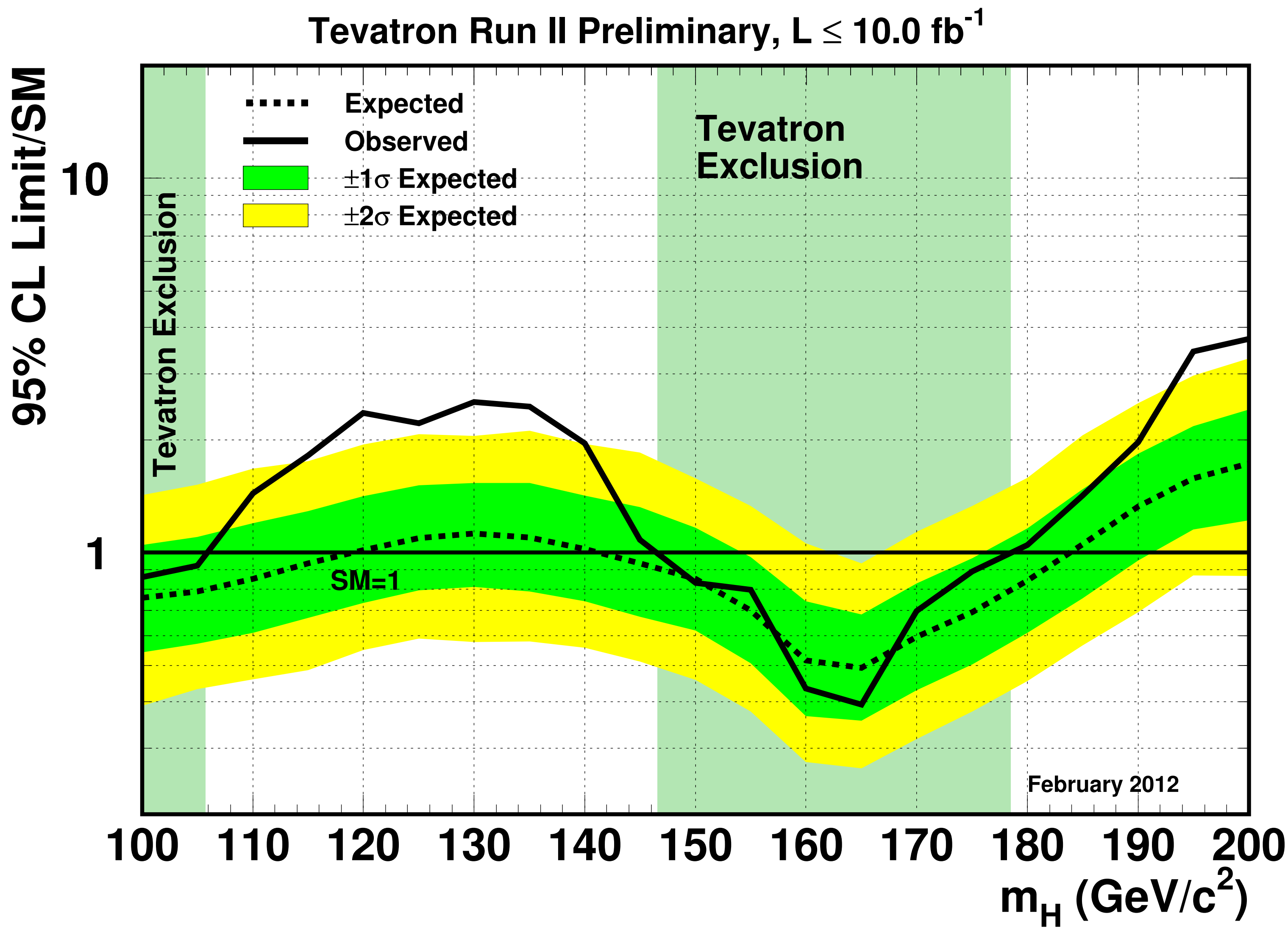
1. Experimental mass bounds excluding the Standard Model Higgs boson

From 1989–2000, experiments at LEP searched for $e^+e^- \to Z \to h^0 Z$ (where one of the Z-bosons is on-shell and one is off-shell). No significant evidence was found leading to a lower bound on the Higgs mass

$$\boxed{m_h > 114.4~\text{GeV} \quad \text{at} \;\; 95\%~\text{CL.}}$$

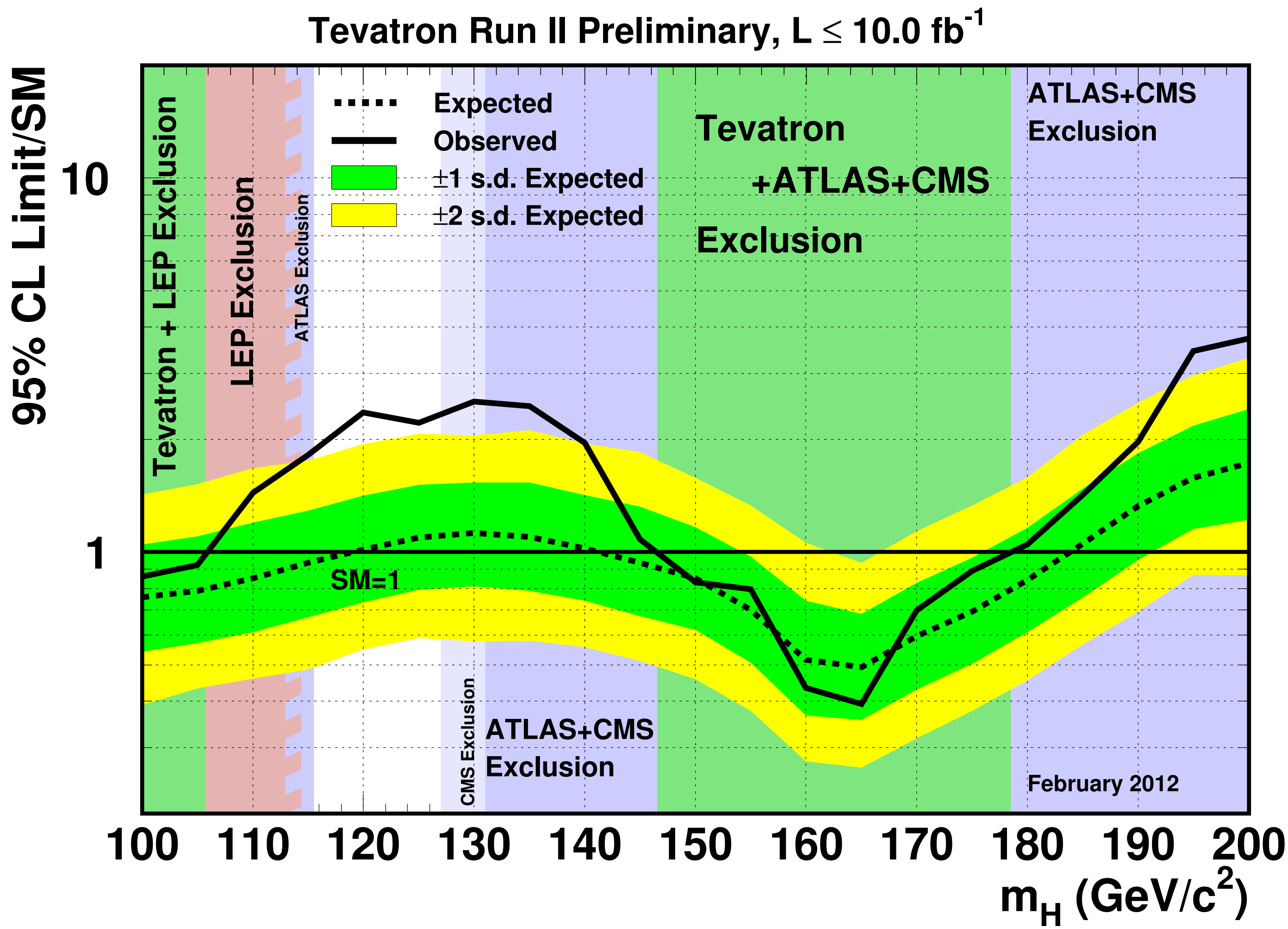
After more then ten years of running, experiments at the Tevatron report in arXiv:1203.3774 [hep-ex] a combined exclusion limit of:

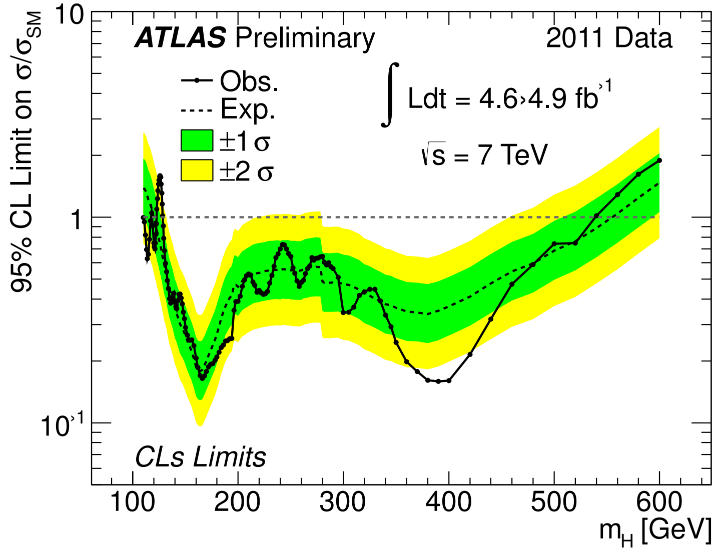
$$\boxed{147~\text{GeV} < m_h < 179~\text{GeV} \quad \text{excluded at} \;\; 95\%~\text{CL.}}$$

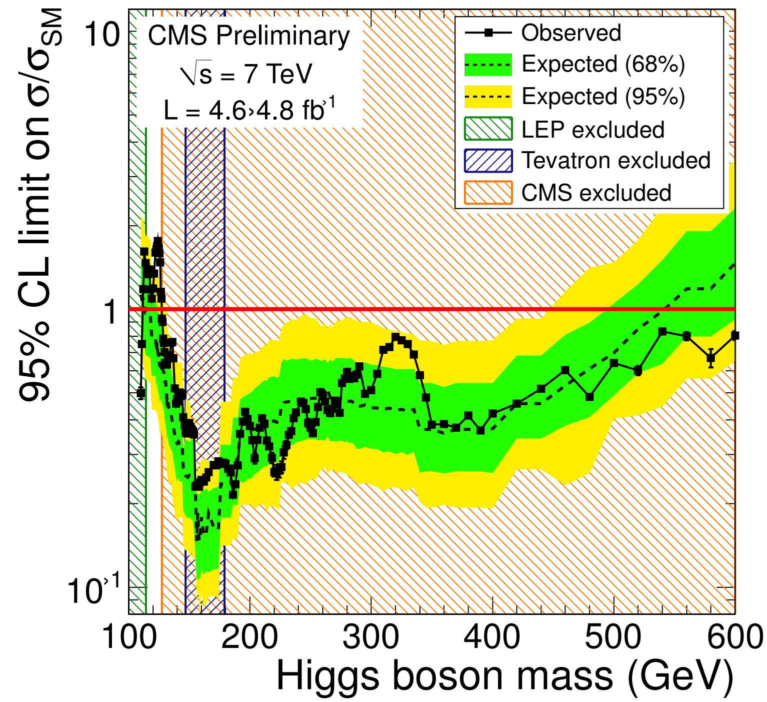


Observed and expected 95% CL upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and DØ analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV) for which both experiments have performed dedicated searches in different channels. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal.

LHC data from 2011 increases the excluded Higgs mass region.







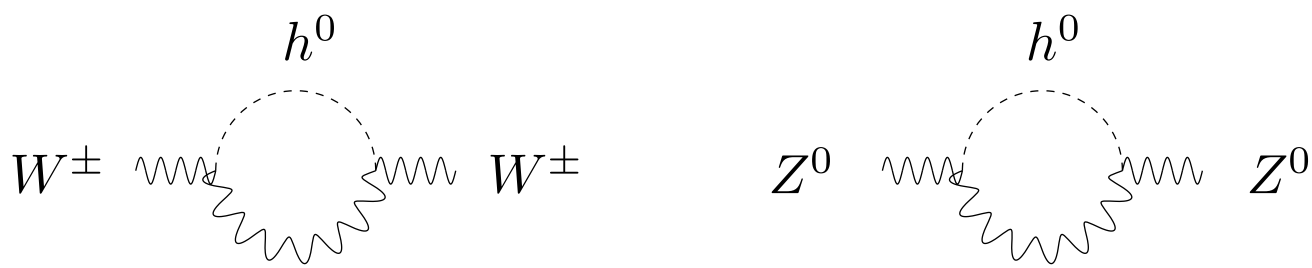
For example, the CMS Collaboration quotes in arXiv:1202.1488 an exclusion limit of:

$$\boxed{127.5 \text{ GeV} < m_h < 600 \text{ GeV} \quad \text{excluded at } \ 95\% \text{ CL.}}$$

The ATLAS Collaboration exclusion is not quite as good at the highest masses. But in Phys.Lett. B710 (2012) 49-66, ATLAS excludes Higgs masses between 112.9 GeV and 115.5 GeV, slightly extending the LEP Higgs mass bound.

2. Upper bound from precision tests of the Standard Model

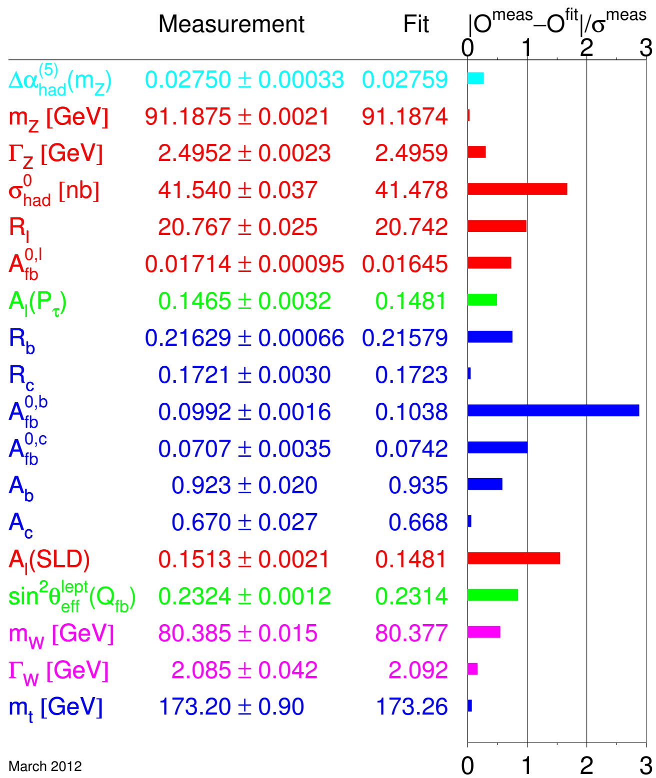
Precise tests of the Standard Model are possible given the large sample of electroweak data from LEP, SLC and the Tevatron. Although the Higgs boson mass (m_h) is unknown, electroweak observables are sensitive to m_h through quantum corrections. For example, the W and Z masses are shifted slightly due to:

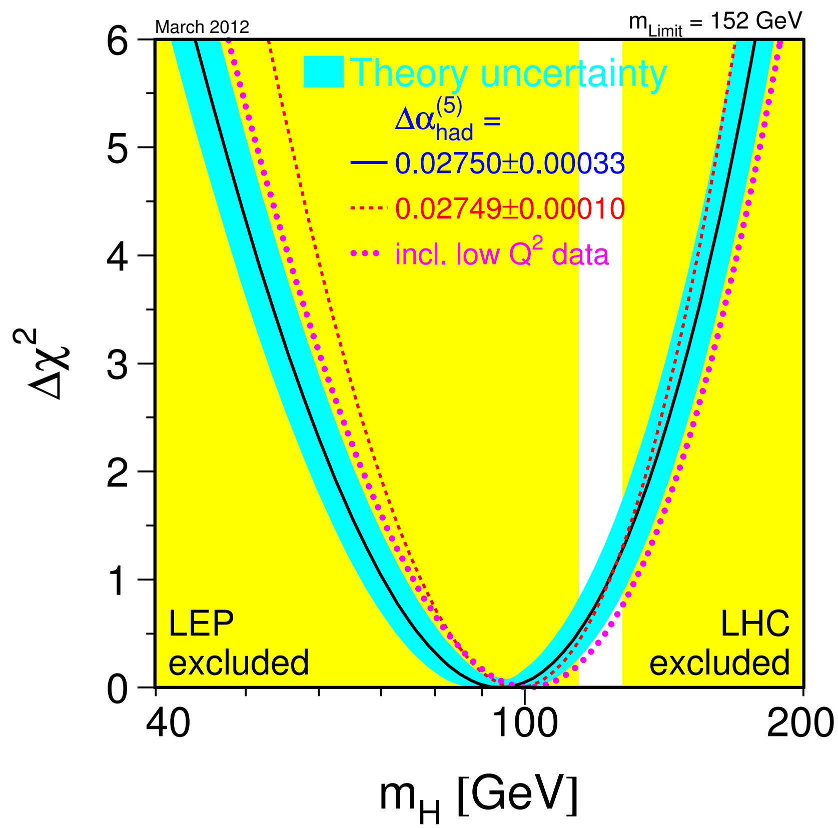


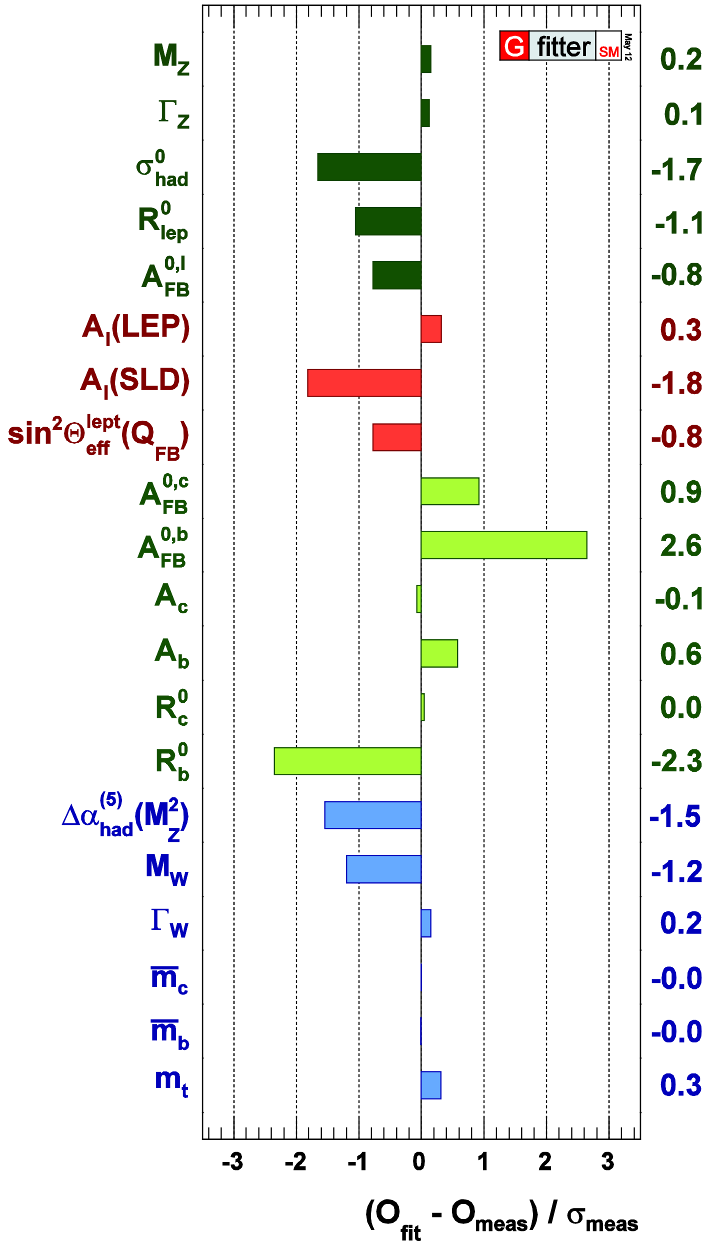
The m_h dependence of the above radiative corrections is logarithmic. Nevertheless, a global fit of many electroweak observables can determine the preferred value of m_h (assuming that the Standard Model is correct).

LEP/Tevatron Electroweak Working Groups: the Standard Model global fit

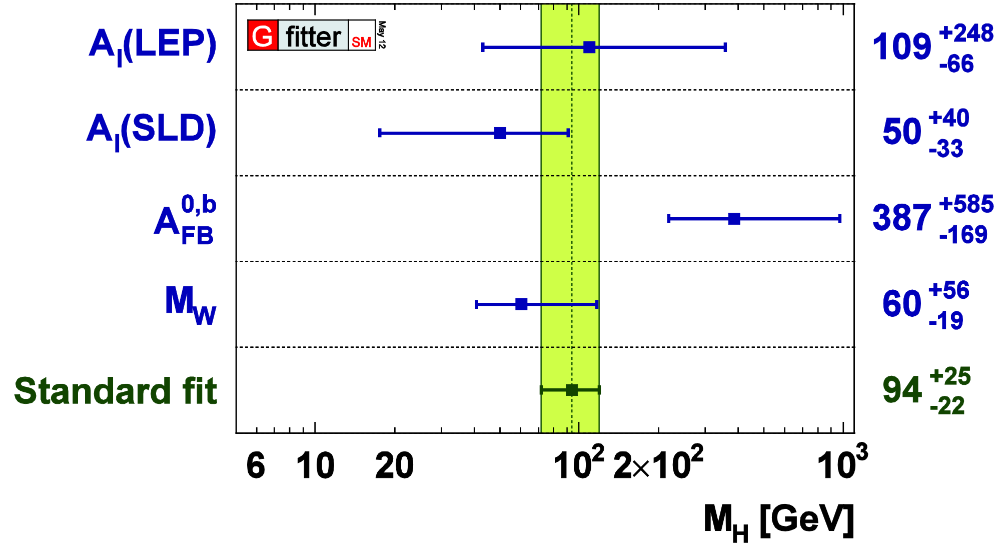
$$m_h = 94^{+29}_{-24}\ \text{GeV} \qquad [m_h < 157\ \text{GeV one-sided 95\% CL}]\,.$$



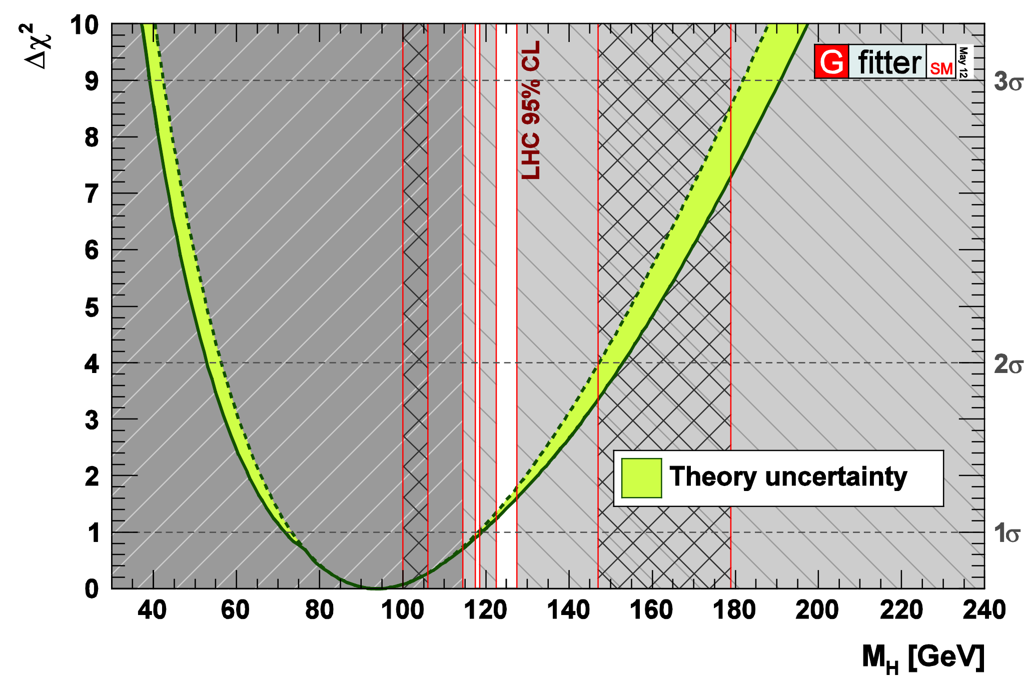




Gfitter SM May 12
M_Z 0.2
Γ_Z 0.1
σ^0_{had} -1.7
R^0_{lep} -1.1
$A^{0,l}_{FB}$ -0.8
$A_l(LEP)$ 0.3
$A_l(SLD)$ -1.8
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ -0.8
$A^{0,c}_{FB}$ 0.9
$A^{0,b}_{FB}$ 2.6
A_c -0.1
A_b 0.6
R^0_c 0.0
R^0_b -2.3
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ -1.5
M_W -1.2
Γ_W 0.2
$\overline{m}_c$ -0.0
$\overline{m}_b$ -0.0
m_t 0.3
-3 -2 -1 0 1 2 3
$(O_{fit} - O_{meas}) / \sigma_{meas}$



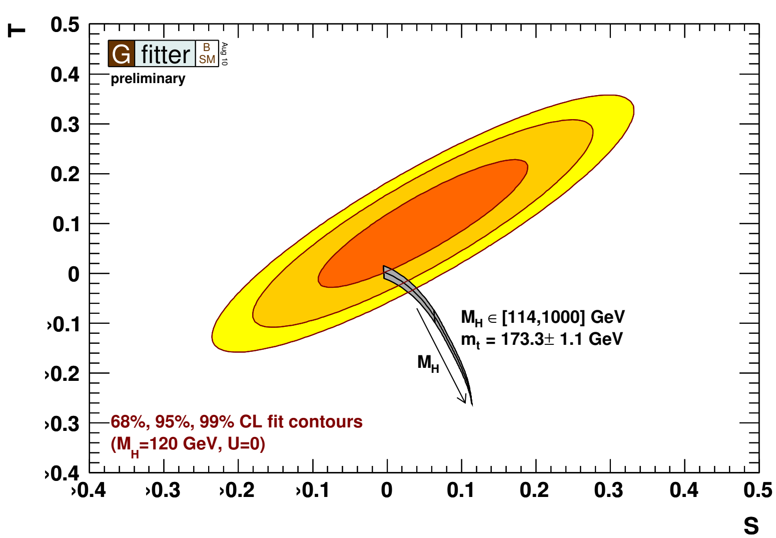
Gfitter SM May 12
$A_l(LEP)$ 109^{+248}_{-66}
$A_l(SLD)$ 50^{+40}_{-33}
$A^{0,b}_{FB}$ 387^{+585}_{-169}
M_W 60^{+56}_{-19}
Standard fit 94^{+25}_{-22}
6 10 20 10^2 2×10^2 10^3
M_H [GeV]

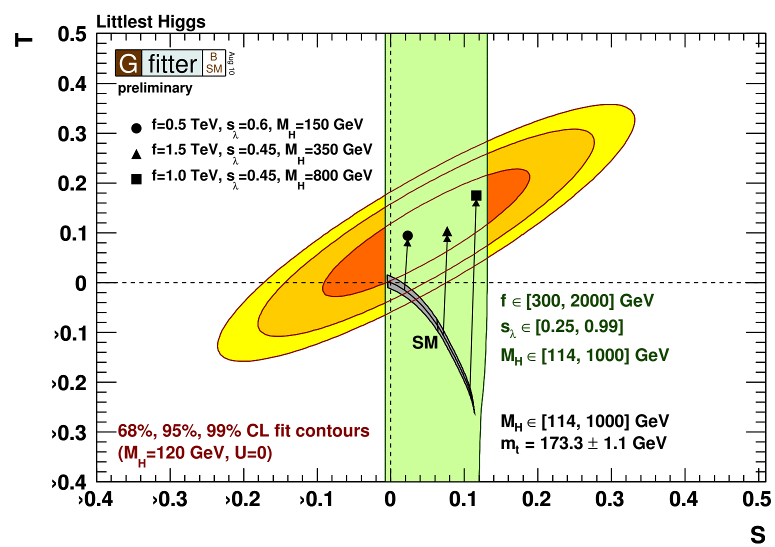


$\Delta\chi^2$
Gfitter SM May 12
LHC 95% CL
Theory uncertainty
3σ
2σ
1σ
0 1 2 3 4 5 6 7 8 9 10
40 60 80 100 120 140 160 180 200 220 240
M_H [GeV]

Is a very heavy Higgs Boson excluded?

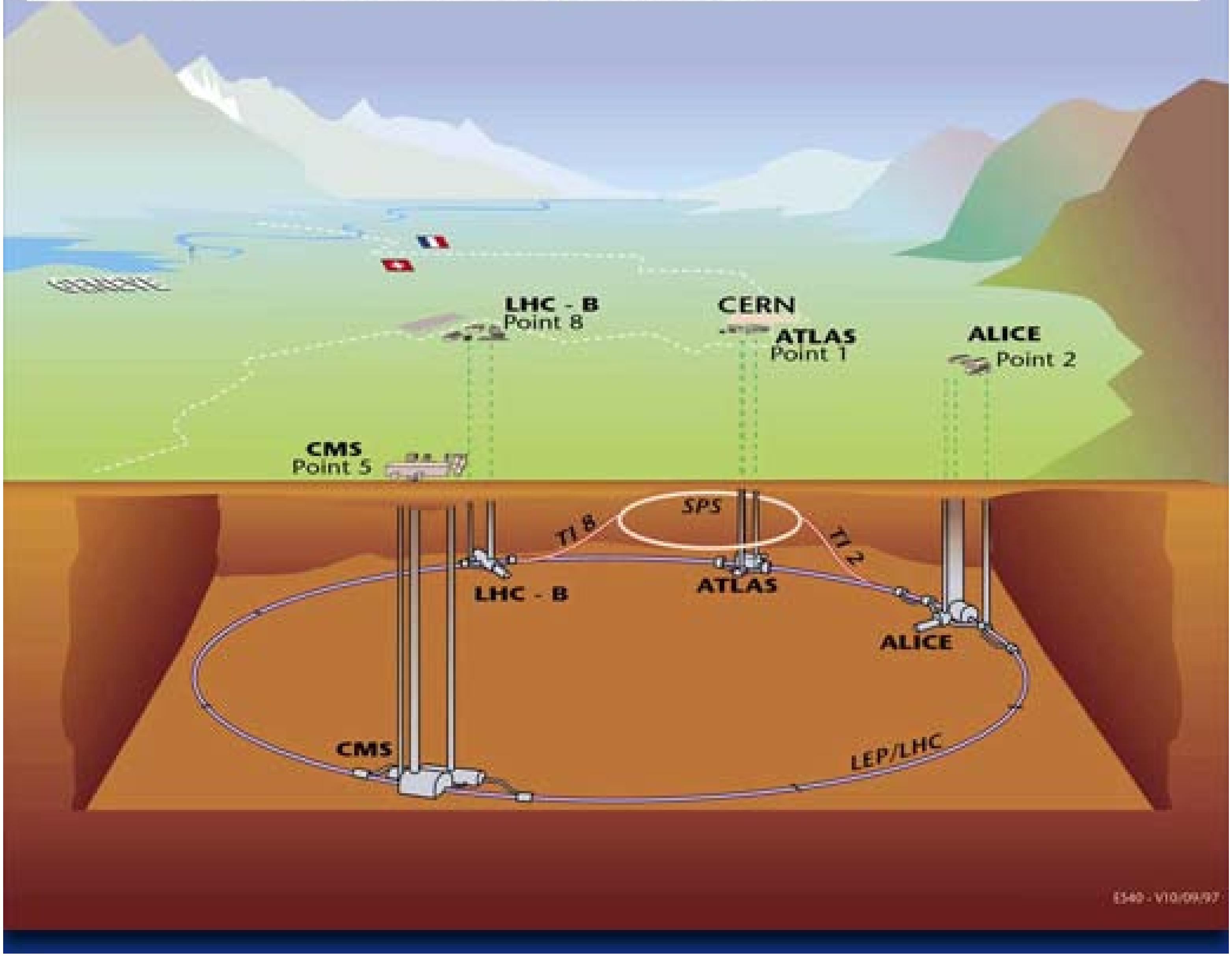
If new physics beyond the Standard Model exists, it almost certainly couples to W and Z bosons. Then, there will be additional shifts in the W and Z mass due to the appearance of new particles in loops. In many cases, these effects can be parameterized in terms of two quantities, S and T [Peskin and Takeuchi], where $S = T = 0$ corresponds to the Standard Model with a Higgs mass of 120 GeV.



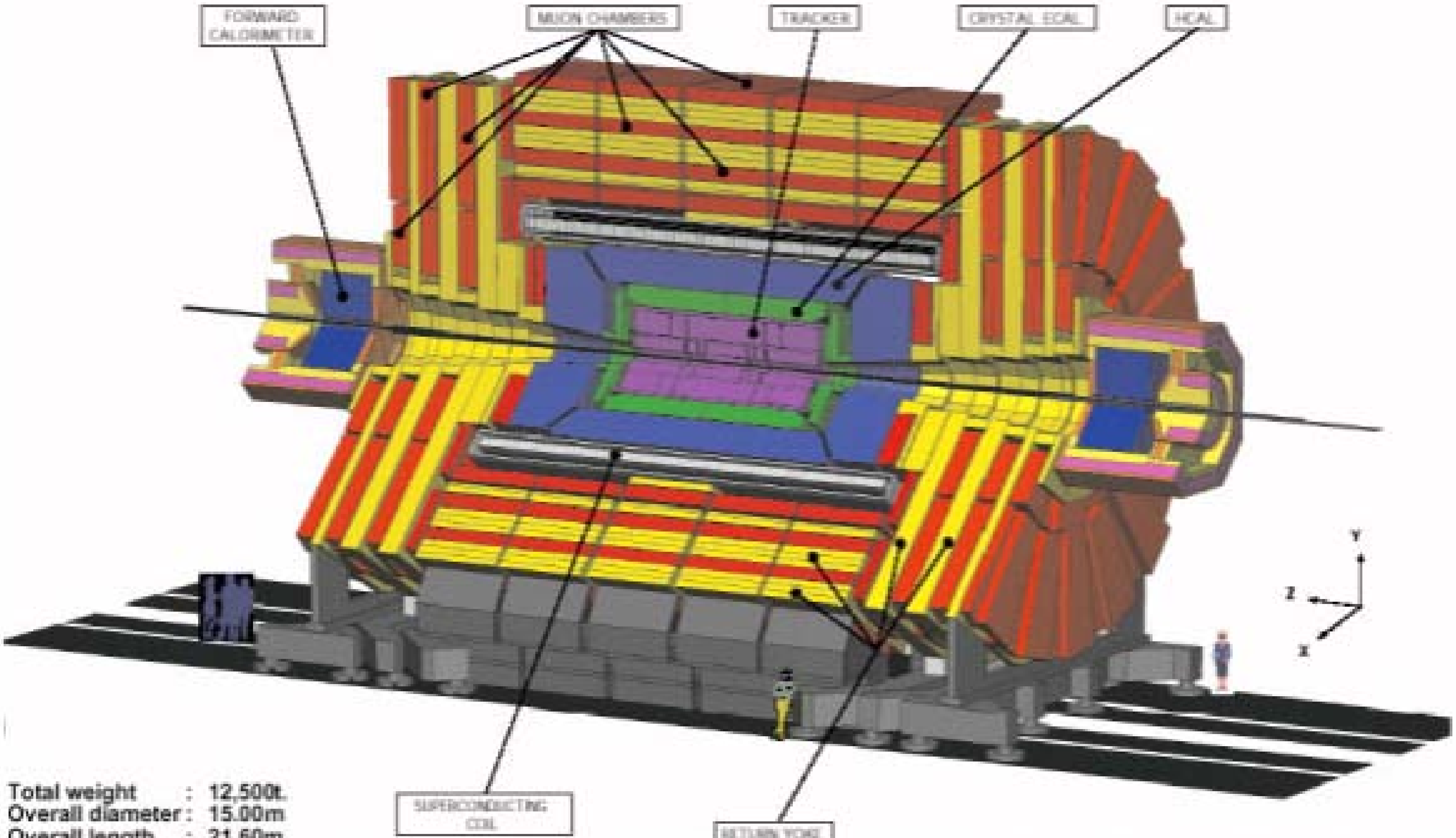


The Large Hadron Collider (LHC) is now in business!

Overall view of the LHC experiments.

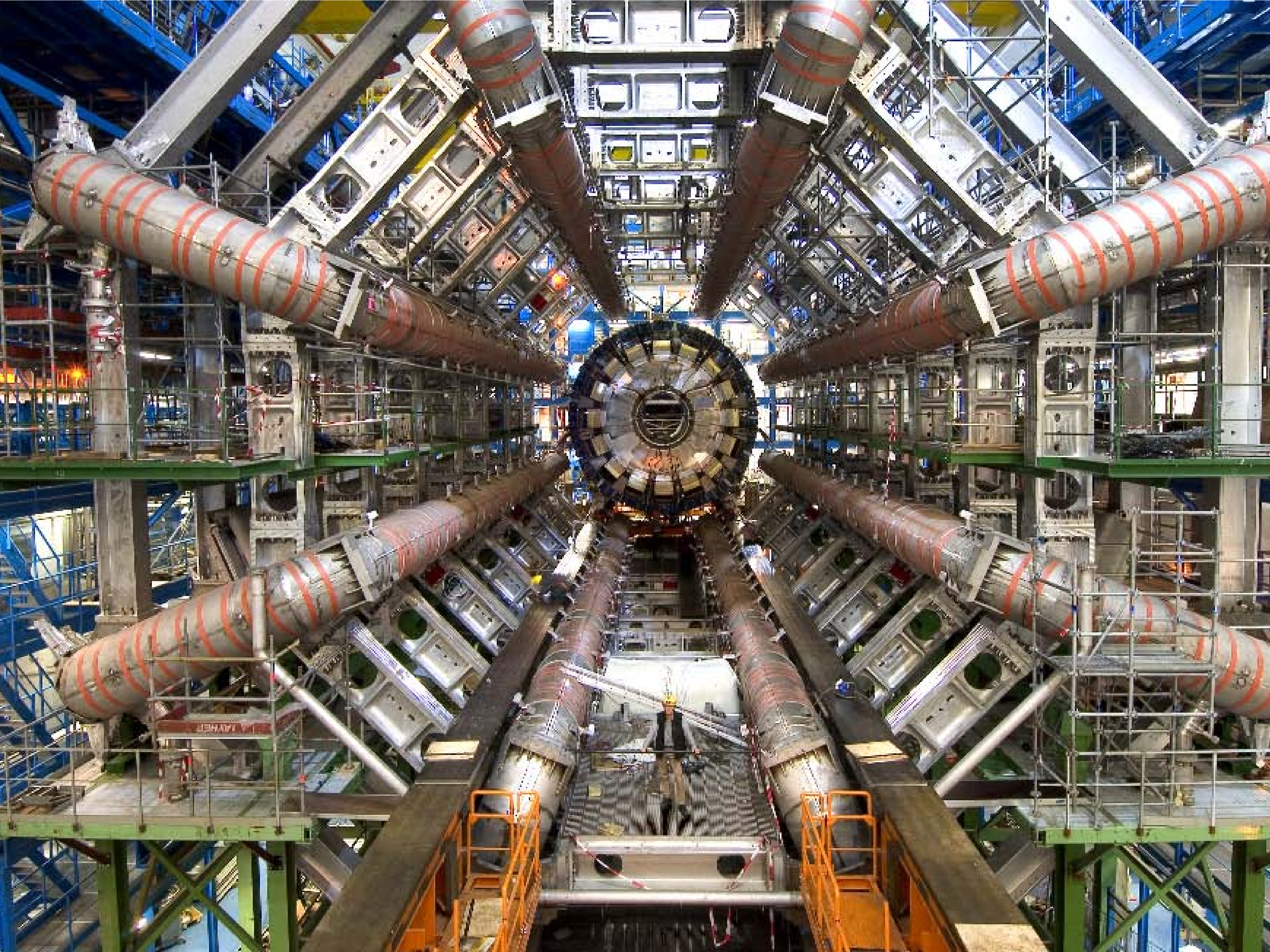


CMS
A Compact Solenoidal Detector for LHC

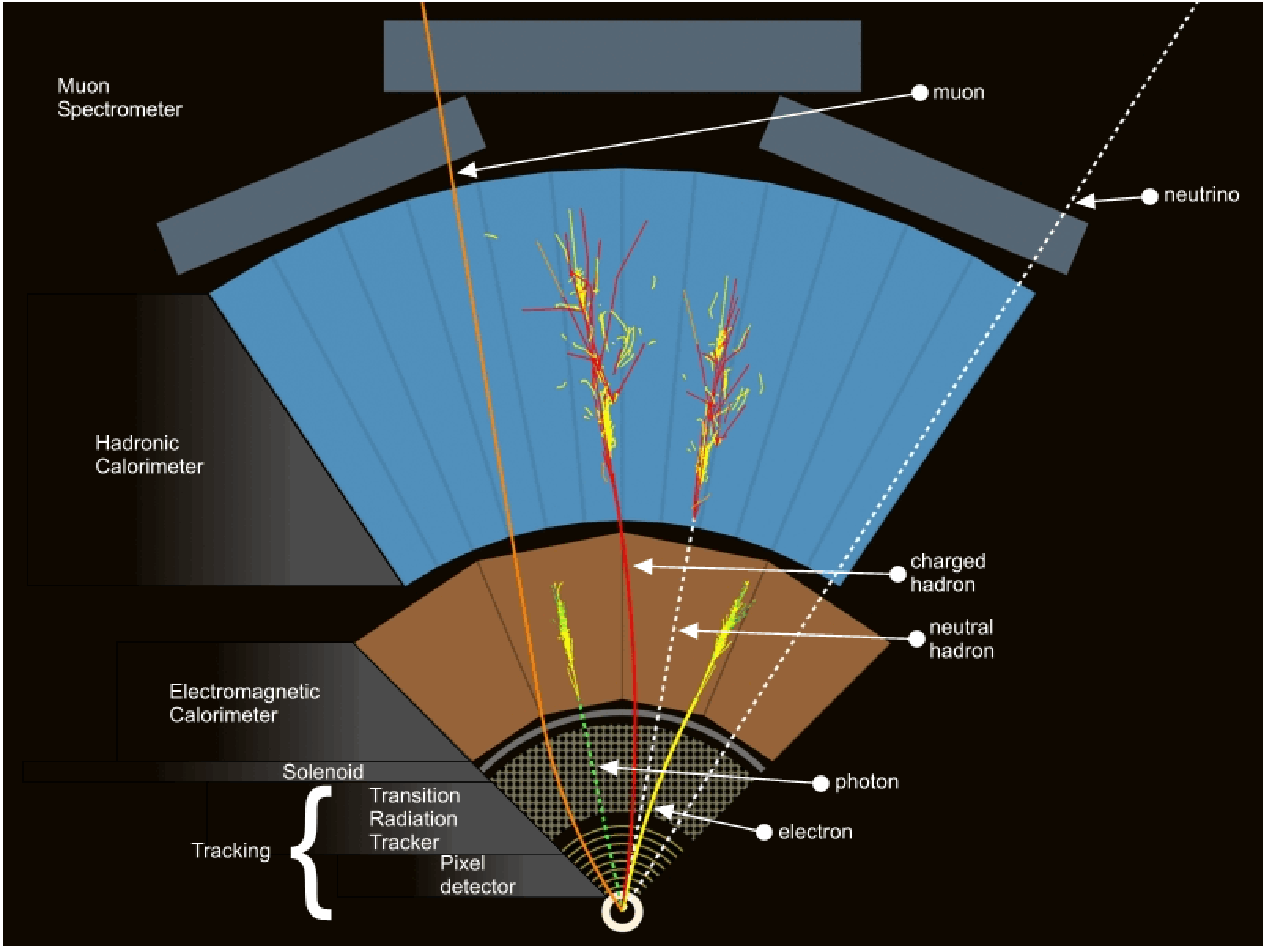


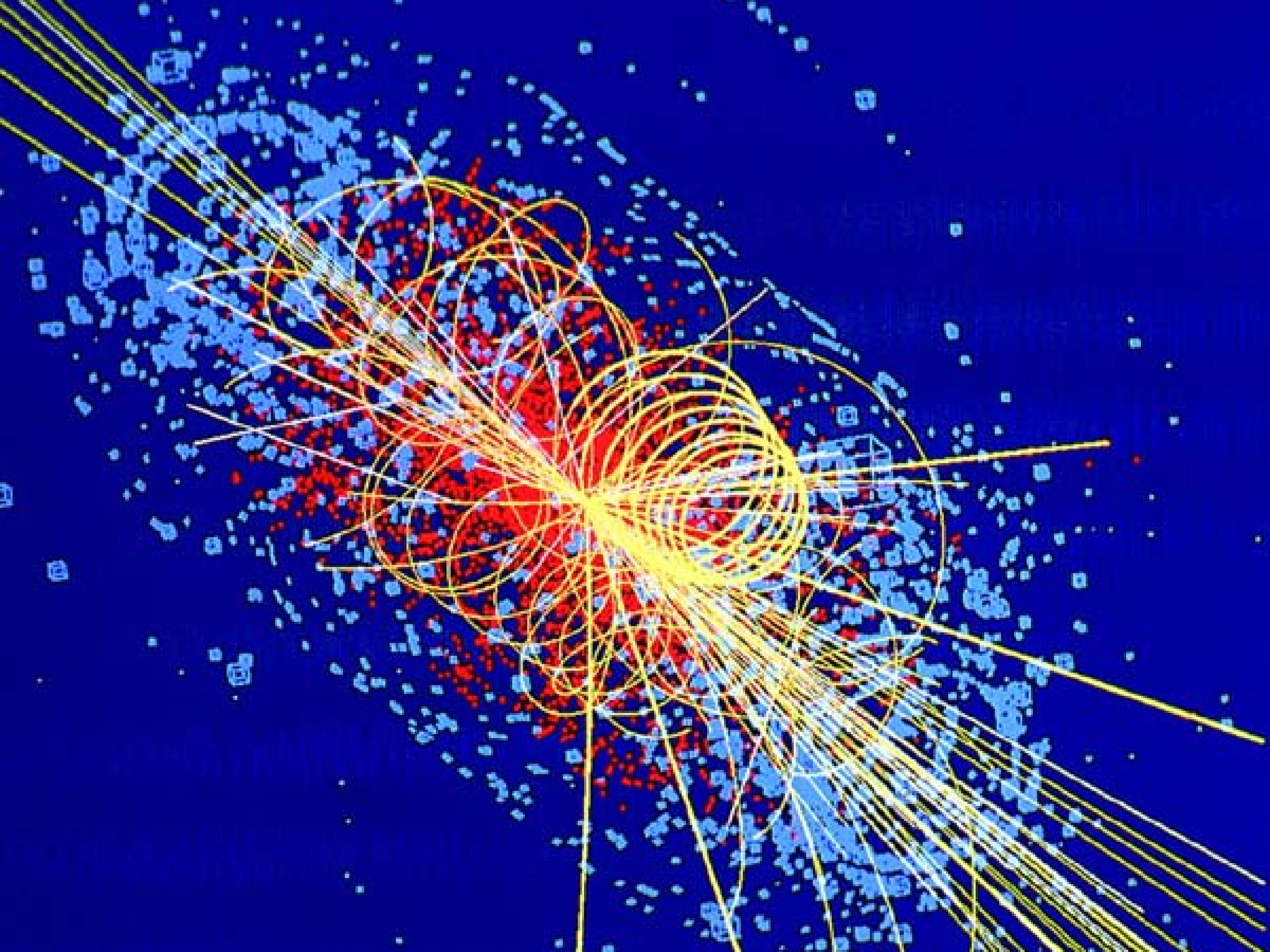
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

CMS-PARA-001-11/07/97 JLB.PP



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

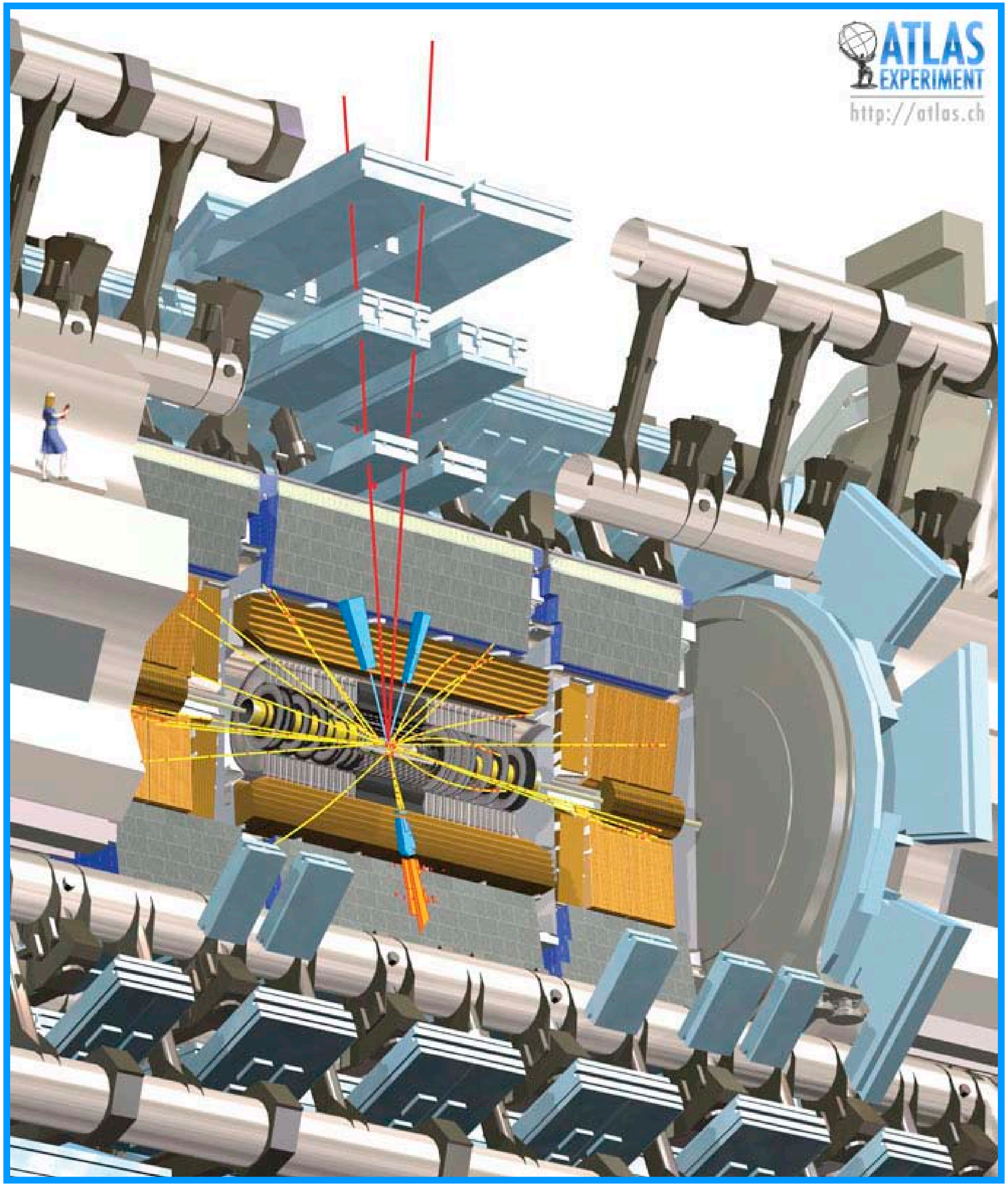




Simulated Higgs boson that decays in the ATLAS detector :

$$H^0 \to ZZ$$

$$Z \to \mu^+ \mu^-$$
$$Z \to e^+ e^-$$



SM Higgs production at hadron colliders

At hadron colliders, the relevant processes are

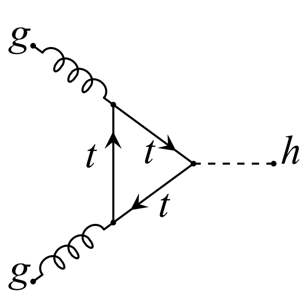
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

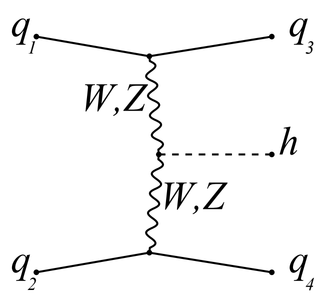
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

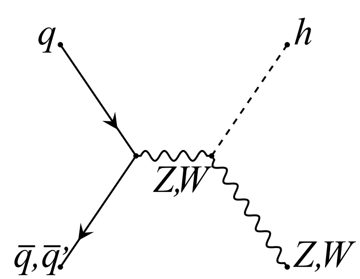
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

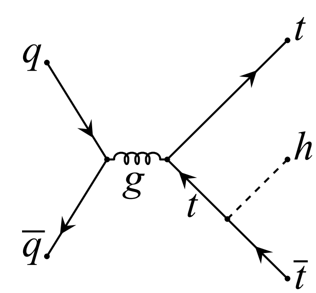
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.

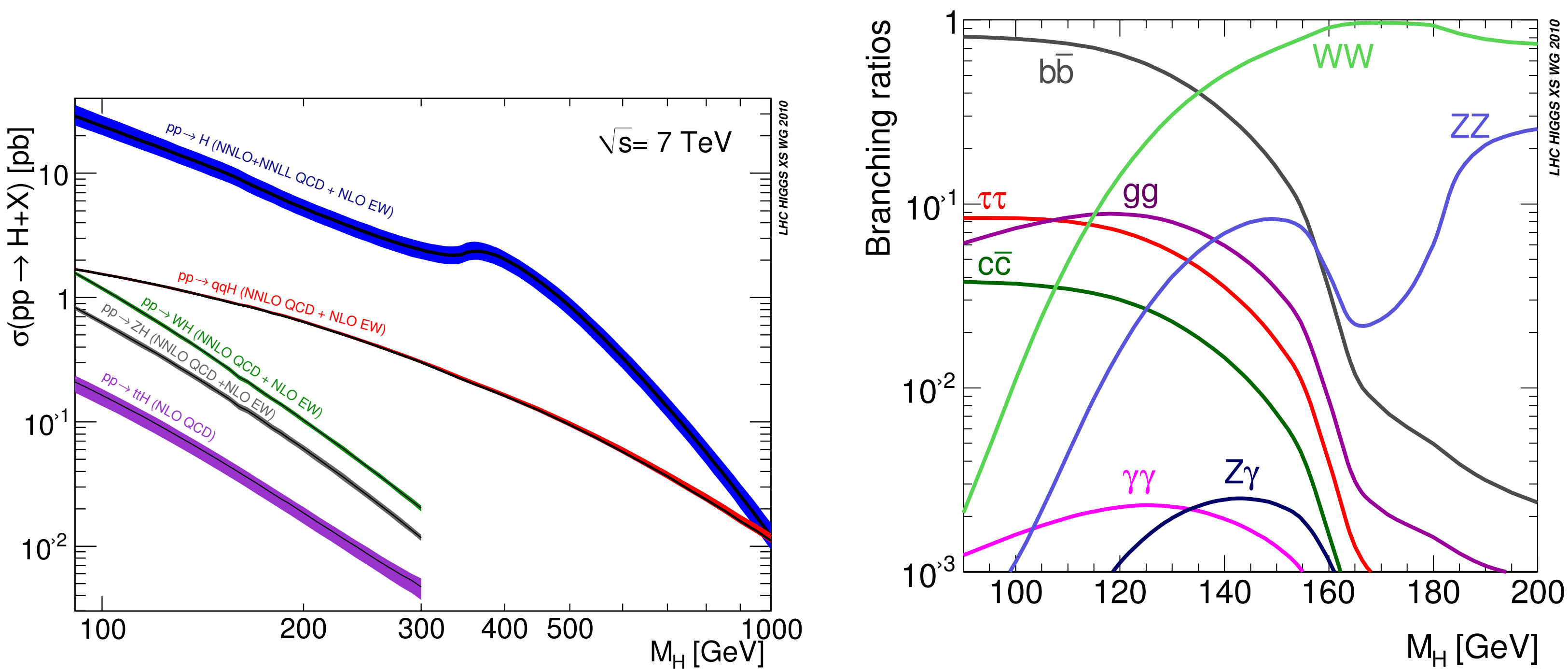








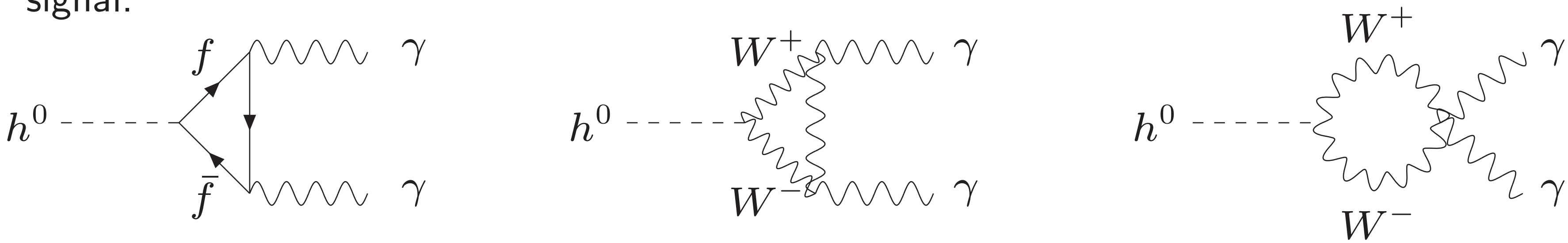
Higgs boson cross sections and branching ratios



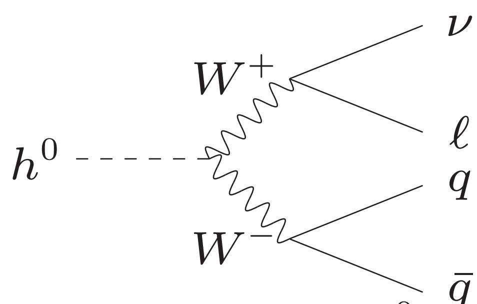
SM Higgs cross-sections at the LHC at $\sqrt{s} = 7$ TeV [left pane] and the SM Higgs branching rations [right pane], taken from the LHC Higgs Cross Section Working Group, available at `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections`.

SM Higgs decays at the LHC

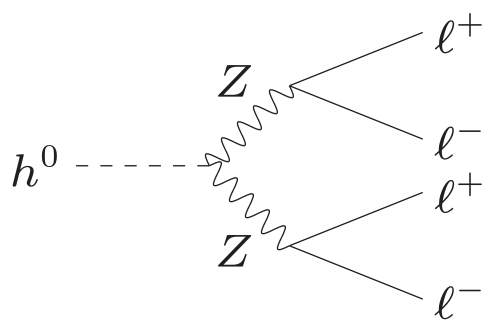
1. For $114 \text{ GeV} \lesssim m_h \lesssim 130 \text{ GeV}$, the rare decay $h^0 \to \gamma\gamma$ is the most promising signal.

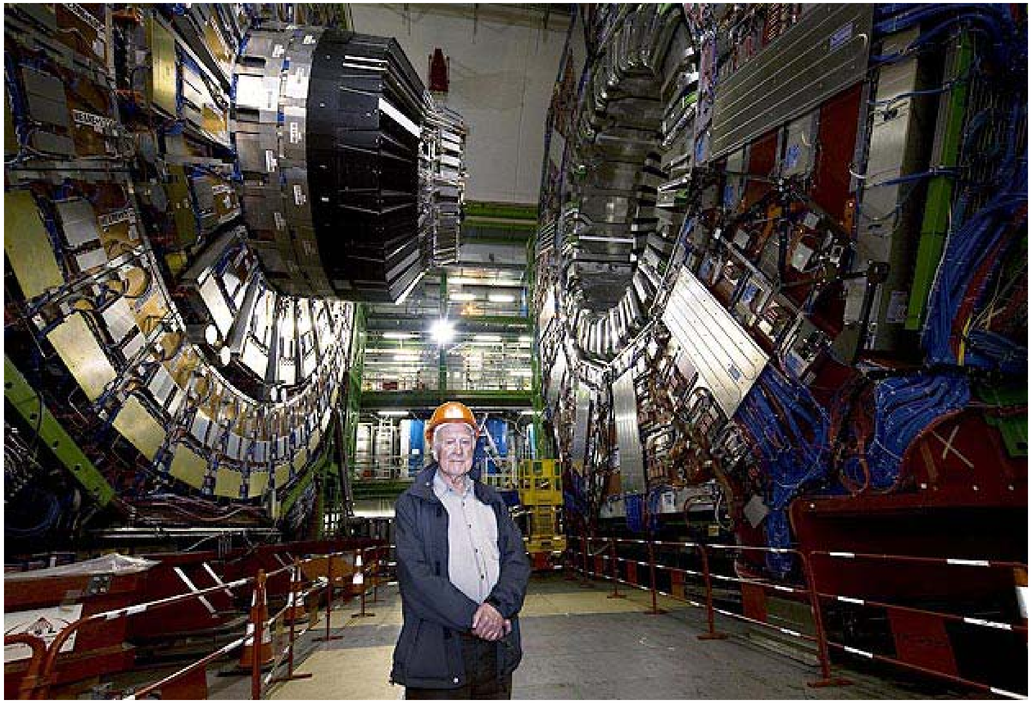


2. For $130 \text{ GeV} \lesssim m_h \lesssim 190 \text{ GeV}$, the decay $h^0 \to WW^{(*)} \to \ell\nu$+hadron jets is the dominant channel; $h \to WW^* \to \ell^+\nu\ell^-\overline{\nu}$ is also useful.



3. For $190 \text{ GeV} \lesssim m_h \lesssim 700 \text{ GeV}$, the decay $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ is the *golden channel*; $h \to ZZ \to \ell^+\ell^-\nu\overline{\nu}$ is also useful.



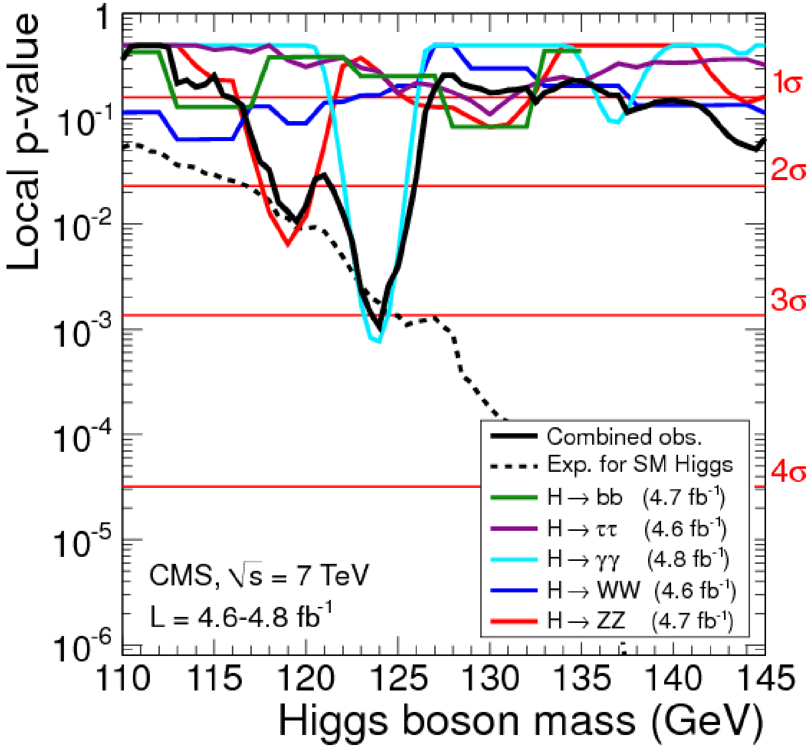


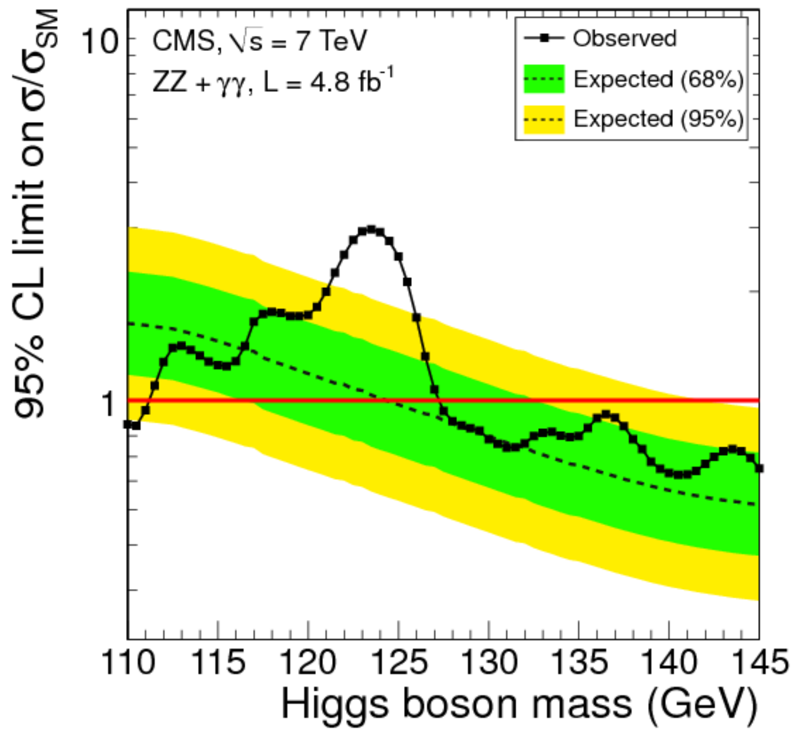
First observations of Higgs at the LHC

Higgs at CMS

Higgs at ATLAS

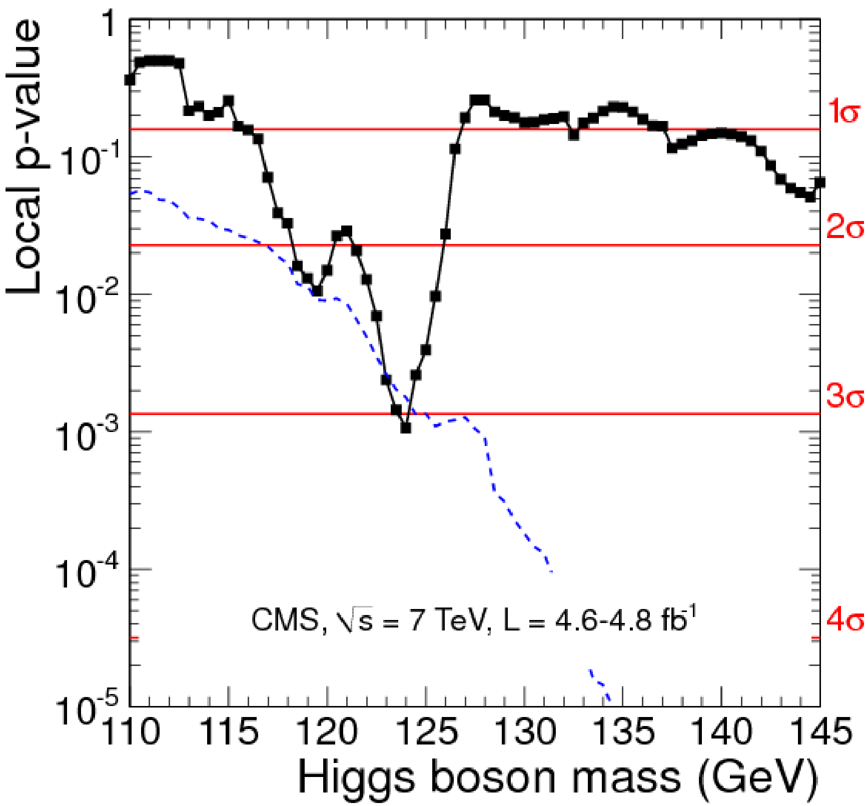
Hints of a Higgs boson signal in the CMS detector



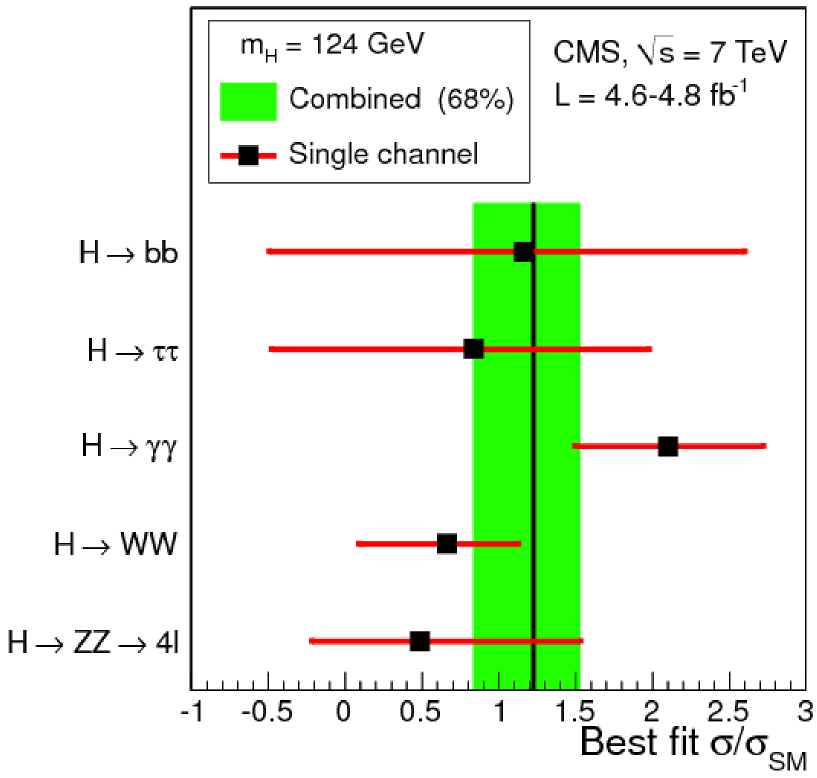


The observed local *p*-value p_0 as a function of the SM Higgs boson mass in the range 110–145 GeV, for the full combination and the individual decay modes. The global significance of the observed maximum excess (minimum local *p*-value) for the full combination in this mass range is about 2.1σ, estimated using pseudoexperiments. The dashed line on the left plot shows the expected local *p*-values $p_0(m_H)$ for the combination, should a Higgs boson with a mass m_H exist.

The 95% CL upper limits on the signal strength parameter $\mu = \sigma/\sigma_{SM}$ for the SM Higgs boson hypothesis as function of the Higgs boson mass, for the ZZ+γγ sub-combinations. The observed values are shown by the solid line. The dashed line indicates the expected median of results for the background only hypothesis, while the green (dark) and yellow (light) bands indicate the ranges that are expected to contain 68% and 95% of all observed excursions from the median, respectively. The limits are obtained with the asymptotic CL_s approximation.



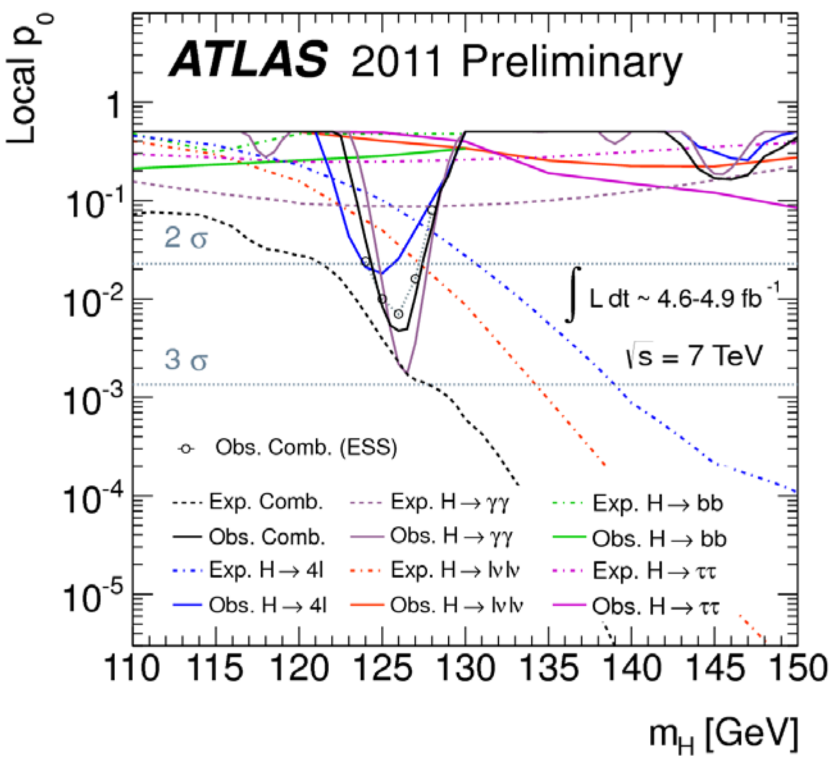
The observed local *p*-value p_0 as a function of the SM Higgs boson mass in the range 110–145 GeV. The global significance of the observed maximum excess (minimum local *p*-value) in this mass range is about 2.1σ, estimated using pseudoexperiments. The dashed line on the plot shows the expected local *p*-values $p_0(m_H)$, should a Higgs boson with a mass m_H exist.



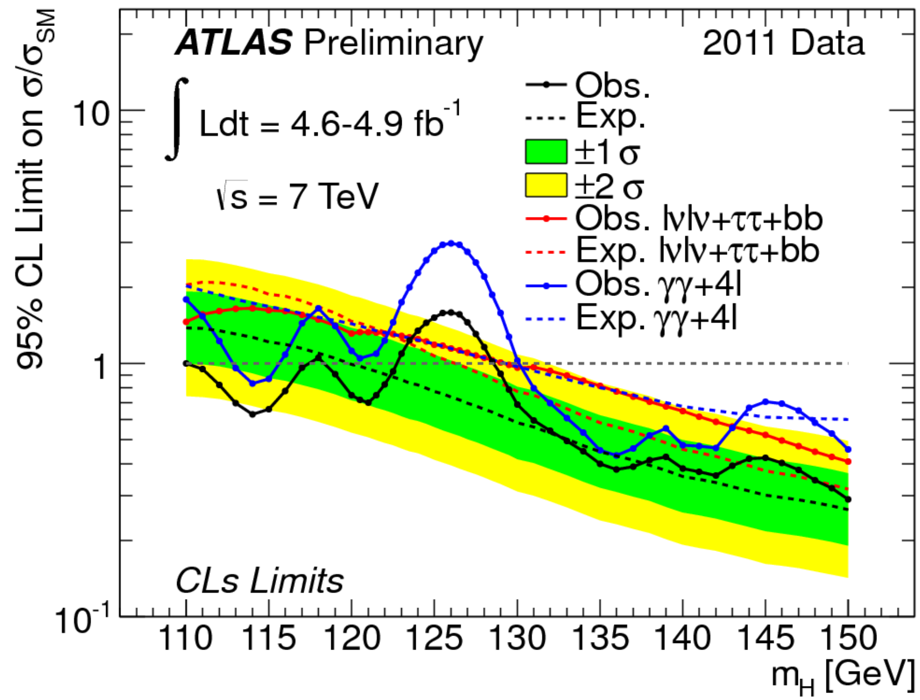
Values of $\hat{\mu} = \sigma/\sigma_{SM}$ for the combination (solid vertical line) and for contributing channels (points), for a hypothesized Higgs boson mass of 124 GeV. The band corresponds to ±1σ uncertainties on the overall $\hat{\mu}$ value. The horizontal bars indicate ±1σ uncertainties on the $\hat{\mu}$ values for individual channels.

Reference: arXiv:1202.1488

Hints of a Higgs boson signal in the ATLAS detector

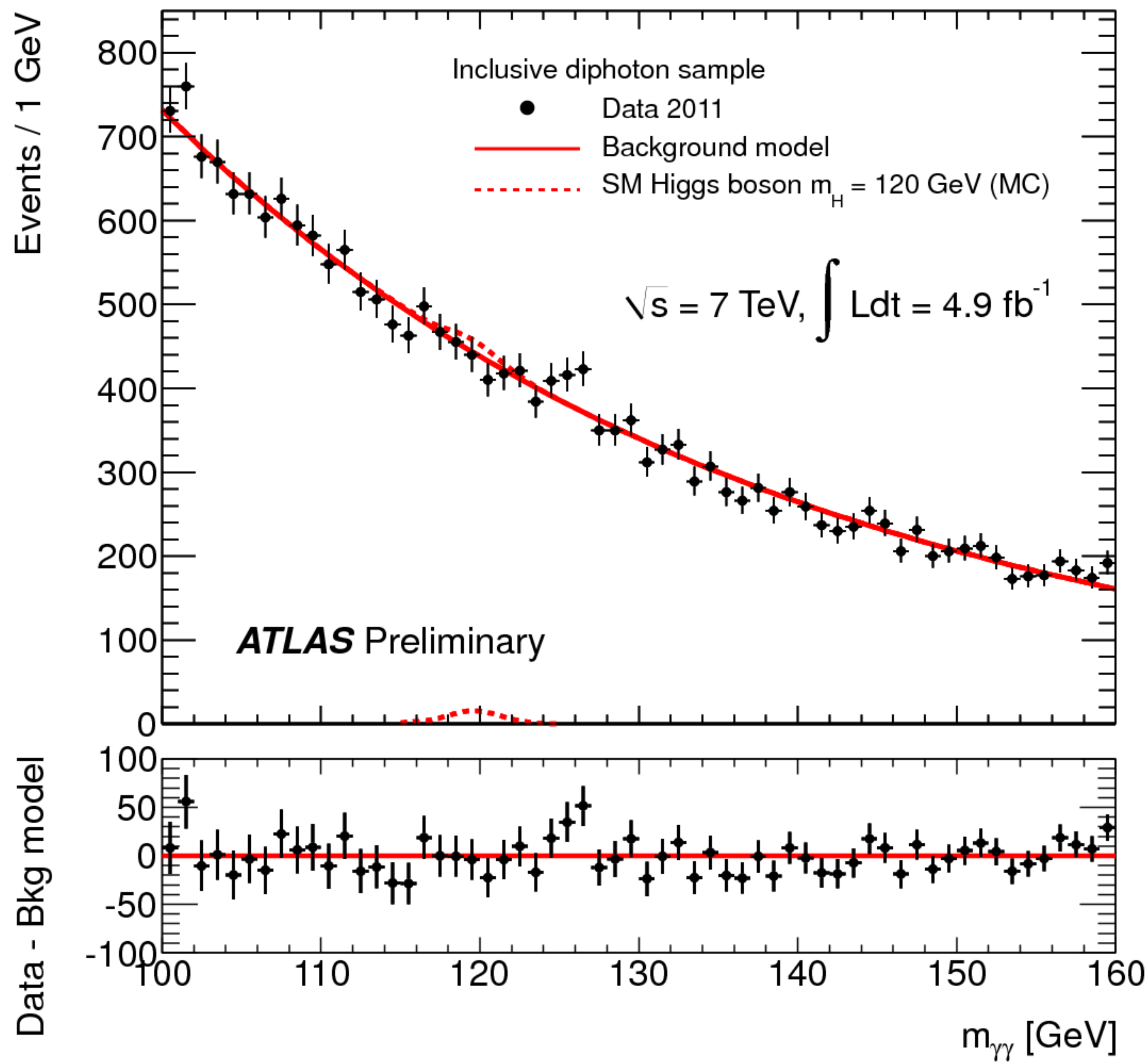


The local probability p0 for a background-only experiment to be more signal-like than the observation, for individual channels and the combination. The full curves give the observed individual and combined p0. The dashed curves show the median expected value under the hypothesis of a SM Higgs boson signal at that mass. The two horizontal dashed lines indicate the p0 corresponding to significances of 2σ and 3σ. The points indicate the combined observed local p0 estimated using ensemble tests and taking into account energy scale systematic uncertainties (ESS).

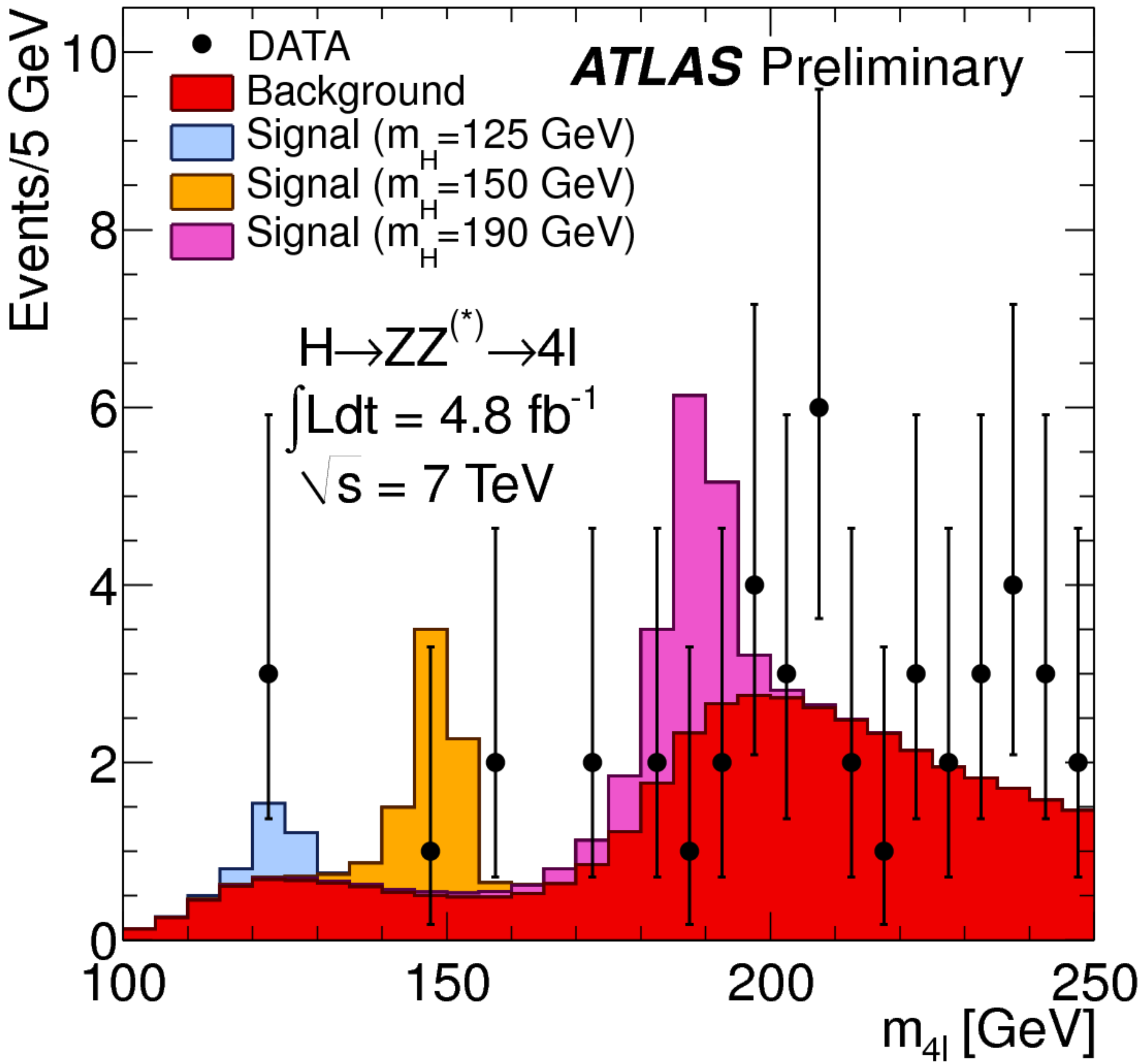


The 95% CL upper limit on the Standard Model Higgs boson production cross section divided by the Standard Model expectation as a function of mH is indicated by the solid curves for the combination of the low mass resolution channels H→WW(∗)→l+νl−ν , H→bb and H→τ+τ− (red) and the combination of the high mass resolution H→γγ and H→ZZ(∗)→l+l−l+l− channels (blue). The dashed curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals for the full combination.

Reference: arXiv:1202.1408



Inclusive diphoton sample
Data 2011
Background model
SM Higgs boson m_H = 120 GeV (MC)
$\sqrt{s}$ = 7 TeV, $\int L dt$ = 4.9 fb^{-1}
ATLAS Preliminary
Events / 1 GeV
Data - Bkg model
$m_{\gamma\gamma}$ [GeV]
800
700
600
500
400
300
200
100
0
100
50
0
-50
-100
100
110
120
130
140
150
160



DATA
Background
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
ATLAS Preliminary
H→ZZ(*)→4l
∫Ldt = 4.8 fb-1
√s = 7 TeV
Events/5 GeV
m_4l [GeV]
0
2
4
6
8
10
100
150
200
250

Coming Attractions

2012 LHC data:

- Center of mass energy increased to 8 TeV
- Nearly 5 fb^{-1} of data collected (equal to the entire 2011 run)
- Analysis of the 2012 data (so far) to be revealed at ICHEP in Melbourne, Australia, July 4—11, 2012
- Expect an additional 10 to 15 fb^{-1} of data by the end of 2012
- There should be sufficient data at the end of 2012 to provide a 5σ discovery of the Higgs boson, if present.

What to look out for

- Will evidence for the Higgs boson be confirmed?
- Do the properties of the Higgs boson match the Standard Model predictions?
- The precision of the Higgs measurements is not likely to be better than about 20%. One can exclude the existence of the "Standard Model Higgs boson," but one cannot claim a discovery of *the* Standard Model Higgs boson.
- Many theoretical models of particle physics (which invoke new phenomena beyond the Standard Model) contain a Higgs particle with Standard Model-like properties
- The fun really starts if a Higgs particle is discovered with some of the properties of the Standard Model, but with some observable deviations.

Whatever happens, one thing is certain: 2012 is sure to be a watershed year in particle physics.