The Higgs Boson: Past, Present and Future

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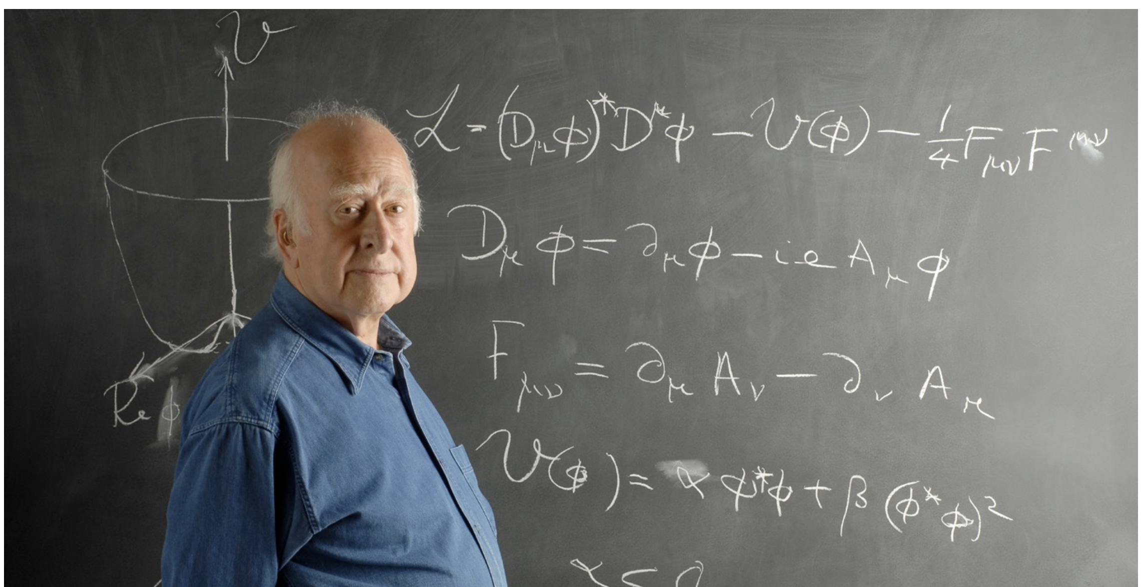
12 November 2013

2013 Inter-Acadamy
Seoul Science Forum
South Korea



The Higgs Boson---Past

- Theoretical origin of the Higgs boson
- Where should we look?
  - Implications of precision electroweak observables
  - An upper bound for the Higgs mass in the MSSM

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
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

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

Something is missing…

What was missing?

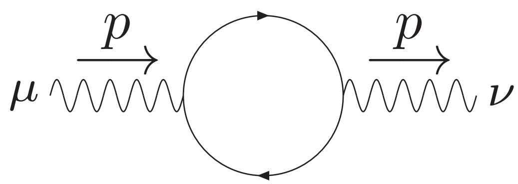
The theory of $W^\pm$ and Z gauge bosons must be *gauge invariant*; otherwise the theory is mathematically inconsistent. Naively, gauge invariance implies that the gauge boson mass must be zero, since a mass term of the form $m^2 A^a_\mu A^{\mu a}$ is not gauge invariant.

So, what is the origin of the $W^\pm$ and Z boson masses? Gauge bosons are massless at tree-level, but perhaps a mass may be generated when quantum corrections are included. The tree-level gauge boson propagator $G^0_{\mu\nu}$ (in the Landau gauge) is:

$$G^0_{\mu\nu}(p) = \frac{-i}{p^2}\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) .$$

The pole at $p^2 = 0$ indicates that the tree-level gauge boson mass is zero. Let's now include the radiative corrections.

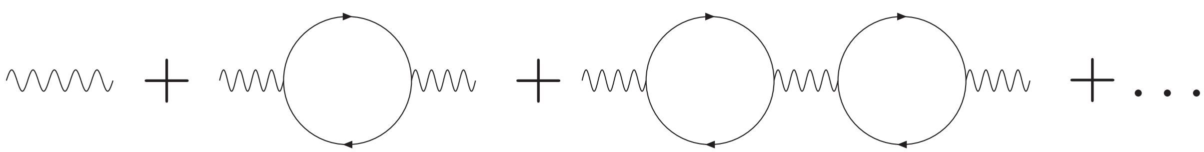
The polarization tensor $\Pi_{\mu\nu}(p)$ is defined as:



$$i\,\Pi_{\mu\nu}(p) \equiv i(p_\mu p_\nu - p^2 g_{\mu\nu})\Pi(p^2)$$

where the form of $\Pi_{\mu\nu}(p)$ is governed by covariance with respect to Lorentz transformations, and is constrained by gauge invariance, i.e. it satisfies $p^\mu \Pi_{\mu\nu}(p) = p^\nu \Pi_{\mu\nu}(p) = 0$.

The renormalized propagator is the sum of a geometric series



$$= \frac{-i(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2})}{p^2[1+\Pi(p^2)]}$$

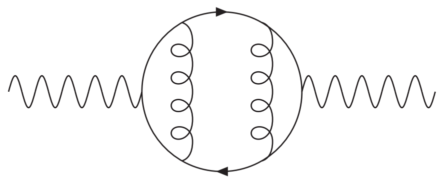
The pole at $p^2 = 0$ is shifted to a non-zero value if:

$$\Pi(p^2) \underset{p^2 \to 0}{\simeq} \frac{-g^2 v^2}{p^2}\,.$$

Then $p^2[1 + \Pi(p^2)] = p^2 - g^2 v^2$, yielding a gauge boson mass of gv.

Interpretation of the $p^2 = 0$ pole of $\Pi(p^2)$

The pole at $p^2 = 0$ corresponds to a propagating massless scalar. For example, due to the strong interactions, one of the contributing intermediate states may be a massless quark/antiquark spin-0 bound state.



The Z and $W^\pm$ couple to neutral and charged weak currents

$$\mathcal{L}_{\rm int} = g_Z j_\mu^Z Z^\mu + g_W (j_\mu^W W^{+\mu} + {\rm h.c.})\,,$$

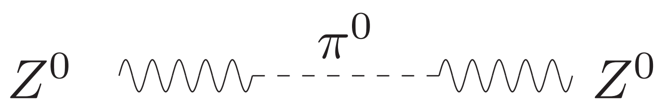
which are known to create neutral and charged pions from the vacuum, e.g.,

$$\langle 0|j_\mu^Z(0)|\pi^0\rangle = i f_\pi p_\mu\,.$$

Here, $f_\pi = 93$ MeV is the amplitude for creating a pion from the vacuum. Indeed, in the absence of quark masses, the pions are pseudoscalar massless quark/antiquark bound states.

Massless scalars (called Goldstone bosons) arise due to spontaneous symmetry breaking of a global symmetry. Massless pions are a consequence of chiral symmetry (in the absence of quark masses) which is spontaneously broken by the strong interactions.

Thus, the diagram:



yields the leading contribution as $p^2 \to 0$ [shown in red] to the $p_\mu p_\nu$ of $\Pi_{\mu\nu}$,

$$i\Pi_{\mu\nu}(p) = i g_Z^2 f_\pi^2 \left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) .$$

Remarkably, the latter is enough to fix the corresponding $g_{\mu\nu}$ part of $\Pi_{\mu\nu}$ [thank you, Lorentz invariance and gauge invariance!]. It immediately follows that

$$\Pi(p^2) = -\frac{g_Z^2 f_\pi^2}{p^2} ,$$

and therefore $m_Z = g_Z f_\pi$. Similarly $m_W = g_W f_\pi$.

Moreover, the ratio

$$\frac{m_W}{m_Z} = \frac{g_W}{g_Z} \equiv \cos\theta_W \simeq 0.88$$

is remarkably close to the measured ratio. Unfortunately, since $g_Z \simeq 0.37$ we find $m_Z = g_Z f_\pi = 35$ MeV, which is too small by a factor of 2600.

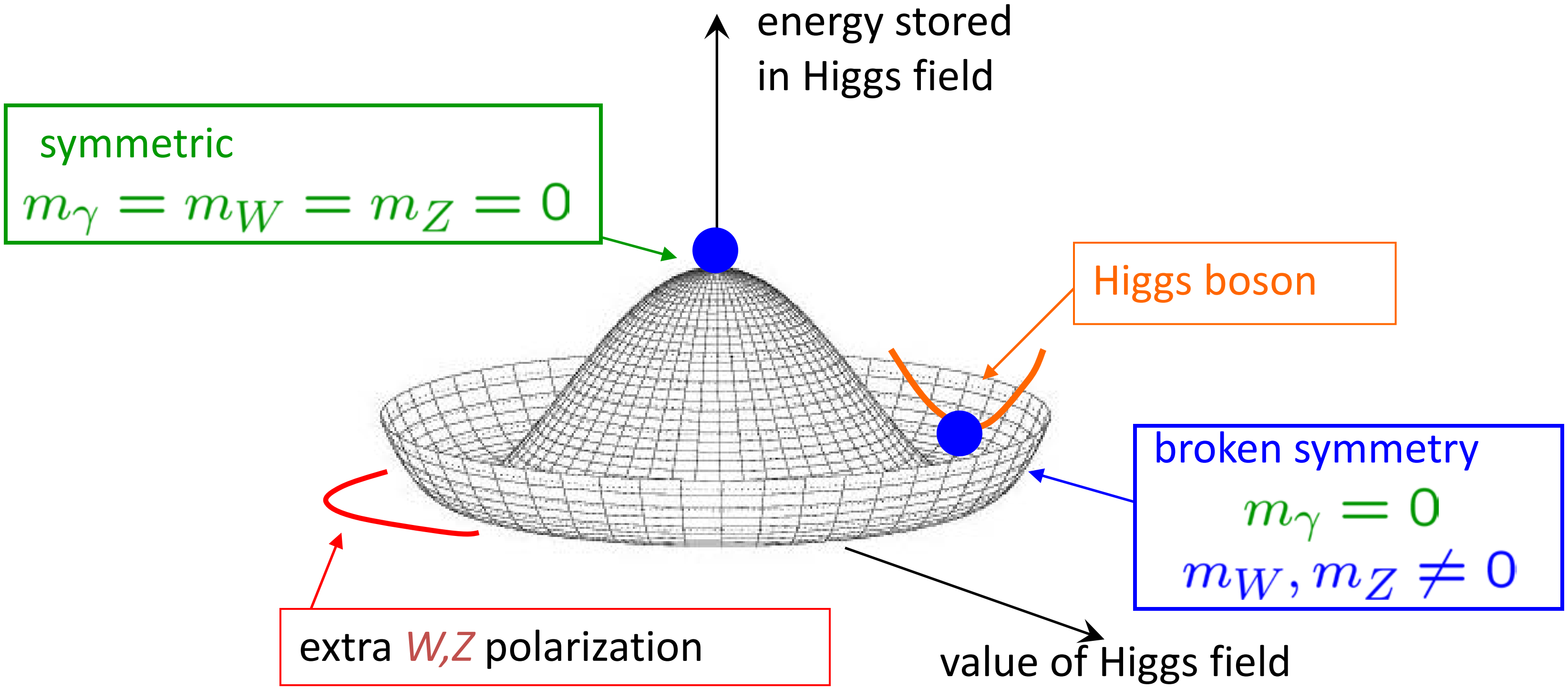
> There must be another source for the gauge boson masses, i.e. new fundamental dynamics that generates the Goldstone bosons that are the main sources of mass for the $W^\pm$ and Z.

Possible choices for electroweak-symmetry-breaking (EWSB) dynamics

- weakly-interacting self-coupled elementary (Higgs) scalar dynamics
- strong-interaction dynamics involving new fermions and gauge fields [technicolor, dynamical EWSB, little Higgs models, composite Higgs bosons, Higgsless models, extra-dimensional EWSB, . . .]

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”.



EWSB Dynamics of the Standard Model (SM)

- Add a new sector of "matter" consisting of a complex SU(2) doublet, hypercharge-one self-interacting scalar fields, $\Phi \equiv (\Phi^+ \ \ \Phi^0)$ with four real degrees of freedom. The scalar potential is:

$$V(\Phi) = \tfrac{1}{2}\lambda(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2\,,$$

so that in the ground state, the neutral scalar field takes on a constant non-zero value $\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV. It is convenient to write:

$$\Phi = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + i\omega^0\right) \end{pmatrix}\,,$$

where $\omega^\pm \equiv (\omega^1 \mp i\omega^2)/\sqrt{2}$.

- The non-zero scalar vacuum expectation value breaks the electroweak symmetry, thereby generating three Goldstone bosons, ω^a $(a = 1, 2, 3)$.

- The couplings of the gauge bosons to the SU(2)$_L\times$U(1)$_Y$ currents are

$$\mathscr{L}_{\rm int} = \tfrac{1}{2} g W^{\mu a} T^a_{\mu L} + \tfrac{1}{2} g' B^\mu Y_\mu \,.$$

Decomposing $T_L = \frac{1}{2}(j_V - j_A)$ into vector and axial vector currents and noting that the electric current, $j_Q = T^3 + \frac{1}{2} Y$ is purely vector,

$$\mathscr{L}_{\rm int} = -\tfrac{1}{2} g W^{\mu a} j^a_{A\mu} + \tfrac{1}{2} g' B^\mu j^3_{A\mu} + \text{vector current couplings}\,.$$

The neutral and charged weak currents can create neutral and charged Goldstone bosons from the vacuum, $\langle 0 | j^a_{A\mu} | \omega^b \rangle = i v p_\mu \delta^{ab}$. The δ^{ab} factor is a consequence of the global *custodial* SU(2)$_L\times$SU(2)$_R$ symmetry of the scalar potential. The resulting gauge boson masses computed as before yields

$$m_W^2 = \tfrac{1}{4} g^2 v^2 \,, \qquad\qquad m_Z^2 = \tfrac{1}{4}(g^2 + g'^{\,2}) v^2 = \frac{m_W^2}{\cos^2\theta_W}\,.$$

- As a result of the custodial symmetry of the EWSB dynamics, the rho-parameter at tree-level is

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1\,.$$

Custodial symmetry is not an exact symmetry of the full Standard Model. As a result, there are small and predictable deviations from $\rho = 1$, which can be deduced from the study of precision electroweak observables.

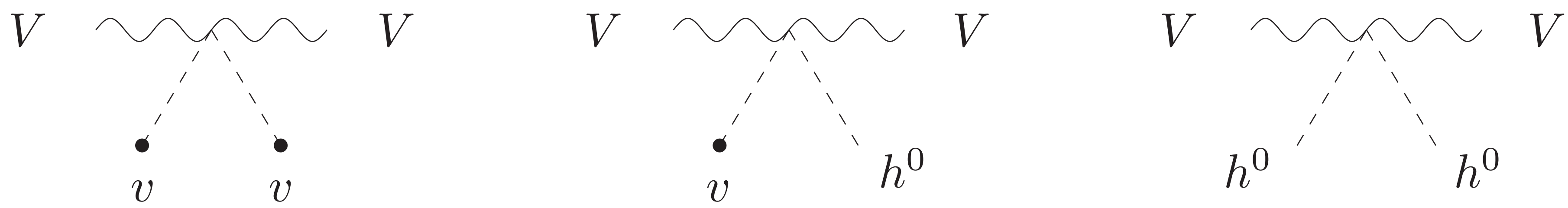
- One scalar degree of freedom is left over—the Higgs boson, with self-interactions

$$V(h) = \tfrac{1}{2}\lambda\left[\left(\frac{h+v}{\sqrt{2}}\right)^2 - \frac{v^2}{2}\right]^2 = \tfrac{1}{8}\lambda\left[h^4 + 4h^3v + 4h^2v^2\right]\,.$$

It is a neutral CP-even scalar boson, whose interactions are precisely predicted, but whose mass $m_h = \lambda v^2$ depends on the unknown strength of the scalar self-coupling—the only unknown parameter of the model.

Mass generation and Higgs couplings in the SM

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:

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

Fermions in the Standard Model

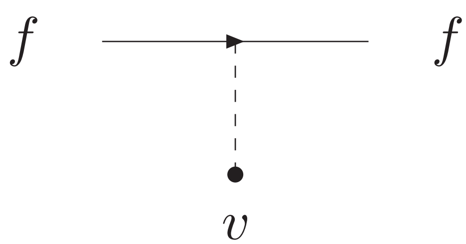
Under the electroweak gauge group, the right and left-handed components of each fermion has different SU(2)$\times$U(1)$_{\mathrm{Y}}$ quantum numbers:

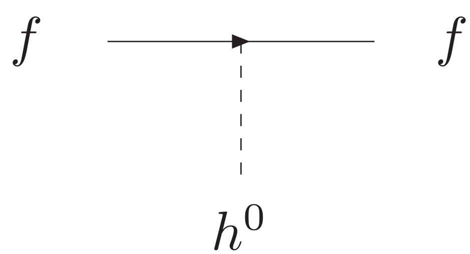
fermions	SU(2)	U(1)$_{\mathrm{Y}}$
$(\nu\,,\,e^-)_L$	2	-1
e^-_R	1	-2
$(u\,,\,d)_L$	2	$1/3$
u_R	1	$4/3$
d_R	1	$-2/3$

where the electric charge is given by $Q = T_3 + \frac{1}{2}Y$.

Before electroweak symmetry breaking, Standard Model fermions are massless, since the fermion mass term $\mathcal{L}_m = -m(\bar{f}_R f_L + \bar{f}_L f_R)$ is not gauge invariant.

The fermions couple to the Higgs field through the gauge invariant Yukawa couplings. The quarks and charged leptons acquire mass via interaction with the Higgs condensate.





Thus, $g_{hf\bar{f}} = m_f/v$, *i.e.*, Higgs couplings to fermions are proportional to the corresponding fermion mass.

Summary of Standard Model Higgs properties

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

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

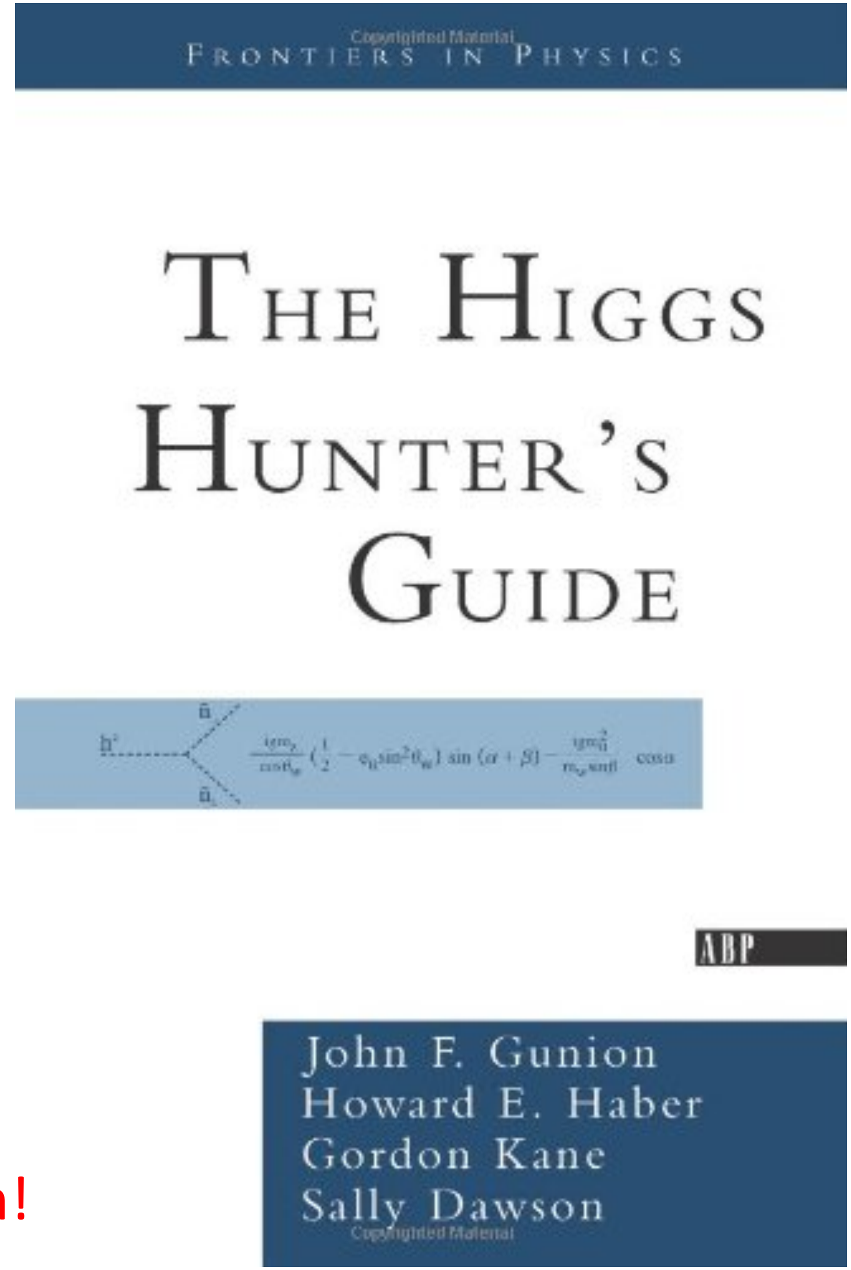
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

By 1990, there was a huge literature on the phenomenology of the Higgs boson of the Standard Model and of Higgs bosons of extended Higgs sectors.

The LEP collider was ready to extend the Higgs search to masses of order the Z mass and beyond.

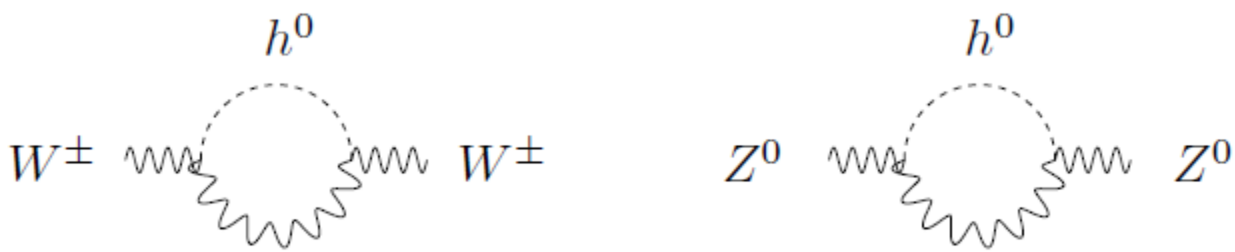
On the horizon was the SSC (soon to be cancelled) and the LHC.



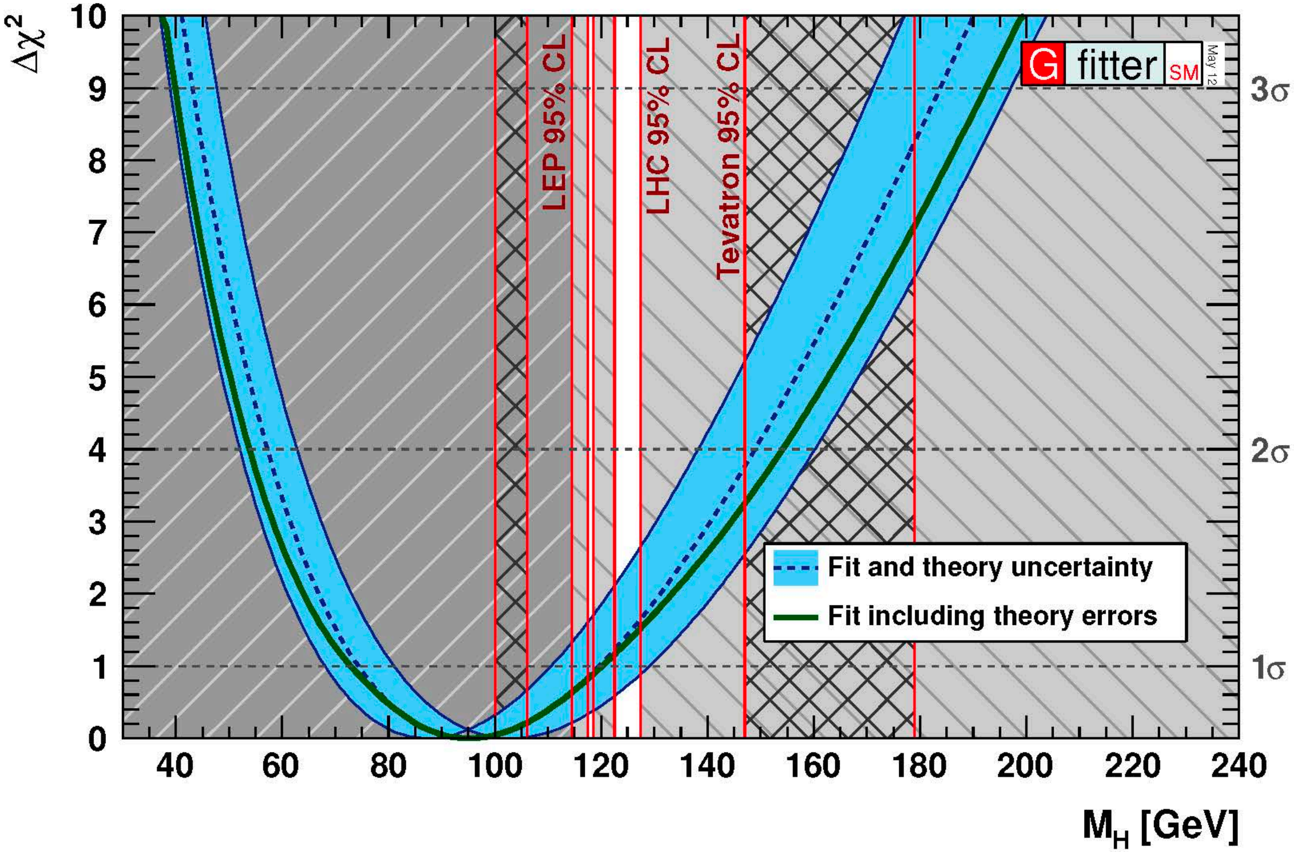
The hunt for the Higgs boson was on!

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.

Where does the EWSB mass scale come from?

How can we understand the magnitude of the EWSB scale? In the absence of new physics beyond the Standard Model, its natural value would be the Planck scale. The alternatives are:

- Naturalness is restored by a symmetry principle—supersymmetry—which ties the bosons to the more well-behaved fermions.

- The Higgs boson is an approximate Goldstone boson—the only other known mechanism for keeping an elementary scalar light.

- The Higgs boson is a composite scalar, with an inverse length of order the TeV-scale.

- The naturalness principle does not hold in this case. Unnatural choices for the EWSB parameters arise from other considerations (landscape?).

Supersymmetry (SUSY) provides a mechanism in which the quadratic sensitivity of scalar squared-masses to very high-energy scales is exactly canceled. Since SUSY is not an exact symmetry of nature, the supersymmetry must be broken. To maintain the naturalness of the theory, the SUSY-breaking scale cannot be significantly larger than 1 TeV.

> The scale of supersymmetry-breaking must be of order 1 TeV or less, if supersymmetry is associated with the scale of electroweak symmetry breaking.

The minimal supersymmetric extension of the Standard Model (MSSM) requires two Higgs doublets to guarantee that gauge anomalies due to higgsino pairs of opposite hypercharge exactly cancel.

In the MSSM, the Higgs quartic couplings are set by the gauge couplings (in contrast to the Standard Model where it is a free parameter). It follows that at tree-level, there is an upper bound $m_h \leq m_Z$, a result that was ruled out by the LEP collider in 1999.

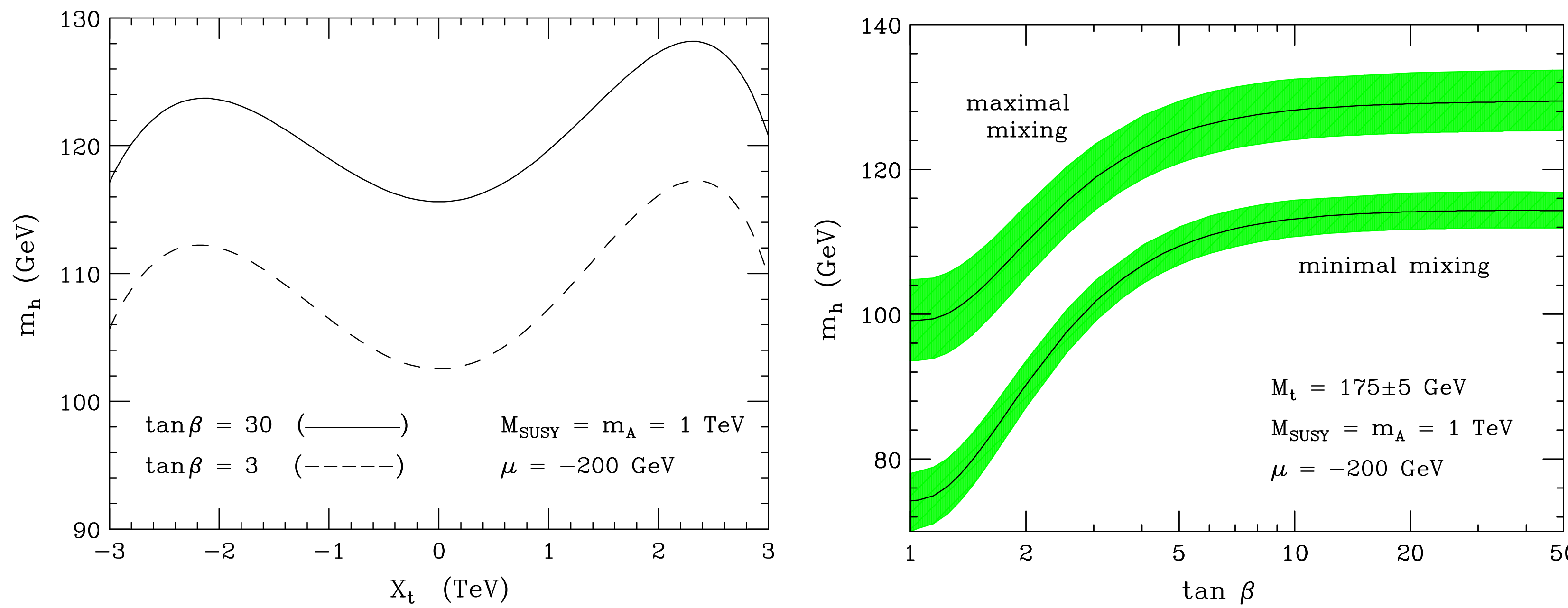
Saving the MSSM Higgs sector—the impact of radiative corrections

We have already noted the tree-level relation $m_h \leq m_Z$, which is already ruled out by LEP data. But, this inequality receives quantum corrections. The Higgs mass can be shifted due to loops of particles and their superpartners (an incomplete cancelation, which would have been exact if supersymmetry were unbroken):

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

where $X_t \equiv A_t - \mu\cot\beta$ governs stop mixing and M_S^2 is the average squared-mass of the top-squarks $\widetilde{t}_1$ and $\widetilde{t}_2$ (which are the mass-eigenstate combinations of the interaction eigenstates, $\widetilde{t}_L$ and $\widetilde{t}_R$).

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, some of the leading three-loop terms, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].



Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

The Higgs Boson---Present

- Higgs boson production and decay
- The discovery of the Higgs boson
- Implications of a SM-like Higgs boson

Higgs production at hadron colliders

At hadron colliders, the relevant processes are

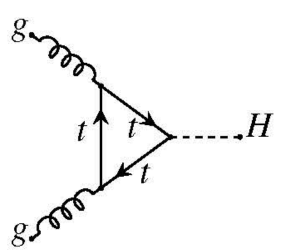
$$gg \to h^0\,, \quad h^0 \to \gamma\gamma\,, VV^{(*)}\,,$$

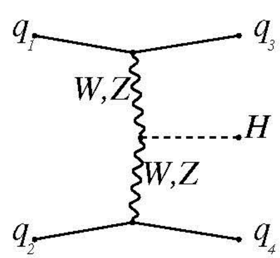
$$qq \to qqV^{(*)}V^{(*)} \to qqh^0, \quad h^0 \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

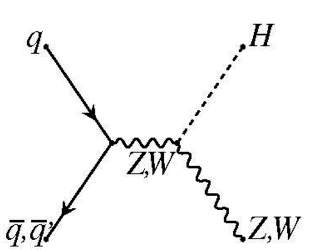
$$q\bar{q}^{(\prime)} \to V^{(*)} \to Vh^0\,, \quad h^0 \to b\bar{b}\,, WW^{(*)}\,,$$

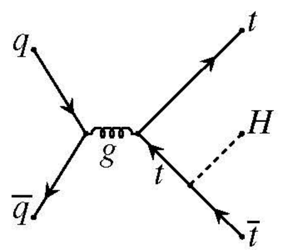
$$gg, q\bar{q} \to t\bar{t}h^0, \quad h^0 \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

where $V = W$ or Z.

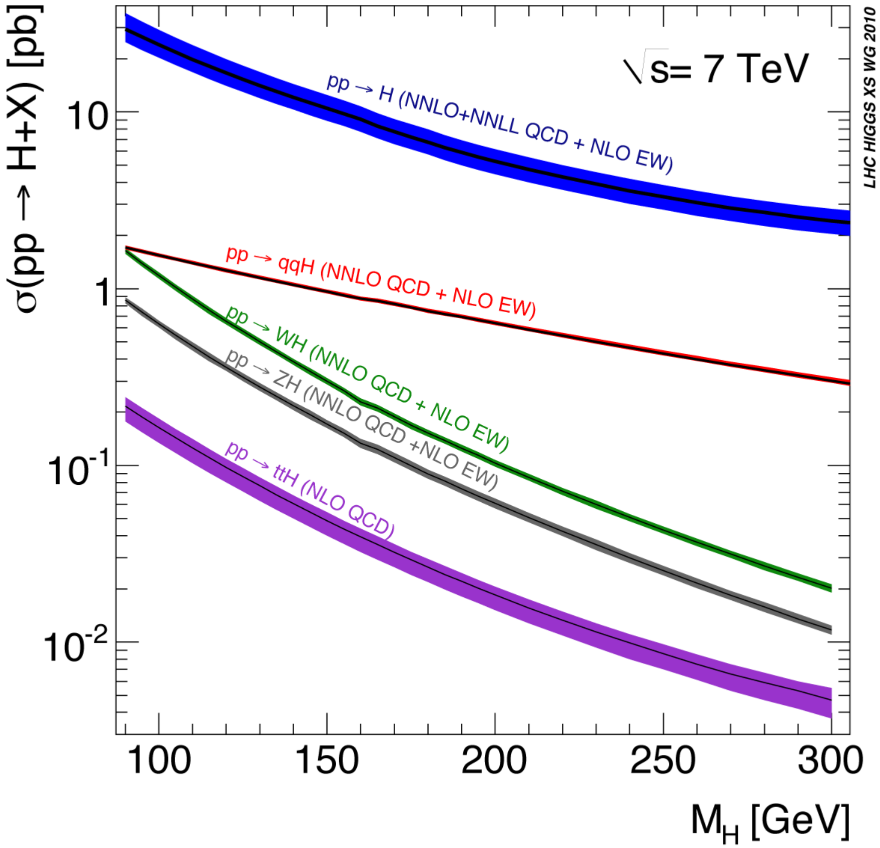


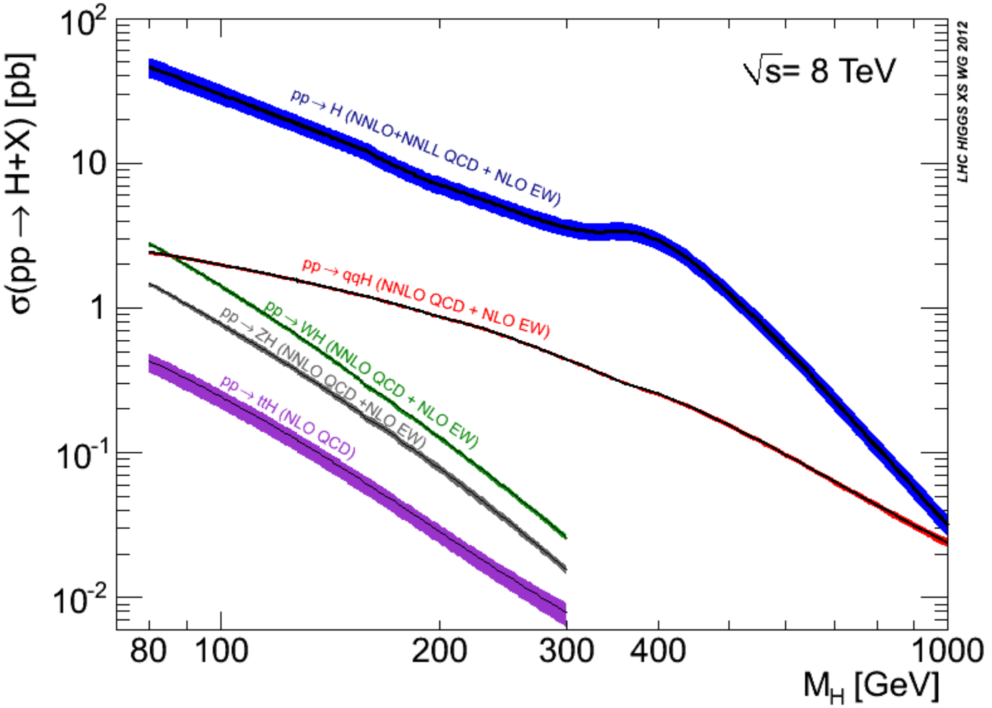






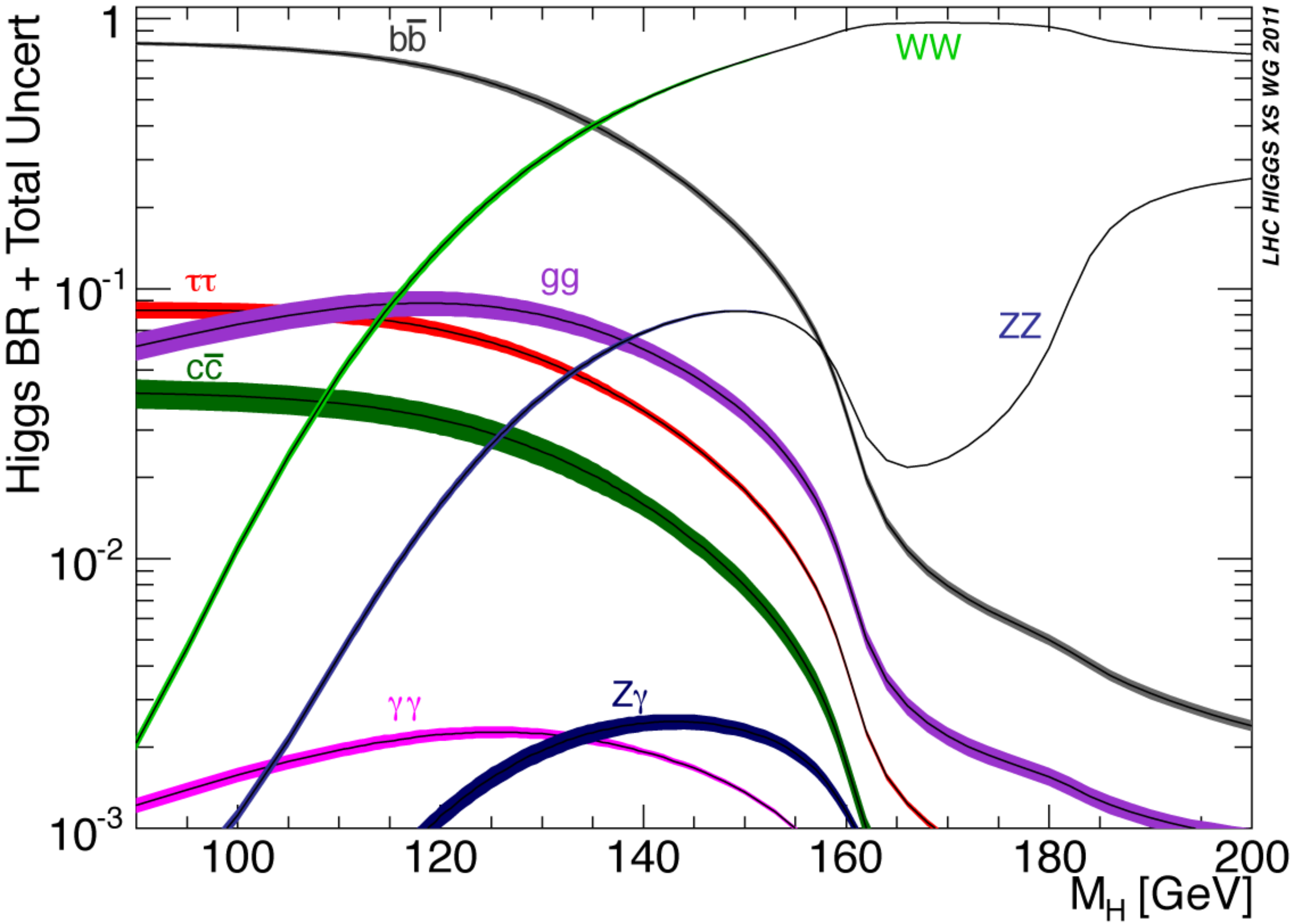
Higgs boson production cross sections at a pp collider





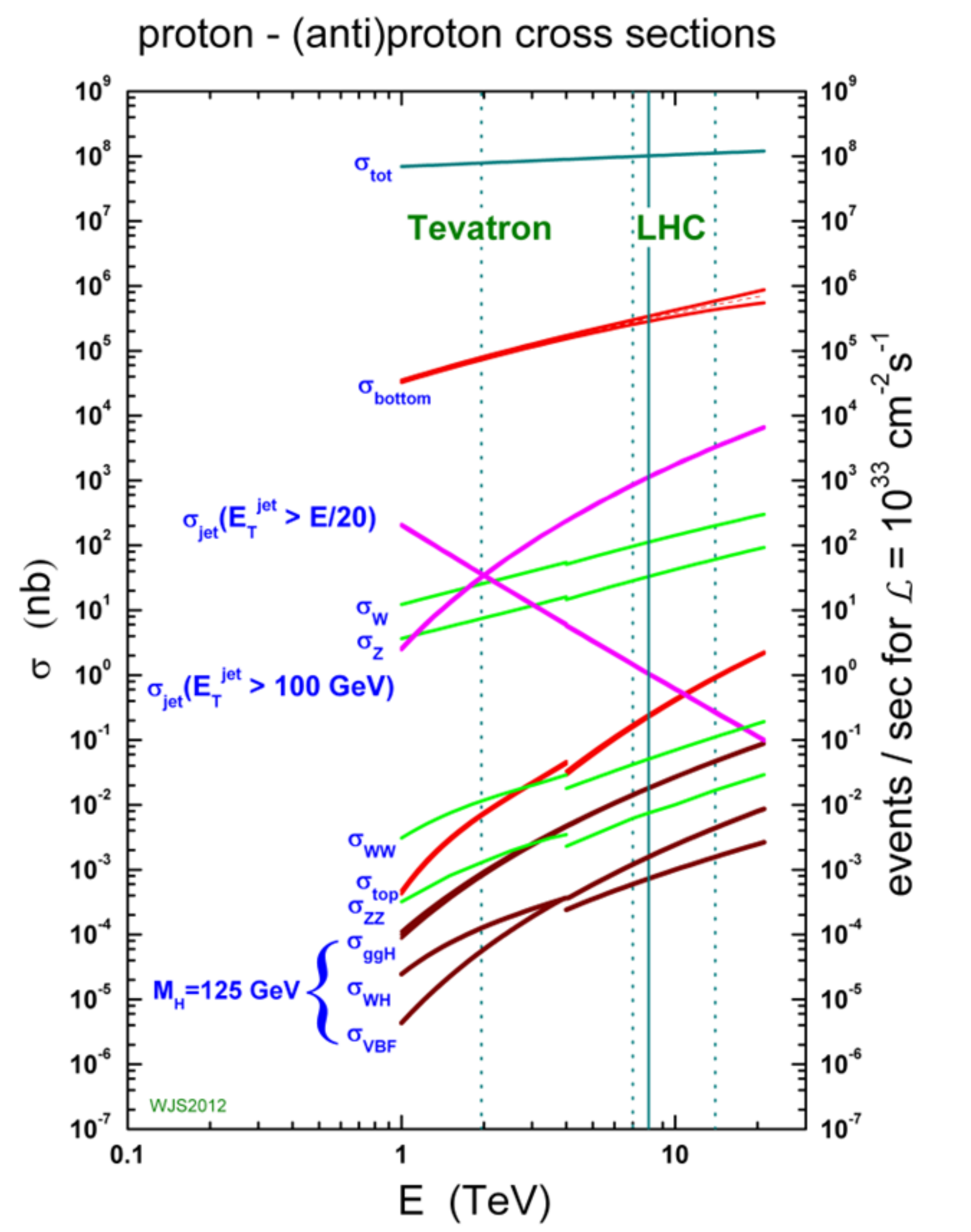
With 25 fb^{-1} of data, one would produce roughly 500,000 Higgs bosons for a Higgs mass of M_H = 125 GeV.

Probability of Higgs boson decay channels



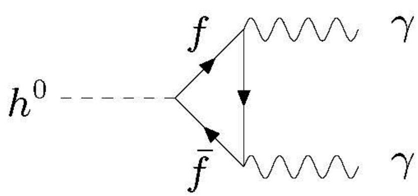
Question: why not search for Higgs bosons that decay into a pair of b-quarks?

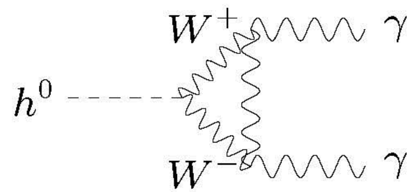
Answer: The Standard Model background is overwhelming. There are more than 10^7 times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

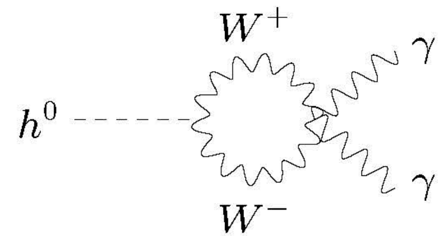


SM Higgs decays at the LHC for $m_h \sim 125$ GeV

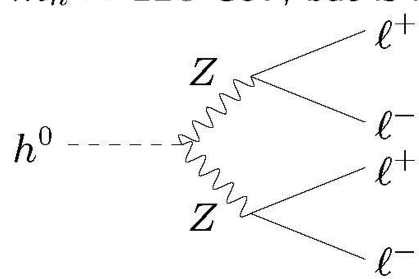
1. The rare decay $h^0 \to \gamma\gamma$ is the most promising signal.



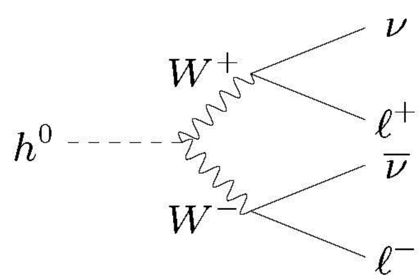




2. The so-called golden channel, $h^0 \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ (where one or both Z bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.



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 LHC Discovery of 4 July 2012

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

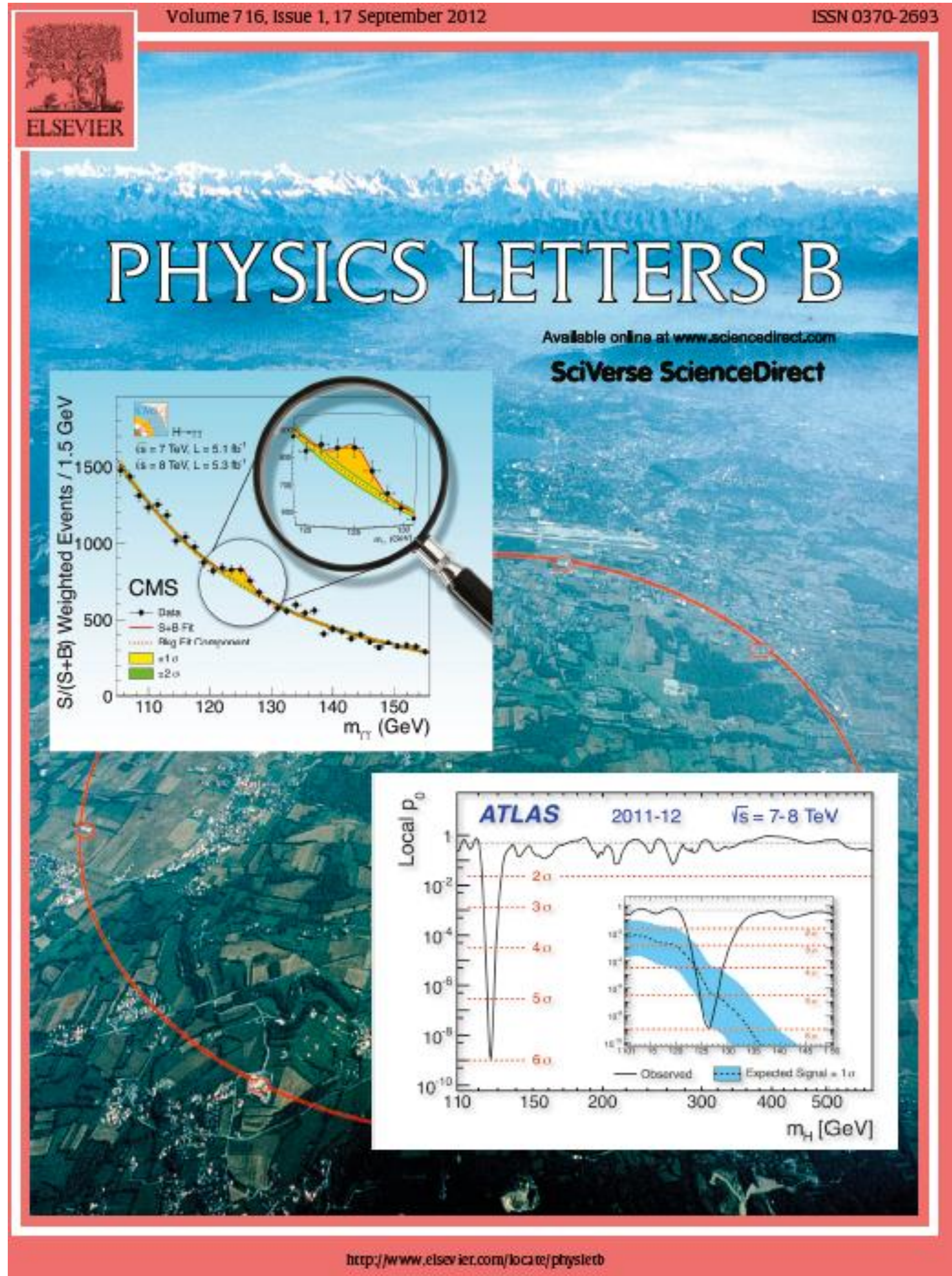
The discovery of the new boson is published in Physics Letters B.

<u>ATLAS Collaboration:</u>

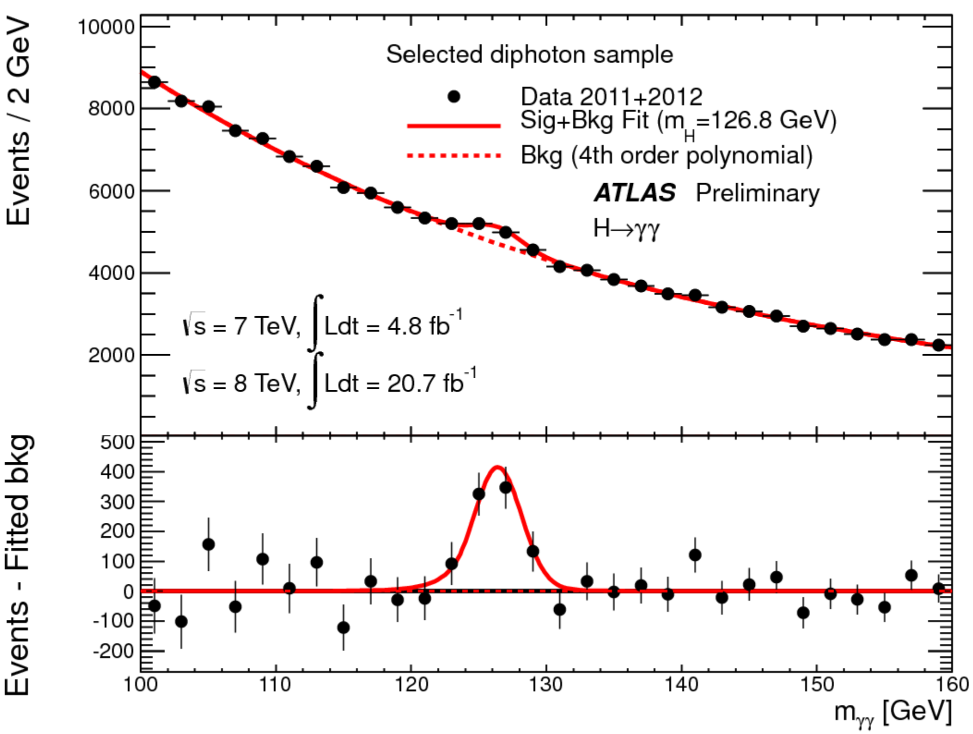
Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

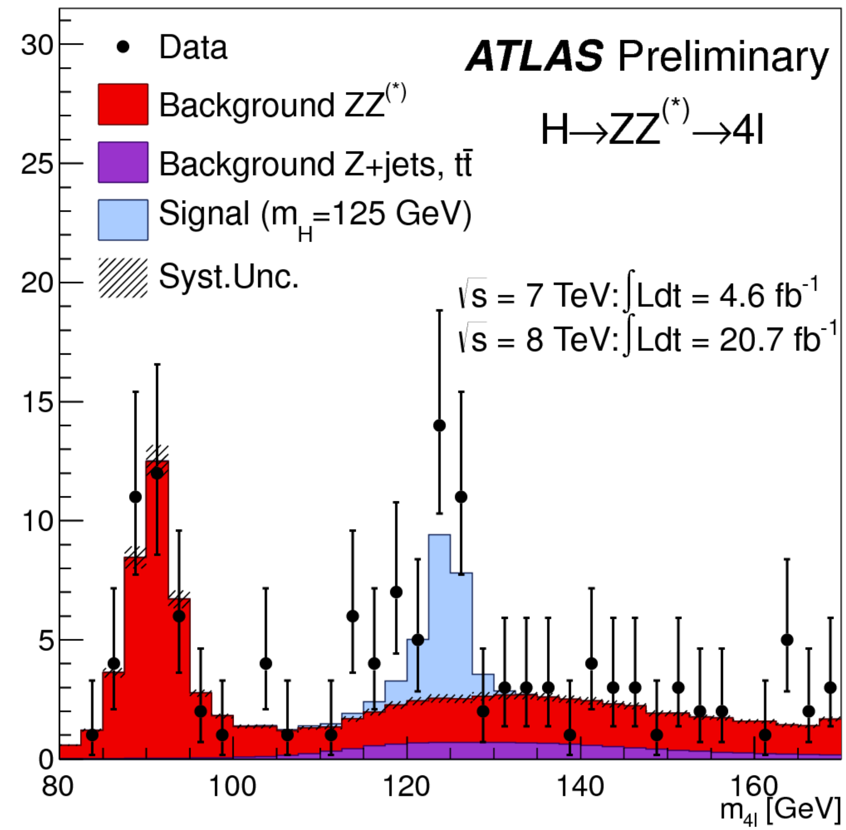
Physics Letters B716 (2012) 30—61



A boson is discovered at the LHC by the ATLAS Collaboration

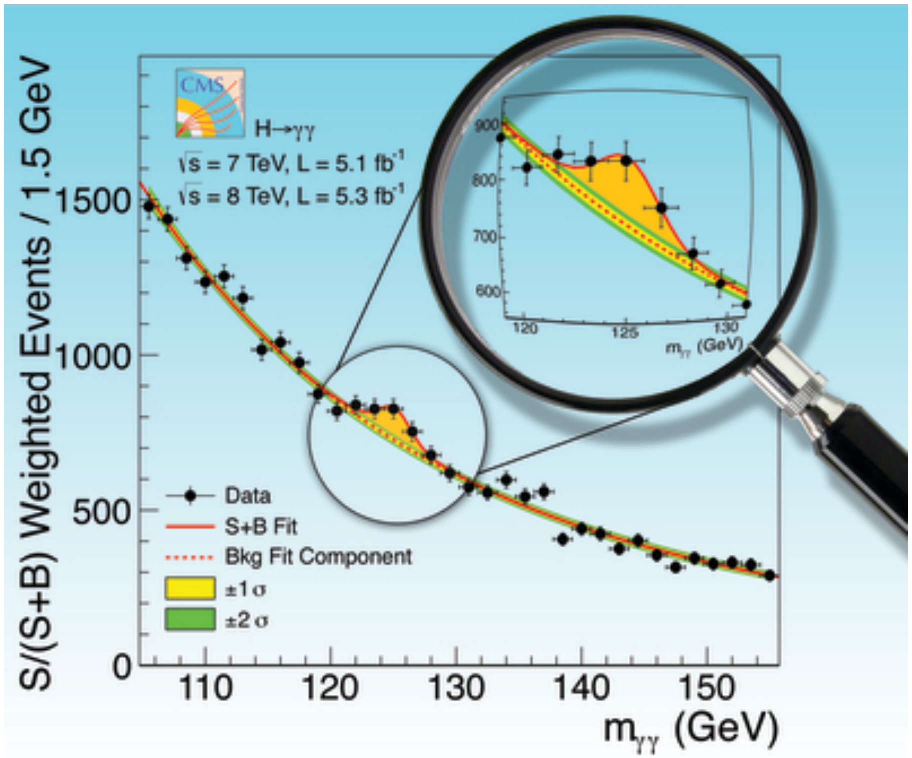


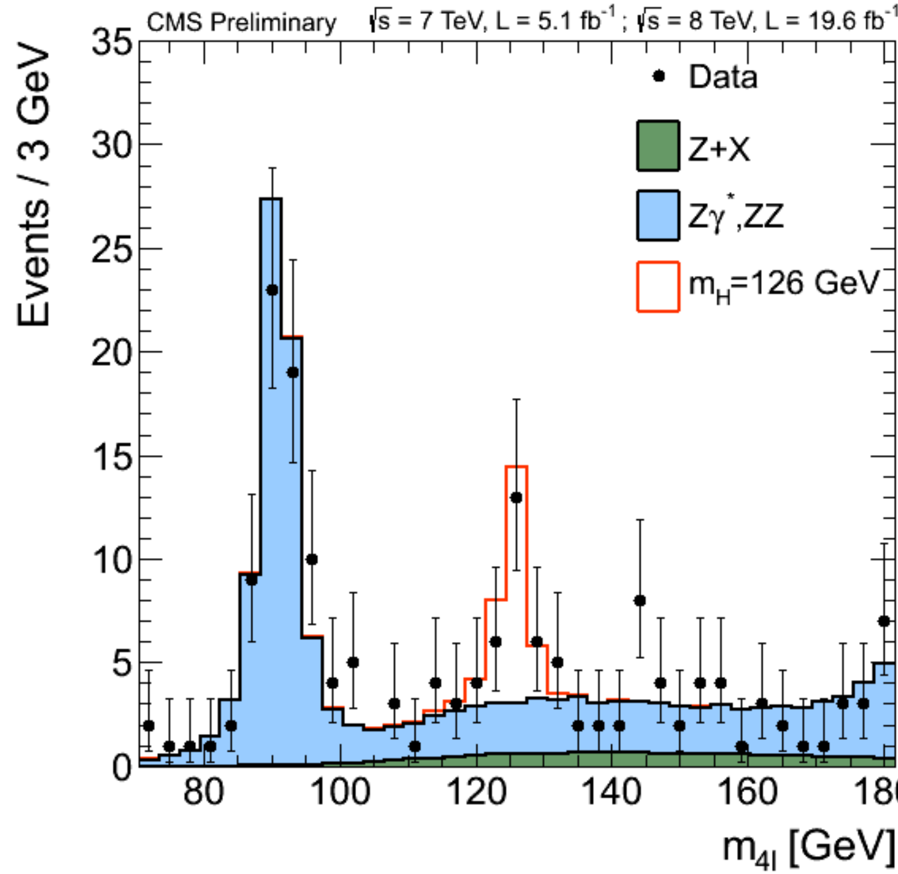
Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.8 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component. Taken from ATLAS-CONF-2013-012 (March, 2013).



The distribution of the four-lepton invariant mass for the selected candidates, compared to the background expectation in the 80 to 170 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 ATLAS-CONF-2013-013 (March, 2013).

A boson is discovered at the LHC by the CMS Collaboration

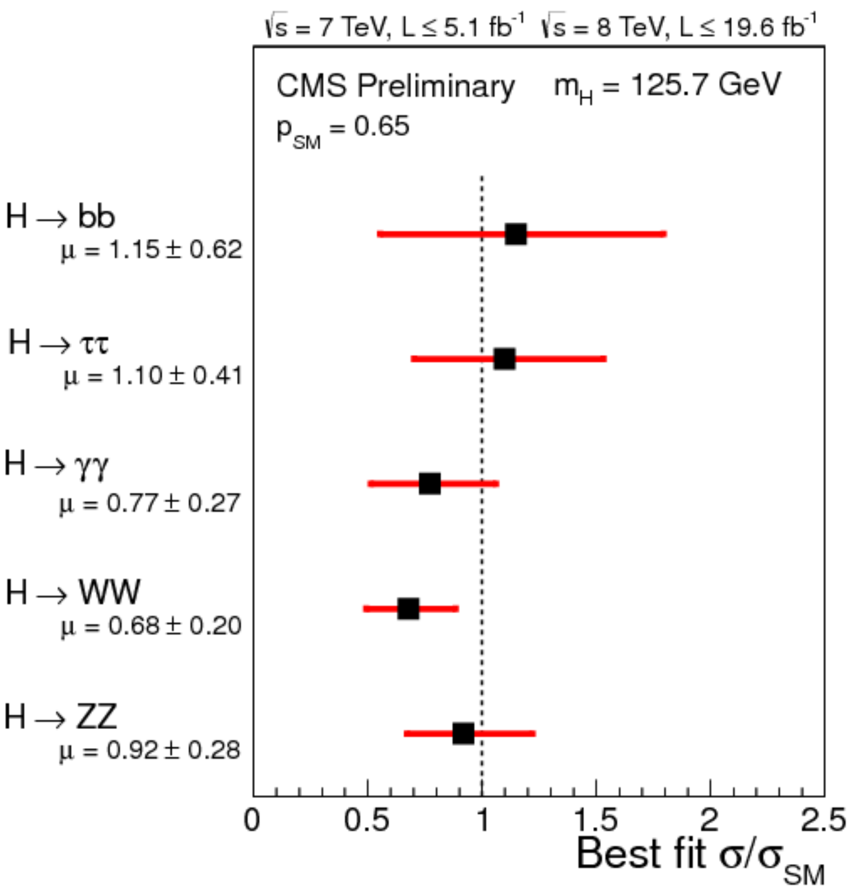


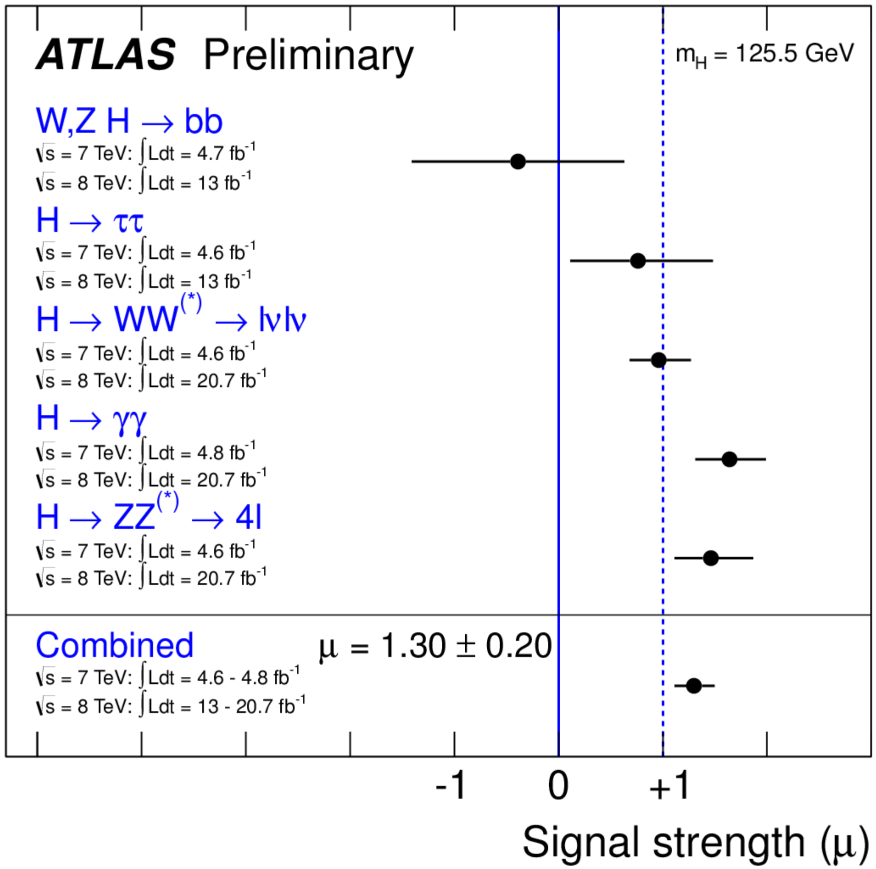


The diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of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

Distribution of the four-lepton reconstructed mass in full mass range for the sum of the 4e, 4μ, and 2e2μ channels. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at √s = 7 TeV and √s = 8 TeV. [70-180] GeV range - 3 GeV bin width. Taken from CMS-PAS-HIG-13-002 (March, 2013).

A Standard Model—like Higgs boson?

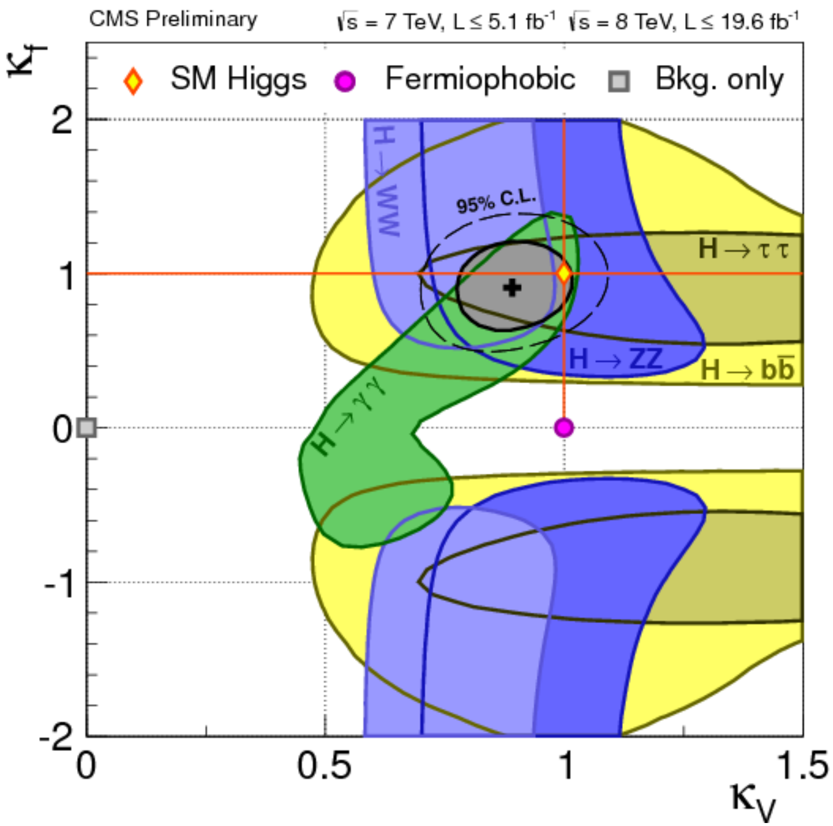




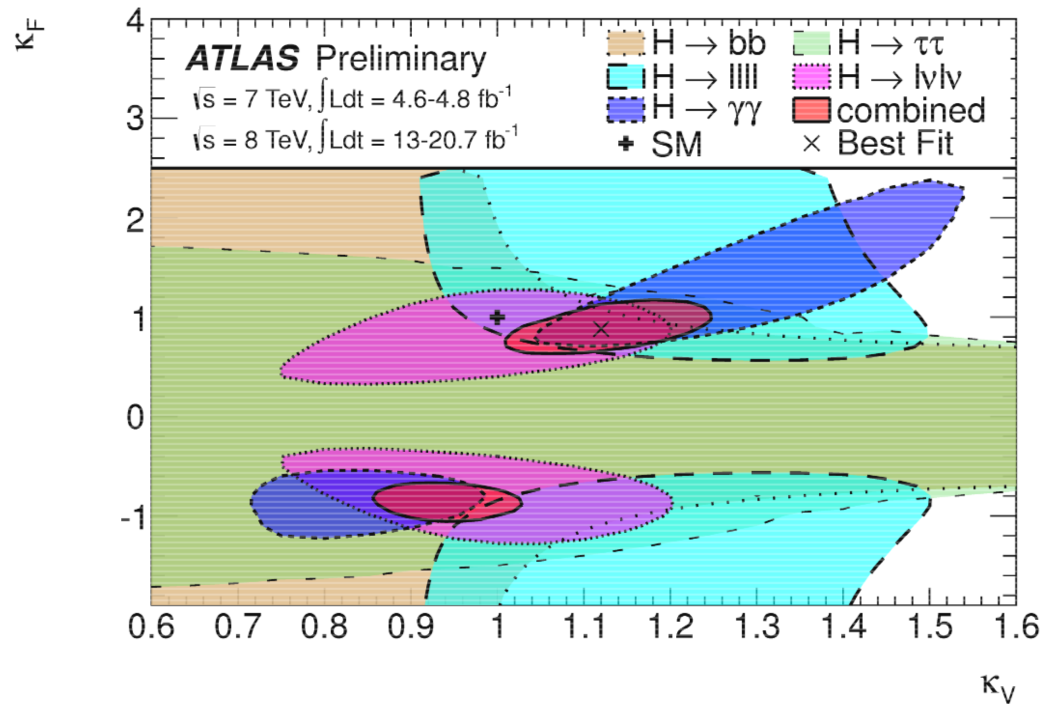
Taken from CMS-PAS-HIG-130-005 (March, 2013)

Taken from ATLAS-CONF-2013-034 (March, 2013)

Search for deviations from SM-Higgs couplings to fermions and WW/ZZ



Taken from CMS-PAS-HIG-130-005 (March, 2013)



Fits for 2-parameter benchmark models probing different coupling strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width: (a) Correlation of the coupling scale factors κ_F and κ_V; (b) the same correlation, overlaying the 68% CL contours derived from the individual channels and their combination; (c) coupling scale factor κ_V (κ_F is profiled); (d) coupling scale factor κ_F (κ_V is profiled). The dashed curves in (c) and (d) show the SM expectation. The thin dotted lines in (c) indicate the continuation of the likelihood curve when restricting the parameters to either the positive or negative sector of κ_F.

Taken from ATLAS-CONF-2013-034 (March, 2013)

Implications of a SM-like Higgs boson

The SM employs a minimal Higgs sector with one Higgs doublet. But, why should nature choose such a minimal structure? The supersymmetric extension of the SM employs two Higgs doublets. Other approaches beyond the SM can employ more complicated scalar sectors.

The decoupling limit (heavy mass decoupling) [Haber and Nir]

In many extended Higgs sectors, one can take a certain mass parameter M large. For $M \gg v$, most Higgs states become heavy. The effective Higgs theory at an energy scale below M is that of the SM Higgs boson!

The alignment limit (weak coupling decoupling) [Craig, Galloway, Thomas]

In all extended Higgs sectors, one can take the limit where one or more Higgs self-couplings vanish. In this case, there exists a scalar mass-eigenstate that aligns with $\mathrm{Re}(H_1^0 - v/\sqrt{2})$, where $\langle H_1^0 \rangle = v/\sqrt{2}$, which behaves precisely as a SM Higgs boson.

Example: Approaching the decoupling/alignment limit in the 2HDM

Couplings of the SM-like Higgs boson h normalized to those of the SM Higgs boson, in the decoupling/alignment limit of the most general two-Higgs-doublet model (2HDM). The normalization of the pseudoscalar coupling of h to fermions is relative to the corresponding scalar coupling. The Z_i are related to the coefficients of the Higgs scalar potential, the ρ_i are complex 3×3 matrices that govern the Higgs-quark Yukawa couplings, and $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$ parameterize neutral Higgs mixing. In the decoupling/alignment limit, s_{12}, $s_{13} \ll 1$. In the alignment limit we also have Z_{6R}, $Z_{6I} \ll 1$.

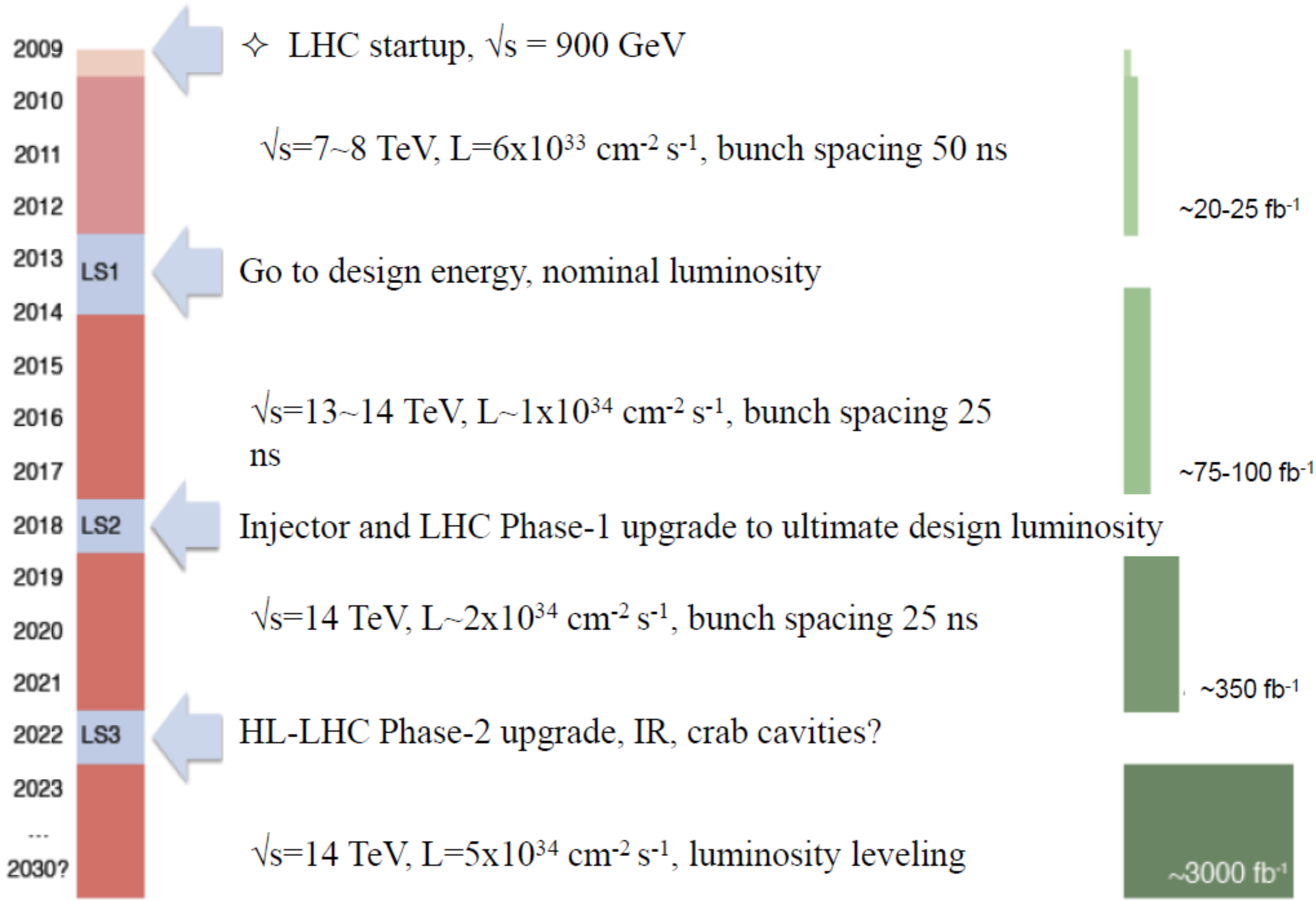
Higgs interaction	2HDM coupling	decoupling/alignment limit
hW^+W^-, hZZ	$c_{12}c_{13}$	$1 - \frac{1}{2}s_{12}^2 - \frac{1}{2}s_{13}^2$
hhh		$1 - 3(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$hhhh$		$1 - 4(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$h\overline{D}D$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^D - c_{12}s_{13}\rho_I^D$	$\mathbb{1} - s_{12}\rho_R^D - s_{13}\rho_I^D$
$ih\overline{D}\gamma_5 D$	$s_{12}\rho_I^D - c_{12}s_{13}\rho_R^D$	$s_{12}\rho_I^D - s_{13}\rho_R^D$
$h\overline{U}U$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^U - c_{12}s_{13}\rho_I^U$	$\mathbb{1} - s_{12}\rho_R^U - s_{13}\rho_I^U$
$ih\overline{U}\gamma_5 U$	$-s_{12}\rho_I^U + c_{12}s_{13}\rho_R^U$	$-s_{12}\rho_I^U + s_{13}\rho_R^U$

A precision Higgs program can detect small deviations from SM Higgs couplings and thus probe the structure of the extended Higgs sector.

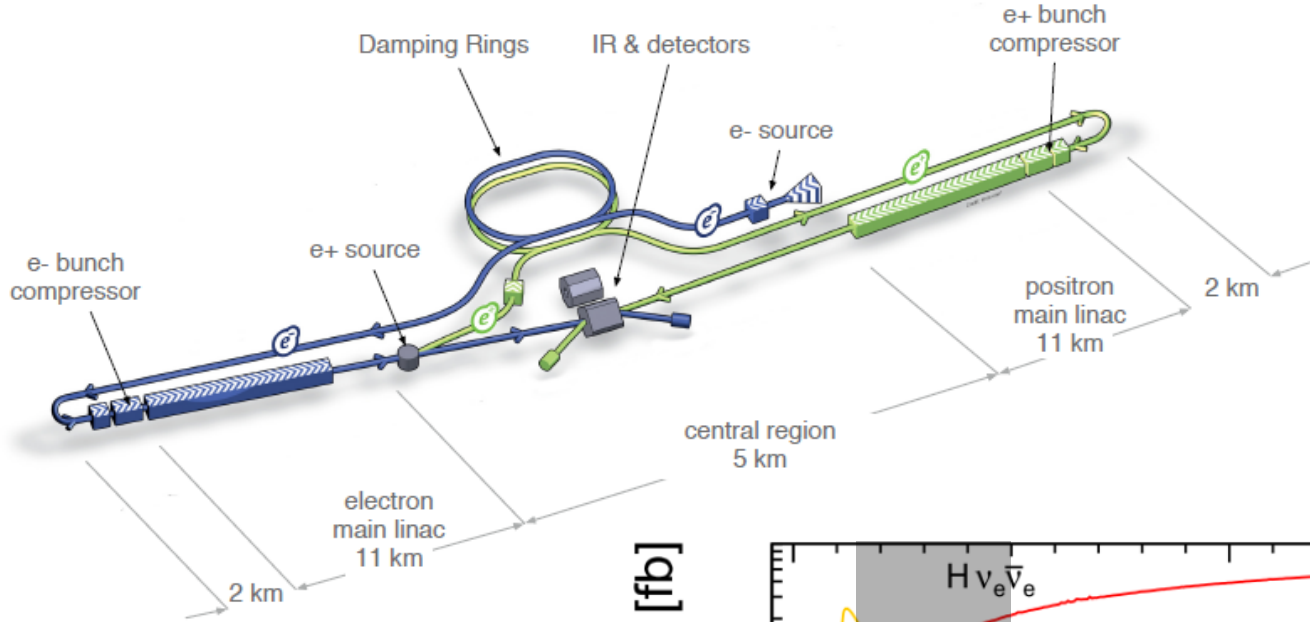
The Higgs Boson---Future

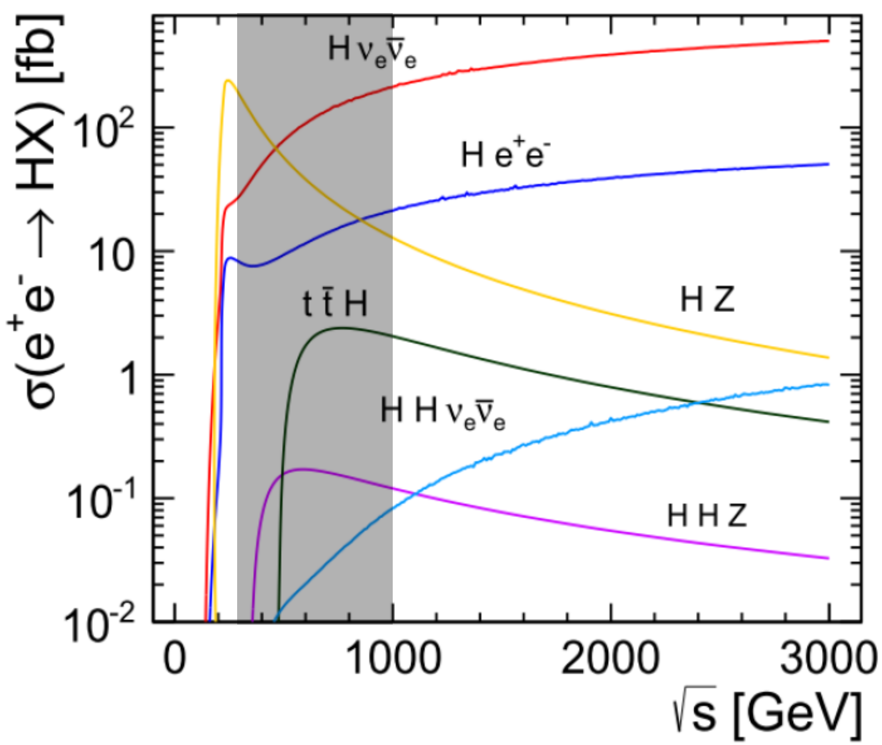
- Higgs boson studies in future running at the LHC
- The ILC as a precision Higgs factory

The LHC Timeline



ILC : e^+e^- Linear Collider at 250 GeV < $\sqrt{s}$ < 1000 GeV





Energy/Luminosity scenarios

Stage #	nickname	$E_{cm}(1)$ (GeV)	Lumi (1) (fb^{-1})	$E_{cm}(2)$ (GeV)	Lumi (2) (fb^{-1})	$E_{cm}(3)$ (GeV)	Lumi (3) (fb^{-1})	Runtime (years)
1	ILC (250)	250	250					1.1
2	ILC (500)	250	250	500	500			2.0
3	ILC (1000)	250	250	500	500	1000	1000	2.9
4	ILC(LumUp)	250	1150	500	1600	1000	2500	5.8

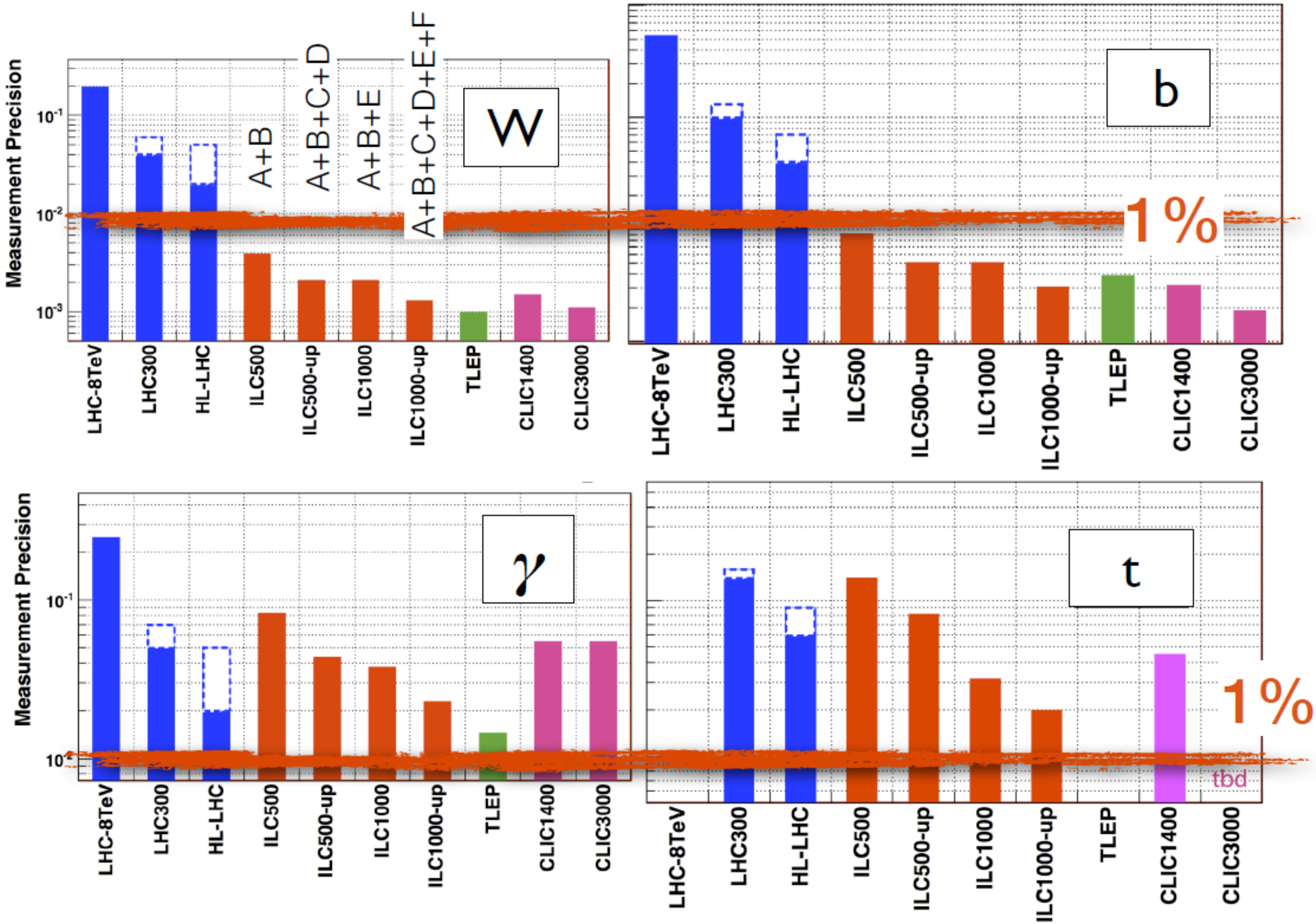
- At each stage, the *accumulated* luminosity of a given energy is listed. The runtimes listed consist of actual elapsed *cumulative* running time at the end of each stage. Assuming that the ILC runs for 1/3 of the time, then the actual time elapsed is equal to the runtime times 3.

- Assume that the ILC is run at its baseline luminosity at 250 GeV (stage 1), then at 500 GeV (stage 2), and finally at 1000 GeV (stage 3)

- Then, stage 4 repeats the successive stages 1, 2 and 3 at the upgraded luminosity.

In real time, this entire program would require 5.8 x 3 = 17.4 years.

Precision in kappa by facility

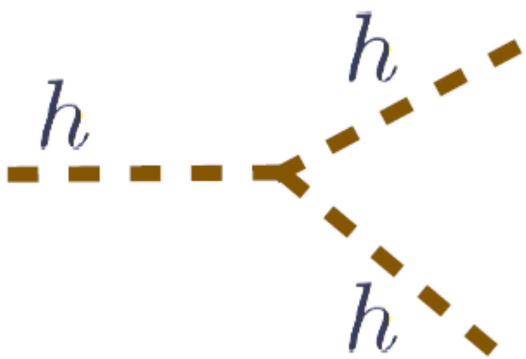


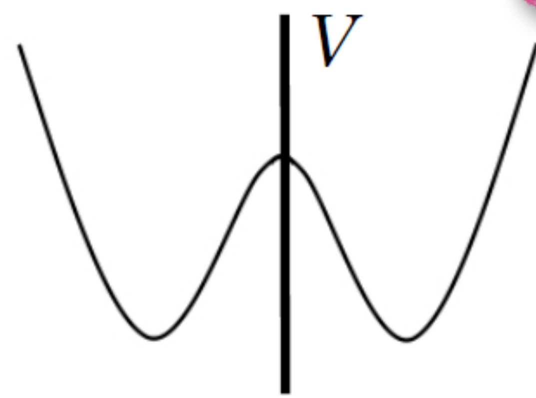
Higgs Self-Coupling

Critical feature of SM

- extremely challenging

$$V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$





	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

Higgs self-coupling is difficult to measure precisely at any facility.

Brock/Peskin Snowmass 2013

Mass and Width

Mass

- LHC: 50 MeV/c2
- ILC: 35 MeV/c2

Total Width

- LHC limits on Γ
- ILC: model-independent
- MC: direct

Table 1-26. *Summary of the Higgs mass and total width measurement precisions of various facilities. "Full ILC" is 250+500+1000 GeV with 250+500+1000 fb^{-1}, while "ILC LumUp" is 1150+1600+2500 fb^{-1} at the same collision energies.*

Facility	LHC	HL-LHC	ILC500	ILC1000	ILC1000-up	CLIC	TLEP (4 IP)	μC
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350	126
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250/500	250/500/1000	1150/1600/2500	500/1500/2000	10,000/1400	
m_H (MeV)	100	50	35	35	?	33	7	0.03–0.25
Γ_H	–	–	5.9%	5.6%	2.7%	8.4%	0.6%	1.7–17%

few %