Higgs Boson : the early story.

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Theoretical Perspectives of Higgs Physics a decade after the Higgs Discovery.

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- Begin at the beginning (I) : Massive W.
- Begin at the beginning (II) : Spontaneous Symmetry Breaking.
- Model of Leptons : Combination of I and II.
- Higgs properties : what we ’knew’ and what we didnt?
- Theory bounds on Higgs mass.!
- ’Indirect’ bounds on Higgs mass.
- ’Landscape’ on the ’eve’ of the Higgs ’discovery’.

Weave in some very early involvement of my own in the story too!

Dedicated to my Ph.D. Supervisor Jack Smith whose supervisor for his Master's thesis was Peter Higgs! My own earliest connection with 'Higgs' !

I started my Graduate studies in 1974 the year $\bar{c}c$ resonance J/Ψ was discovered, indicating correctness of the gauge field theoretic description of weak interactions based on the minimal gauge group $SU(2)_L \times U(1)$ gauge group.

Higgs boson as a real entity was beginning to be taken seriously.

One small thing: We are celebrating 10 years of the Higgs discovery and more than half a century of the Higgs (particle) itself.

Let us begin at the beginning . For Weak interactions the beginning was the V-A theory put forward by Sudarshan-Marshak and Feynman-Gell Mann.

$$\mathcal{H}_{\text{int}}^{\beta\,\text{decay}} = \frac{G_F C_V}{\sqrt{2}} \left[(\bar{n}\gamma^\mu \left(1 - \left|\frac{C_A}{C_V}\right| \gamma_5\right) p)(\bar{\nu}^e \gamma_\mu (1 - \gamma_5)\, e) \right] + \text{h.c.}$$

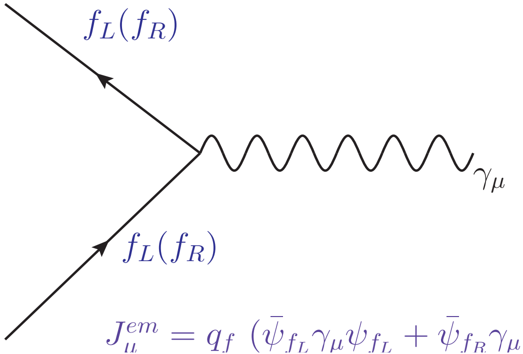
For μ decay $\left|\frac{C_A}{C_V}\right| = 1$, with appropriate changes in the fermion labels.

So in fact basically:

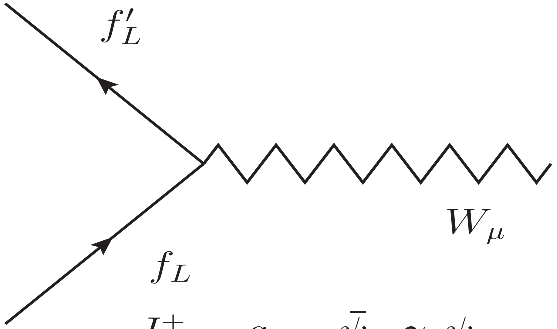
$$\mathcal{H}_{eff}^{4fermion} = -4\frac{G_\mu}{\sqrt{2}}\left[\left(\bar{\psi}_{3L}\gamma^\mu\psi_{1L}\right)\left(\bar{\psi}_{4L}\gamma_\mu\psi_{2L}\right) + h.c.\right]$$

Existence of ONLY vector and axial vector currents means that the 'pointlike' four-fermion interaction can be thought of as being caused by an exchange of a spin 1 particle, the Weak boson. (Introduced by Schwinger **before** the $V{-}A$ theory but mentioned by S-M in their paper.)

Extension of ’known’ QED (Anticipating gauge theory here!):

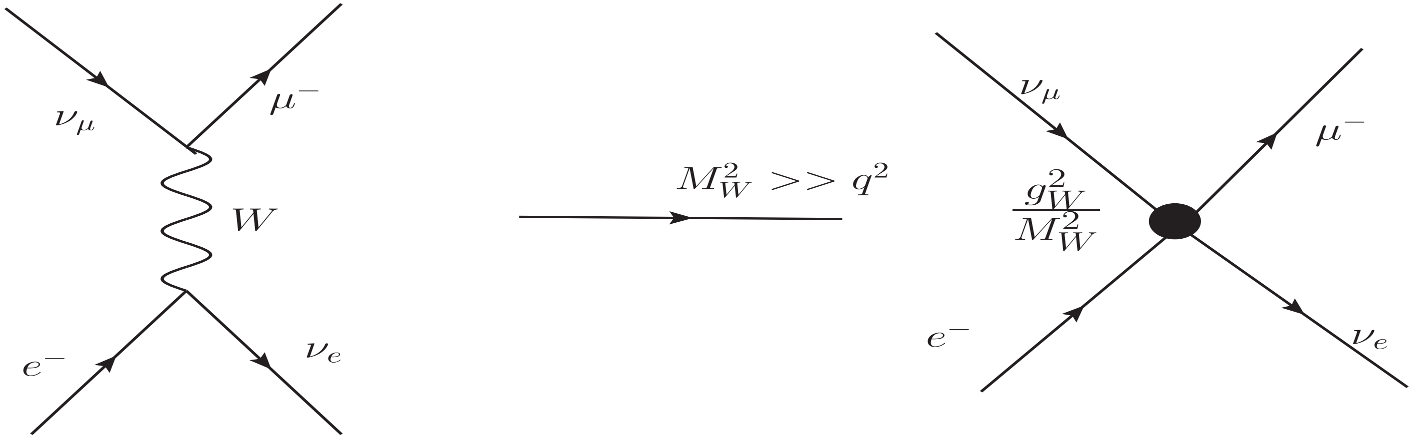


$J^{em}_\mu = q_f\ (\bar{\psi}_{f_L}\gamma_\mu\psi_{f_L} + \bar{\psi}_{f_R}\gamma_\mu\psi_{f_R})$



$J^+_\mu = g_{weak}\bar{\psi}_{f'_L}\gamma_\mu\psi_{f_L}$

Since the weak interaction Hamiltonian describes a point interaction



If one calculates cross-sections in the V-A theory there is a problem:

$$\sigma^{\text{tot}}(\nu_\mu + e \to \nu_e + \mu^-) = \frac{G_\mu^2\ s}{2\pi} = \frac{G_\mu^2\ m_e\ E_{\nu_\mu}}{\pi}$$

This violates unitarity for

$$s\ >\ 4\sqrt{2}\pi G_\mu^{-1}$$

For a massive W unitarity will be preserved. Therefore m_W should be less than the energy at which this will happen. We find that $M_W\ \leq\ \sim 300$ GeV. **Basically not infinite!**

Thus problem of bad high energy behaviour of the point like fermi theory was cured when one introduced a massive W boson

But then it raised another problem.

Now if one computes $\nu\bar{\nu} \to W^+W^-$ these amplitudes violate unitarity at high energies because of the longitudinal degrees of freedom of the W.

Glashow in fact noticed that if we think of a gauge theory based on $SU(2) \times U(1)$ gauge group, this amplitude becomes well behaved. (will discuss this later)

But there is a problem with gauge theories where gauge bosons have masses.

QED as a gauge theory was very well understood and established.

Yang and Mills had already put forward the Non-Abelian gauge theories.

Gauge theories of weak interaction were not possible because the nonzero mass term would break the gauge invariance!

Nobody had an idea how to sort this problem! In fact not many other than the inventors of the Standard Model were thinking of weak interactions as gauge theories.

A simultaneous development was understanding of the symmetries. This was happening in the context of strong interactions.

What was seen that many symmetries were approximate symmetries : iso spin, flavour SU(3)...

For pure leptonic weak currents $|C_V/C_A| = 1$. For β decays $\frac{C_A}{C_V} \neq 1$. This was understood in terms of effects of strong interactions on the **Axial Vector current** which is **partially** conserved. This was the breaking of chiral symmetry. So people were discussing how broken symmetries could be described.

Goldberger and Treiman had proved that C_A magnitude could be understood if the divergence of axial vector current was proportional to the π field.

Spontaneous breaking of a symmetry:

The vacuum does not exhibit the symmetries of the Lagrangian.

The SSB was first introduced in the context of strong interactions theories in fact.

Weinberg, Salam and Goldstone proved a path breaking theorem Phys. Rev. 127, 965 (1962):

Abstract: Some proofs are presented of Goldstone's conjecture, that if there is continuous symmetry transformation under which the Lagrangian is invariant, then either the vacuum state is also invariant under the transformation, or there must exist spinless particles of zero mass.

Since no spinless massless particles were known to exist this seemed to be the end of the idea of SSB in field theory.

However Nambu made sense of the whole thing by pointing out that one could justify Goldberger-Trieman relation by understanding that the chiral symmetry of the strong interactions is spontaneously broken.

If this symmetry were an exact symmetry π would be massless. Since the symmetry is actually not exact , we have an almost massless pion. The pseudo-goldstone boson.

This clarified the implications of the SSB for strong interactions.

The spontaneously broken symmetry was 'visible' in the interactions of the Goldstone boson (in this case the π).

Anderson P.M. Anderson, Phys. Rev. 130, 439 (1963) showed in the non relativistic context that including Yang-Mills interaction the problem with zero mass Goldstone excitations vanishes!

Abstract:

It is also shown that Schwinger's criterion that the vector field $m \neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m = 0$, but that the example of superconductivity illustrates that the physical spectrum need not. *Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.*

Two theoretical issues:

Local gauge invariance requires massless gauge bosons. How to get massive gauge bosons and still have a Lagrangian that respects gauge symmetry?

Spontaneous breaking of a continuous symmetry always leads to massless scalars in the theory.

Combine SSB with a local gauge theory and we get a healthy way of getting massive gauge bosons, still respecting the gauge invariance!

P. W. Higgs, Phys. Lett. **12** (1964) 132; Phys. Rev. Lett. **13** (1964) 508.

F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321.

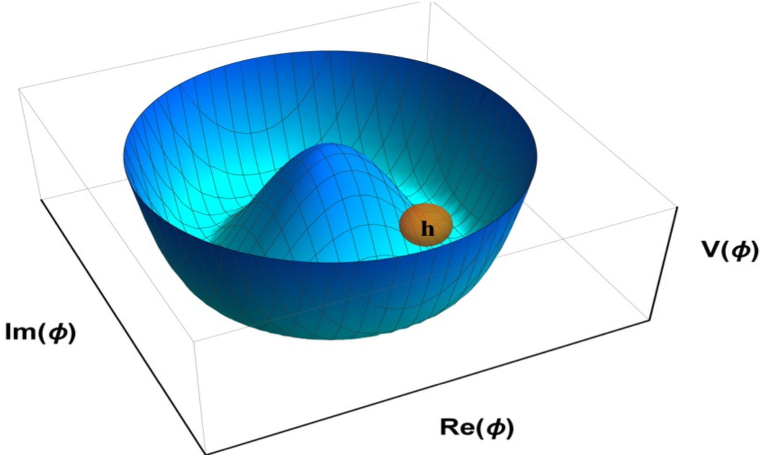
Higgs, Englert or Brout were not worrying about the Electro Weak interaction, but were interested in seeing how the massless Goldstone bosons which must exist in a theory with SSB, can be removed from physical spectrum. They proved that this could be done only if one marries the SSB with a local gauge theory.

Start with a Lagrangian invariant under a local gauge transformation with a complex scalar field ϕ, but with the wrong sign for the quadratic term.

$\mathcal{L} = (D_\mu\Phi)^\dagger(D^\mu\Phi) - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\phi)^2 - 1/4F_{\mu\nu}F^{\mu\nu}$

The physical vacuum will correspond to $\langle|\phi|\rangle = \frac{v}{\sqrt{2}}$, where $v = (-\mu^2/\lambda)^{1/2}$. m_A arises from the GI term $(D_\mu\Phi)^\dagger(D^\mu\Phi)$.

Mass of the gauge boson $m_A = gv$ and a physical scalar η with mass $m_\eta = \sqrt{2}\mu$.



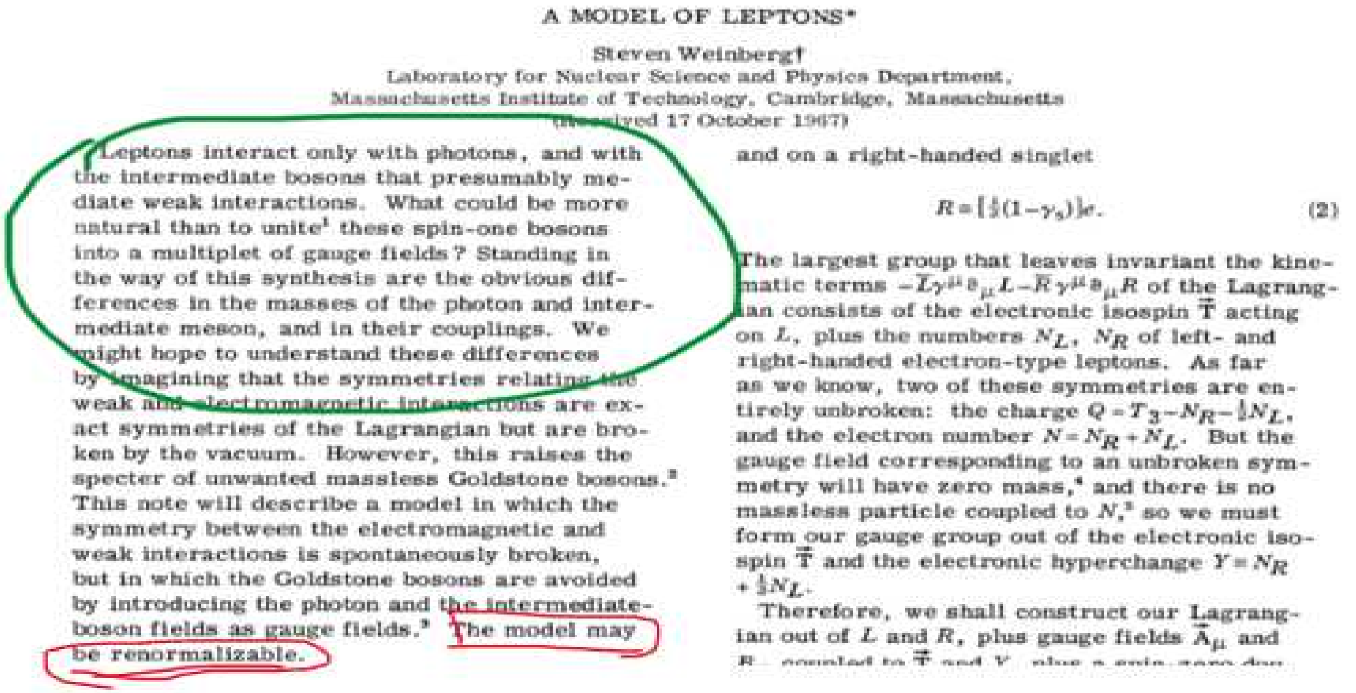
In the above example one started with a complex scalar and one massless gauge bosons and after SSB ended up with one massive gauge boson and one massive scalar!

In general the number of scalars required will depend on the pattern of symmetry breaking . We will come to it later! After all we do have one massless gauge boson in nature : the Photon!

Neither of the proponents of this SSB mechanism knew about the issue with EW interactions. So they did not apply this solution to the problem! Higgs specifically says so in an interview.

Salam and Weinberg independently noticed that the Higgs mechanism gave a way to give masses to the gauge bosons in a gauge invariant way!

They imagined that since the nonzero mass is now generated in a gauge invariant manner, the gauge symmetry would guarantee good high energy behaviour.



A MODEL OF LEPTONS*

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(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

and on a right-handed singlet

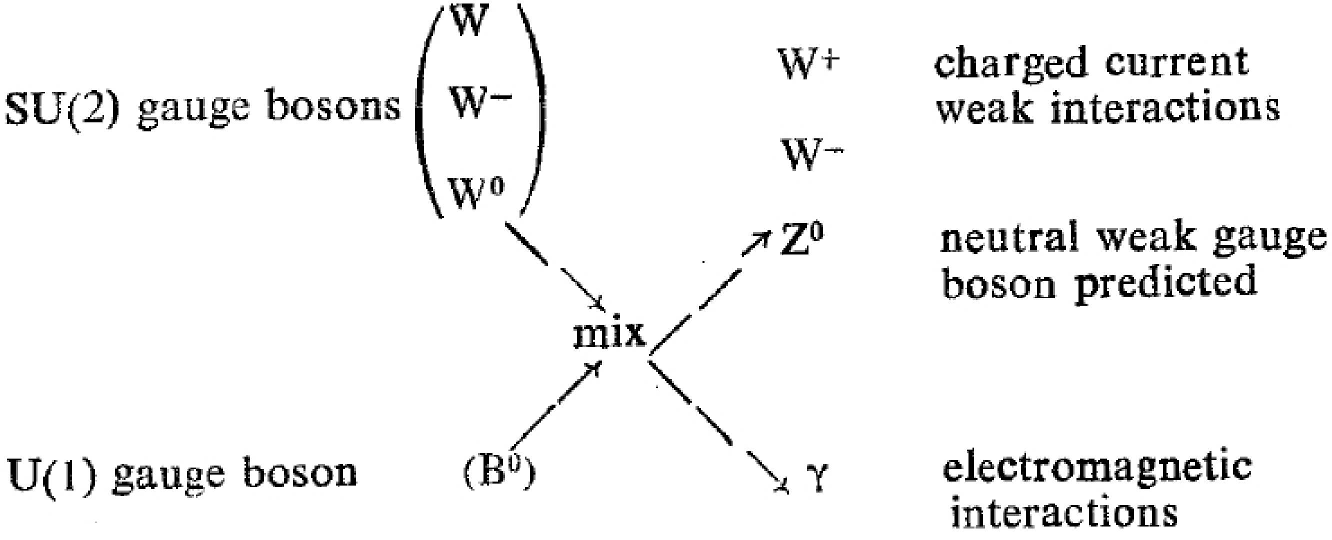
$$R=[\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y=N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero dou

$$\mathfrak{L}=-\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \qquad (4)$$



Glashow's paper Nucl.Phys. 22 (1961) 579-588. had EW unification but no 'model' for the nonzero masses of the weak bosons and hence no prediction for relation between m_W and m_Z. Much before the Higgs/Englert/Brout papers.

Weinberg's 'Model of Leptons' went beyond the Glashow 1964 paper.

1)Unified description of the electromagnetic and weak interaction as a $SU(2)_L \times U(1)$ theory with massive W/Z and massless γ.

2)He (and Salam) used Higgs mechanism. The choice of the representation to which the scalar field Φ belonged was the minimal one required to break $SU(2)_L \times U(1)_Y$ to $U(1)_{\text{emag}}$.

Glashow's paper and Salam/Weinerg's work differed because the latter contained the the additional scalar.

This is the 'Higgs'boson introduced in the theory because Weinberg/Salam used the Higgs mechanism to give masses to the W/Z in a gauge invariant way!

Weinberg-Salam used the Higgs mechanism to make massive gauge bosons consistent with Gauge invariance . But this was ONLY one way of achieving it. It was likely, not necessarily probable, that Weinberg's model was right and still there would be NO elementary Higgs!

The 1967 papers also showed that the Higgs mechanism can generate also the fermion masses in a gauge invariant way.

This means that the choice of the representation to which the scalar Φ belongs, decides the couplings of the Higgs boson with fermions and gauge bosons.

Even if one granted that it was elementary what else did we know of the Higgs?

Nothing was known 'a priori' about its mass, but the couplings to all the gauge bosons and fermions were known thanks to the mass generation mechanism.

Φ was chosen arbitrarily to be a complex $SU(2)_L$ doublet as that had the right number of scalars to give masses to three of the *four* massless gauge bosons.

$\mathcal{L}_{gauge}^{massless}$	$+\ \mathcal{L}_\Phi$		$\mathcal{L}_{gauge}^{massive}$	$+\ \mathcal{L}_h$
4 massless gauge bosons	4 scalar fields	$\Rightarrow SSB, Unitary gauge$	3 massive, 1 massless gauge bosons	1 physical scalar
8 d.o.f.	4 d.o.f.		11 d.o.f	1 d.o.f.

Important: Ratio of m_W to m_Z depended on weak mixing angle $\sin\theta_W$ AND the representation to which the scalar Φ depended.

For the choice of the doublet: $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

New particles and Interactions:

Robust: **1) Existence of the Z boson and the weak neutral currents, with the relative strength of the charged and neutral current interactions being given by ρ, predicted to be 1 for the choice of the doublet.**

2)Existence of the additional scalar(s). The choice of the doublet ad hoc. That is the reason I call it less robust. But ρ depends on the choice. Experimentally finding $\rho = 1$ would then predict one scalar in the simple choice of a single doublet.

Standard Model Lagrangian consists of 'proved' gauge sector, Yukawa sector and scalar sector:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\,\not{D}\psi + f_e^*(\bar{\nu},\bar{e})_L\Phi e_R + f_u^*(\bar{u},\bar{d})_L\Phi^C u_R$$
$$+ \ldots.. + h.c. + |D_\mu\Phi|^2 - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

After spontaneous symmetry breaking ($\mu^2 < 0$)

$$\langle\Phi\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

Vacuum not symmetric but the Lagrangian still is. Scattering amplitudes are gauge invariant.

One scalar degree of freedom h left. Mass of W, Z related to g_1, g_2 and v. v can be determined in terms of the μ decay constant G_μ;

$v = \sqrt{-\mu^2/\lambda}$, and $v = (G_\mu \sqrt{2})^{-1/2} \simeq 246\ \mathrm{GeV}$.

the Lagrangian for the scalar is:

$$\frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2} - V_1(h)$$

with

$V_1(h) = \lambda v h^3 + \frac{\lambda}{4} h^4$ and $m_h^2 = 2\lambda v^2$.

Note connection between λ and m_h!

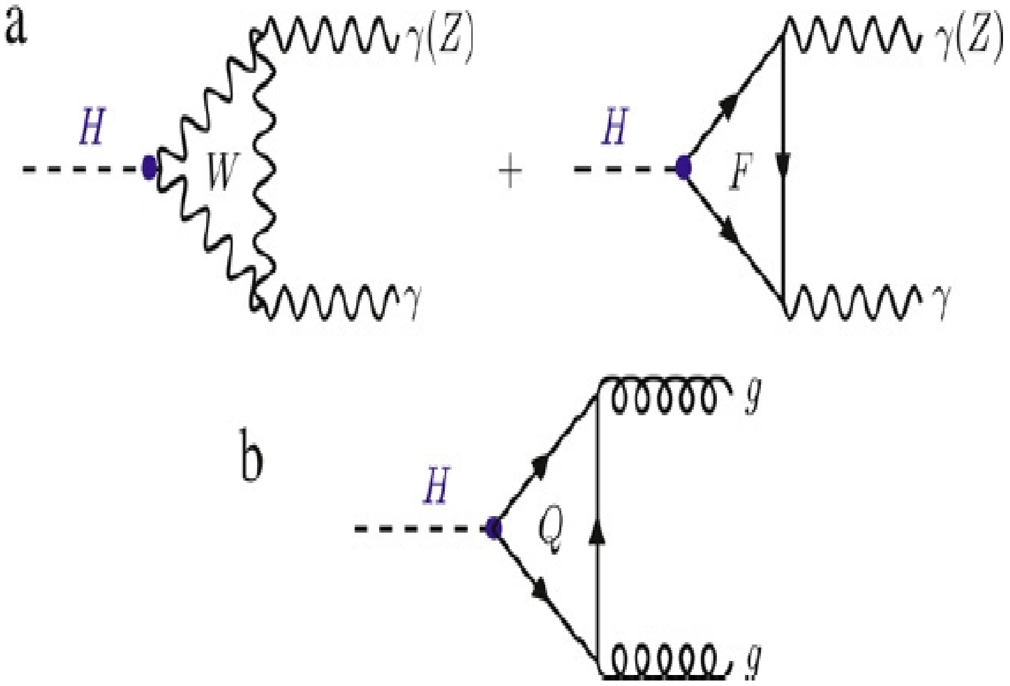
h is J = 0, CP even, Hypercharge Y= 1 and $SU(2)_L$ doublet.

Tree level $\bar{f}fh$, hVV , $hhVV$ couplings $\propto$ mass:

$$\lambda_f = \frac{m_f}{v}; \quad g_V = 2\frac{M_V^2}{v}; \quad g_{hhVV} = 2\frac{M_V^2}{v^2}.$$

Couplings to gg and $\gamma\gamma$ are loop induced!

The most important couplings for the Higgs search at the LHC are $\gamma\gamma h$ and gg-h couplings, which are loop induced.



SM case

1) In the SM, the contribution is due to W, t loops for the $h\gamma\gamma$ vertex, whereas for the hgg it is the top contribution.

2) New particles beyond the SM contribute in the loops and the contributions are non decoupling for chiral fermions which get their mass from the Higgs mechanism. I.e. they are independent of the mass of the heavy fermions in the loop.

3)For $m_h = 125$ the $\gamma\gamma$ width $\propto |A_W + A_{top}|^2$, is dominated by W contribution: $A_W = -7$ and $A_{top} \sim \mathcal{O}(1)$, about 0.2 of the $W-$ contribution.

4)In the early days when the t quark had not yet been discovered and considered to be light, in fact for heavier Higgs bosons the dominant production mode was not ggh but rather the W-fusion!

So when did everybody start taking the Higgs seriously?

1) Weak neutral current discovery in 1974 at the predicted rates relative to the weak charged current.

2)Discovery of the $c\bar{c}$ resonance ,J/ψ, at the right mass as predicted by the M.K. Gaillard and B. Lee from the observed K_0–$\bar{K}_0$ mixing!

Both these supported the correctness of gauge theory description of weak interactions. By this time renormalisability of spontaneously broken gauge theories was proved by 't Hooft and Veltman.

These increased the belief in the gauge theoretic description of weak interactions and spontaneous symmetry breaking was an ingredient .

The phenomenological studies started from a seminal paper. Profile of the Higgs boson: J.Ellis, M.K. Gaillard and D. Nanopoulos, Nucl.Phys.B 106 (1976) 292

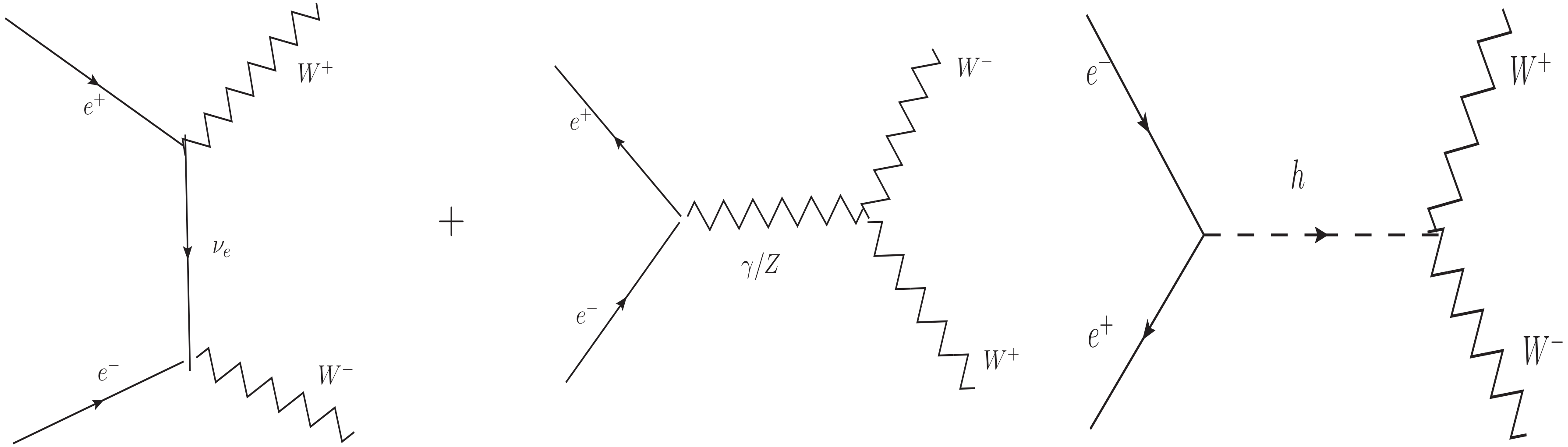
The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. ..... Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam Model.

What about its mass?

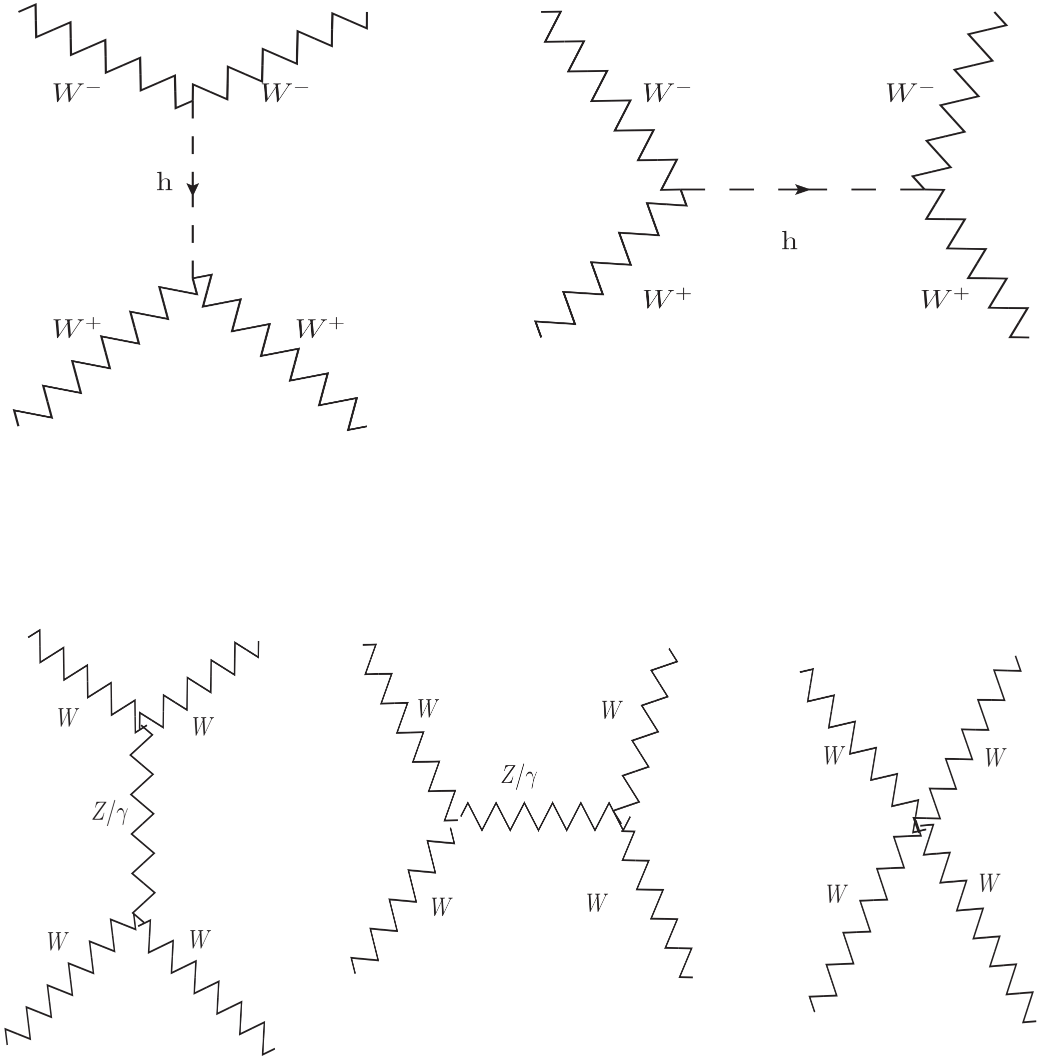
Dependent on a completely arbitrary parameter, not related at tree level to any other parameter of the Standard Model.

Can some theoretical considerations tell us something about its mass?

High energy behaviour of $\nu_e\bar{\nu}_e \to W^+W^-, e^+e^- \to W^+W^-$



Contribution to the amplitude from the t-channel diagram $\propto s$ due to Longitudinal W-bosons is exactly cancelled by the s-channel diagram containing the Z-exchange diagram ONLY only for the ZWW couplings as in the SM, which are determined by the $SU(2)_L \times U(1)_Y$ gauge invariance. For e^+e^- the third diagram contributes a term which grows with energy only logarithmically with s and numerically very small.



Each of these amplitudes has bad high energy behaviour, $\propto s^{\alpha}$, $\alpha = 1/2$.

These cancel against each other ONLY for couplings of the Z and h with the W pair as expected in the SM.

If there exist heavy fermions then one needs the $hf\bar{f}$ couplings to be exactly as in the SM!

Looks like there are deep relationships between unitarity and renormalisabilty.

C. Quigg, H.B. Thacker and B.W. Lee, Phys. Rev. D noticed the following:

Cancellation of leading divergencies is independent of the mass of the Higgs, but the $WW \to WW$ amplitude has a m_h dependent piece

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) = -\sqrt{2} G_\mu M_h^2 \left(\frac{s}{s - M_h^2} + \frac{t}{t - M_h^2} \right).$$

This will violate unitarity for $m_h > \left(\frac{8\pi\sqrt{2}}{3G_\mu}\right)^{1/2} \sim 1000$ GeV. A more correct calculation keeping the logarithms gives 780 GeV.

This can also be understood somewhat simply by thinking that for very large m_h the self coupling λ is large. So normally one said that at large m_h the Higgs is strongly interacting!

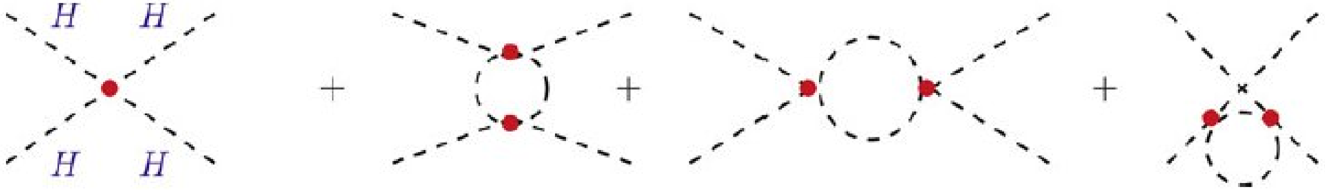
Pertubative Uniatrity:

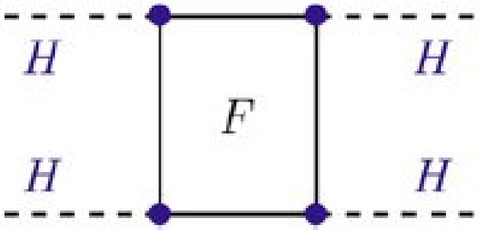
Demanding that W^+W^- scattering amplitude satisfy perturbative unitarity in fact one can derive the particle content of one generation of the SM Tiktopoulos, Cornwall as well as S.D. Joglekar $\sim$ 1974

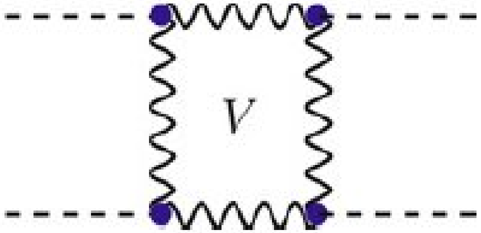
But the unitarity is guaranteed ONLY for $m_h < 780$ GeV B.Lee and Thacker

Triviality and Stability Bounds: demanding that the quartic coupling in the Higgs potential $V_h = \lambda v h^3 + \lambda/4 h^4$ remains perturbative and positive, under loop corrections.

The corrections come from:







At large m_h and large λ considerations of triviality give an upper bound. That used to be of great concern !

Remember: $m_h^2 = \lambda v^2$. For large λ the loop corrections dominated by the h–loops.

At one loop running of λ given by:

$$\frac{d\lambda(Q^2)}{d\log Q^2} = \frac{3}{4\pi}\lambda^2(Q^2)$$

Solving this, one gets

$$\lambda(Q^2) = \frac{\lambda(v^2)}{[1 - \frac{3}{4\pi^2}\lambda(v^2)\log(\frac{Q^2}{v^2})]}$$

For large $Q^2 \gg v^2$ then $\lambda(Q^2)$ develops a pole (the Landau pole).

If we demand that λ remain always in perturbative regime, we can ONLY have $\lambda = 0$. Theory will be trivial.

One can take an alternate view:

Demand that the scale at which λ blows up is above a given scale Λ.

For a given m_h the scale at which the pole lies

$$\Lambda_C = v \; \exp\left(\frac{2\pi^2}{3\lambda}\right) = v \exp\left(\frac{4\pi^2 v^2}{3M_h^2}\right)$$

Using $\Lambda_C = \Lambda = 10^{16}$ GeV, we will find $m_h \lesssim 200$ GeV. **Upper Bound: called triviality bound**

Thus just the mass of m_h can give indication of the scale of new physics beyond the SM

Stability Bound

When m_h is small and λ not large, the fermion/gauge boson loops are important. Fermions loops come with a negative sign!

Now the RGE for λ is given by

$$\frac{d\lambda(Q^2)}{d\log(Q^2)} \simeq \frac{1}{16\pi^2}[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2)]$$

λ_t is the Yukawa coupling for the top. At small m_h and hence small $\lambda(v)$, at some value of Q, λ can turn negative. Potential will be unbounded. Vacuum will be unstable.

Stability Bound

The condition is

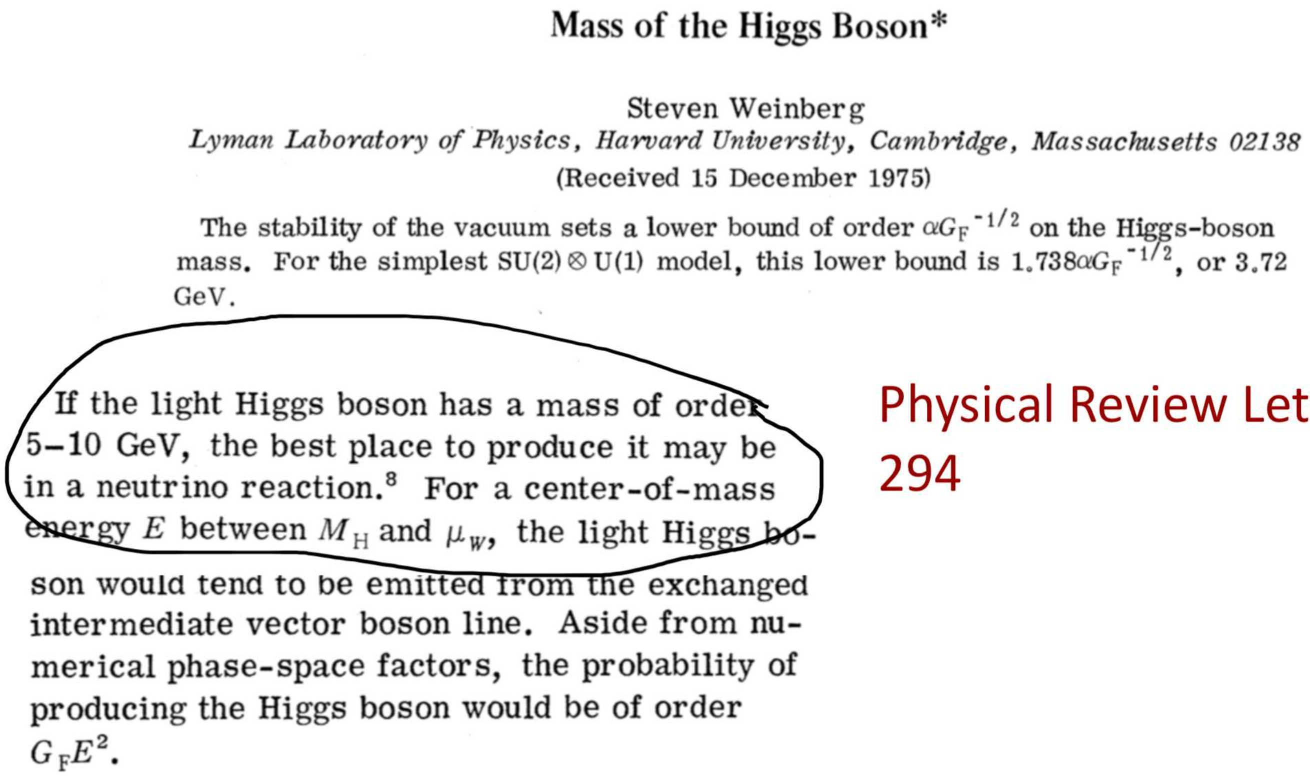
$$m_h^2 > \frac{v^2}{8\pi^2} \log(Q^2/v^2) \left[12 m_t^2/v^4 - \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2)\right].$$

If we demand that the $\lambda(Q)$ is positive upto Λ_C we then get a lower bound.

For example:

$\Lambda_C = 10^3 GeV$, $M_h \gtrsim$ 70 GeV

Earliest calculations of such stability bounds by Linde, Weinberg.



Mass of the Higgs Boson*

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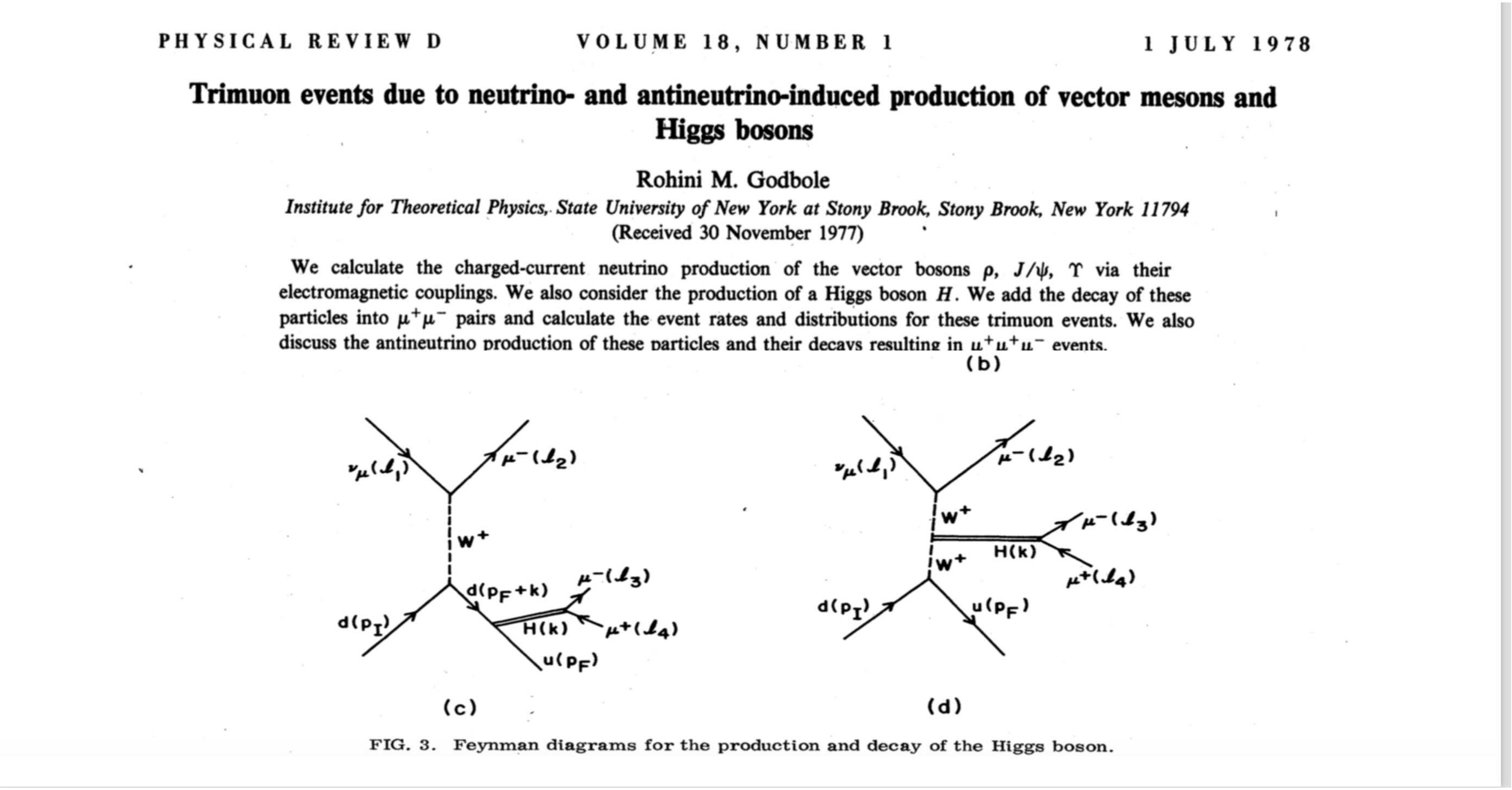
(Received 15 December 1975)

The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest SU(2) ⊗ U(1) model, this lower bound is $1.738\alpha G_F^{-1/2}$, or 3.72 GeV.

If the light Higgs boson has a mass of order 5–10 GeV, the best place to produce it may be in a neutrino reaction.[8] For a center-of-mass energy E between M_H and μ_W, the light Higgs boson would tend to be emitted from the exchanged intermediate vector boson line. Aside from numerical phase-space factors, the probability of producing the Higgs boson would be of order $G_F E^2$.

Physical Review Letters 36 (1976) 294



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Trimuon events due to neutrino- and antineutrino-induced production of vector mesons and Higgs bosons

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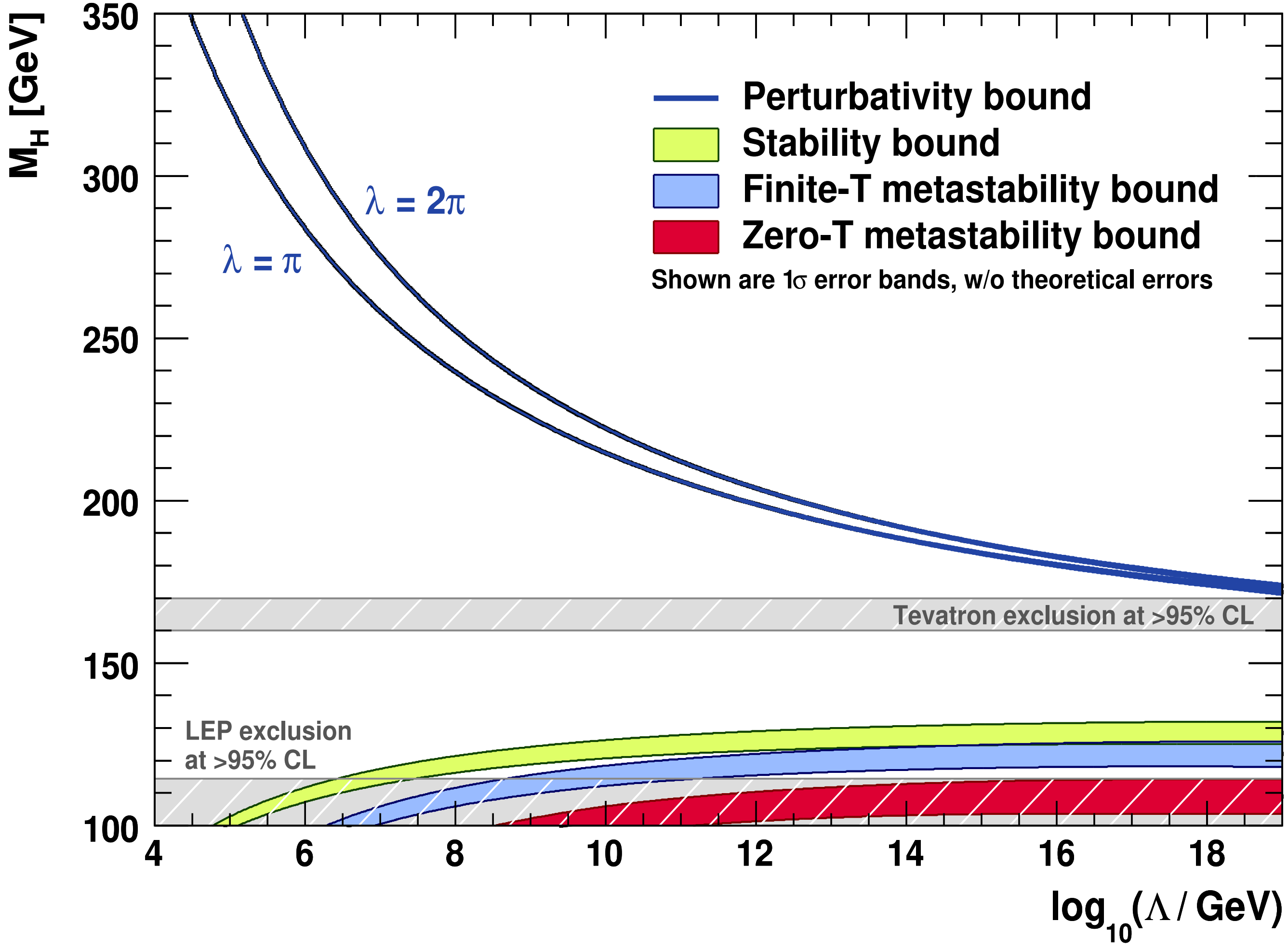
(Received 30 November 1977)

We calculate the charged-current neutrino production of the vector bosons ρ, J/ψ, Υ via their electromagnetic couplings. We also consider the production of a Higgs boson H. We add the decay of these particles into $\mu^+\mu^-$ pairs and calculate the event rates and distributions for these trimuon events. We also discuss the antineutrino production of these particles and their decays resulting in $\mu^+\mu^+\mu^-$ events.

FIG. 3. Feynman diagrams for the production and decay of the Higgs boson.



From a paper by Ellis, Giudice et al, PLB 679, 369-375 (2009). Includes higher order effects compared to the formulae here.

So the task set to LHC was to find a Higgs in this vast mass mass range

70 $< m_H <$ $\sim$ 1000 GeV.

With the known mass of the t at that time in the first studies lot of attention was focussed on the VBF production. In fact the famous boosted jets idea' was suggested by Butterworth and collaborators to reduce the QCD background for the heavy higgs searches!

Two reasons:

1) ggh rates were not so promising

2) For the heavier Higgs (strongly interacting) the WW dynamics would have important information.

Thus in some sense LHC was a no-lose machine for the Higgs!

In fact there was a lot of discussion of the VBF mechanism. One did not quite yet have the madgraph, madevent generators. many of us wrote our own programs to calculate $|\mathcal{M}|^2$ and hence the cross-sections.

Full $qq \to WW \to h$ was done by Chanowitz et al., but people (among them Saurabh Rindani, Rohini Godbole) also used to study 'Effective W approximations' which are now making a comeback in the context of newer discussions in the context of $\mu^+\mu^-$ colliders!

So the 'Higgs hunters' adapted their tools as they had a better idea where to 'hunt'!

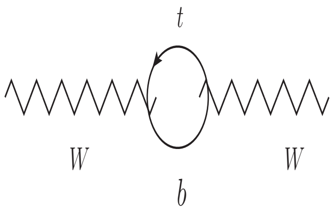
Between 1986 and 2007 a lot of water has flown under the bridge and we knew more about the Higgs mass using theory and precision measurements!

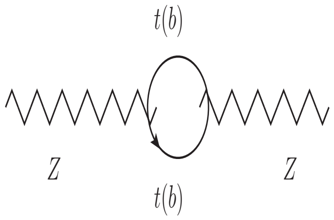
At tree level the mass of the higgs m_h is not related to any other parameters of the SM. However, SM is a gauge field theory.

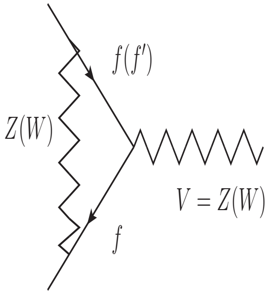
Quantum corrections link different parameters. For example corrections due to loops containing a h can modify the W/Z mass.

These effects can in fact give 'indirect' information on m_h from the precision measurements of the SM parameters.

The SM is a QFT. There will be loop corrections to m_W, m_Z.







$$\rho_{corr} = 1 + \Delta\rho$$

$$\Delta\rho \simeq \frac{3G_F M_t^2}{8\pi^2\sqrt{2}} = 0.01$$

There is also a diagram with h in the loop.

The corrections for the Z and W are different. The dominant corrections come from loop containing the heaviest quarks t, b (and sub dominant ones from h) ρ changes from value 1. (Veltman: screening theorem about the h contribution being small) Before top quark was found, its value was indirectly obtained from measuring ρ.

Logical steps in Precision testing of the SM and the indirect limits:

- SM has three parameters g_2, g_1 and v. All the SM couplings, gauge boson masses functions of these.

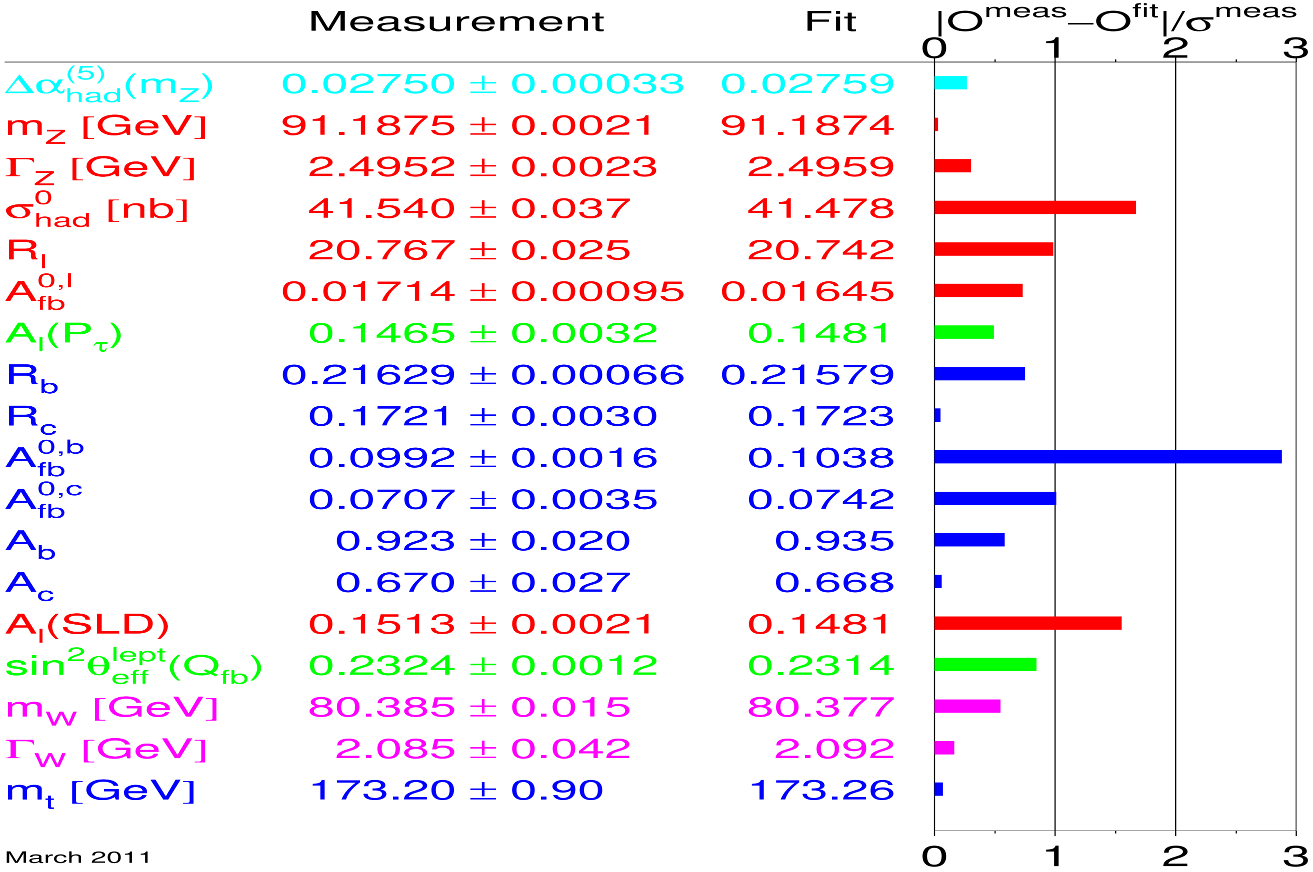
- A large number of EW observables measured quite accurately.

- m_Z, α_{em} and G_μ are most accurately measured. Trade g_2, g_1 and v for these.

- All observables depend on these three apart from M_f (mainly M_t) *and* M_h, and of course α_s.

- Calculate all observables using **1 loop EW** radiative corrections which can be computed in a renormalisable quantum field theory.

- Compare with data, make a SM fit. Tests the SM at loop level.



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

see http://lepewwg.web.cern.ch

March 2011:

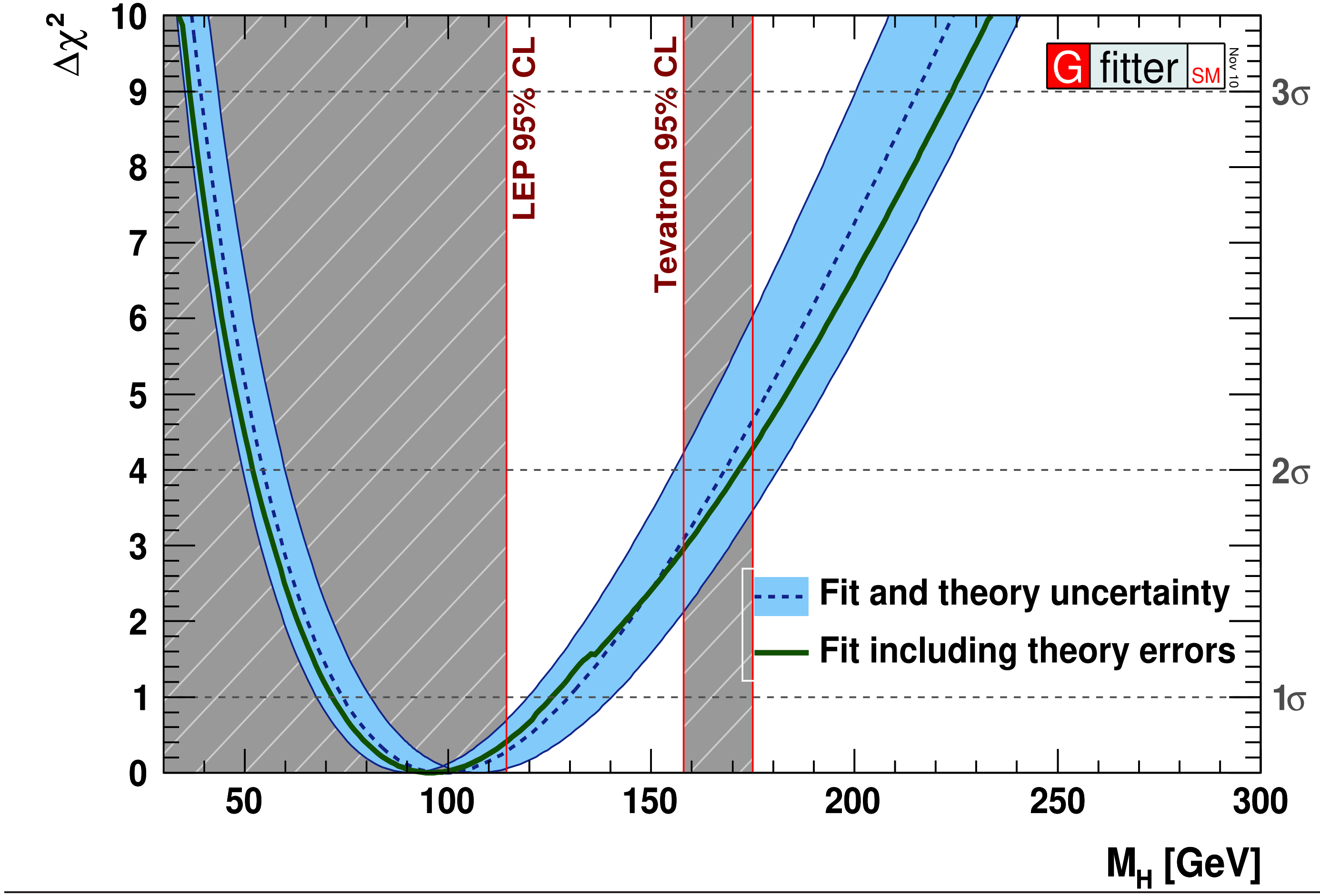
$m_W = 80.385 \pm 0.015$ GeV (direct measured), 80.377 GeV (theory prediction indirect, difference from measured value less than 1 σ)

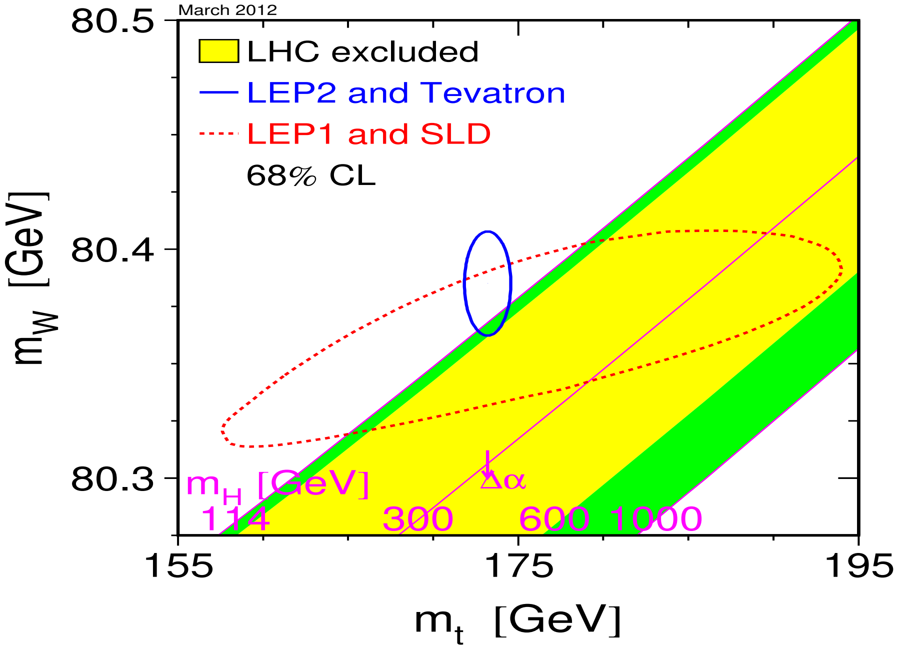
$m_t = 173.20 \pm 0.90$ GeV (measured) 172.26 GeV (theory)

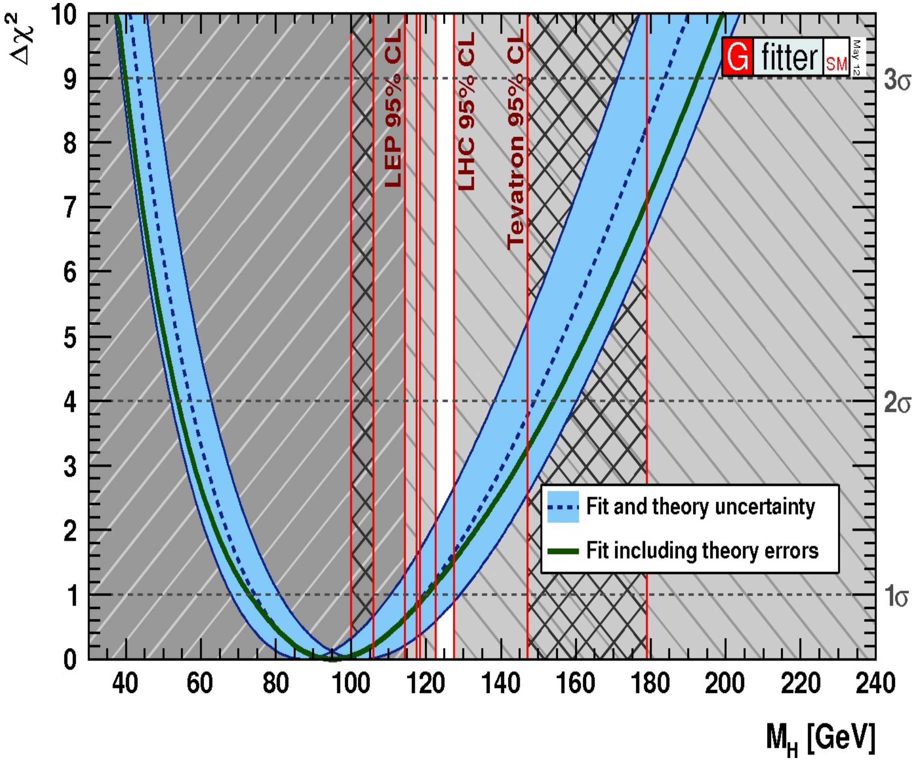
In fact before top mass was measured at the Tevatron the fits made a prediction for it. The agreement between measurement and prediction was a triumph. Veltman and 't Hooft got the Nobel prize only after this happened!

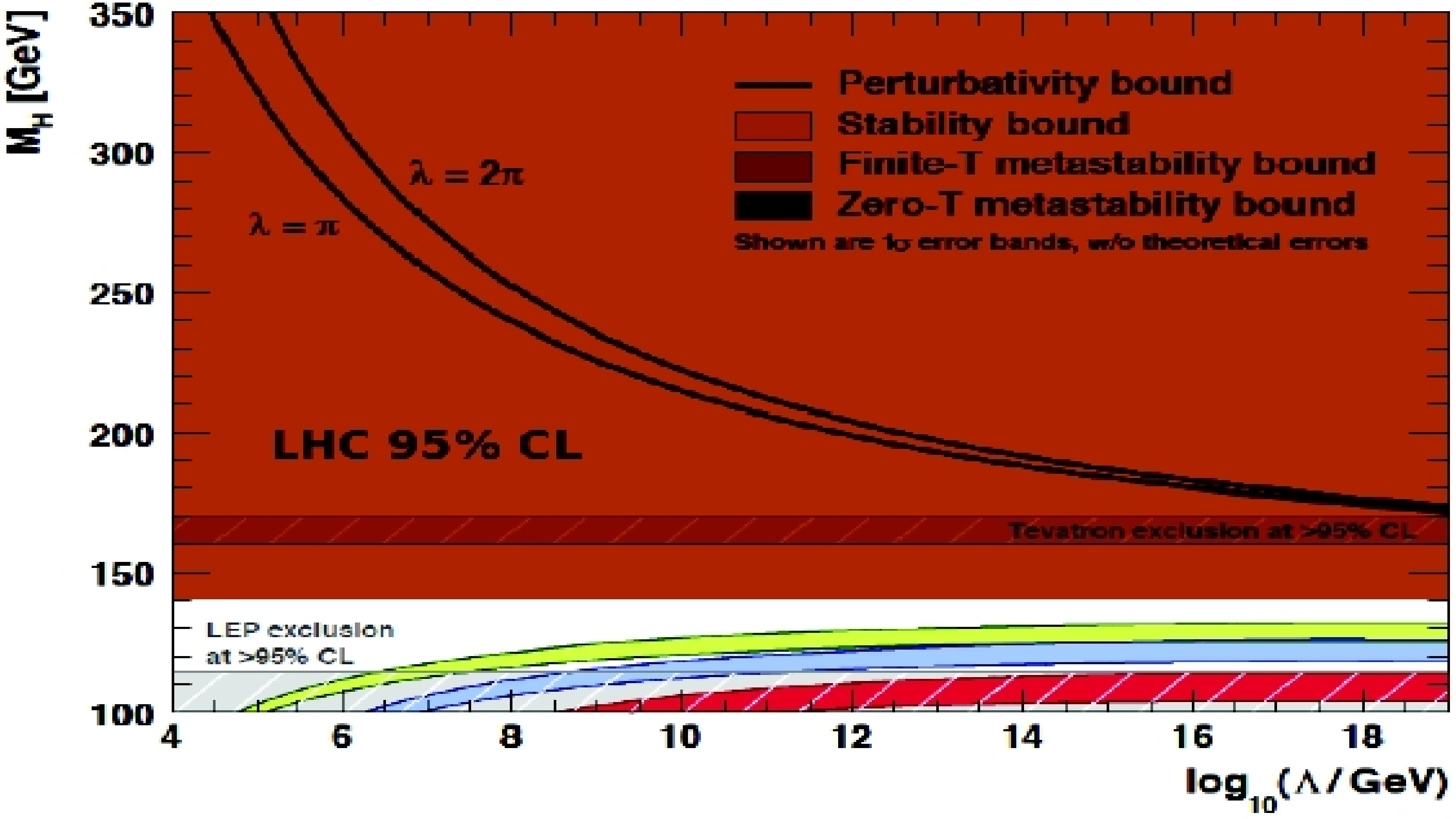
Once top was found and m_t measured the game was to predict m_h.

Now fast forward to 2011: dawn of Higgs discovery. Higgs mass in the SM should be less than 160 GeV (Indirect information!)




March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
600
1000
Δα
155
175
195
m_t [GeV]


Δχ²
10
9
8
7
6
5
4
3
2
1
0
LEP 95% CL
LHC 95% CL
Tevatron 95% CL
G fitter SM
May 12
3σ
2σ
1σ
Fit and theory uncertainty
Fit including theory errors
40
60
80
100
120
140
160
180
200
220
240
M_H [GeV]



December 2011

Allowed Higgs mass range was restricted to a very narrow range with all the different constraints. If the Higgs had not been discovered ten years ago where it was, perhaps it would have been even more fun!

But to the relief of all of us who lived through the four decades from 1974 - 2012, LHC did find the Higgs in that 'narrow' slither!

Gave the final confirmation of the 'correctness' of the 'model of leptons!'.Triumph of Gauge principle and SSB!

Where do we go onwards?

Testing the Higgs self coupling : Di-Higgs production

Using the higgs as a tool to probe BSM through the Higgs portal

Personal connection-III

Data reported on July 4 2012 and expectation for the Higgs?

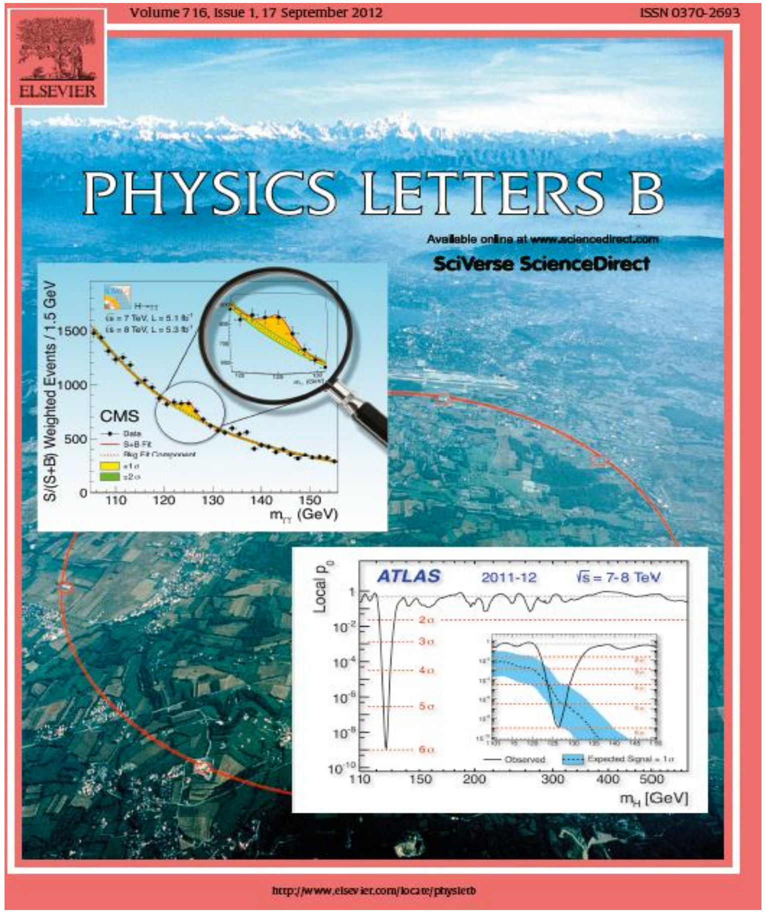
Both the collaborations reported enhanced $\gamma\gamma$ rate. **compared with expectations for a Higgs!** BUT NOT for the ZZ channel.

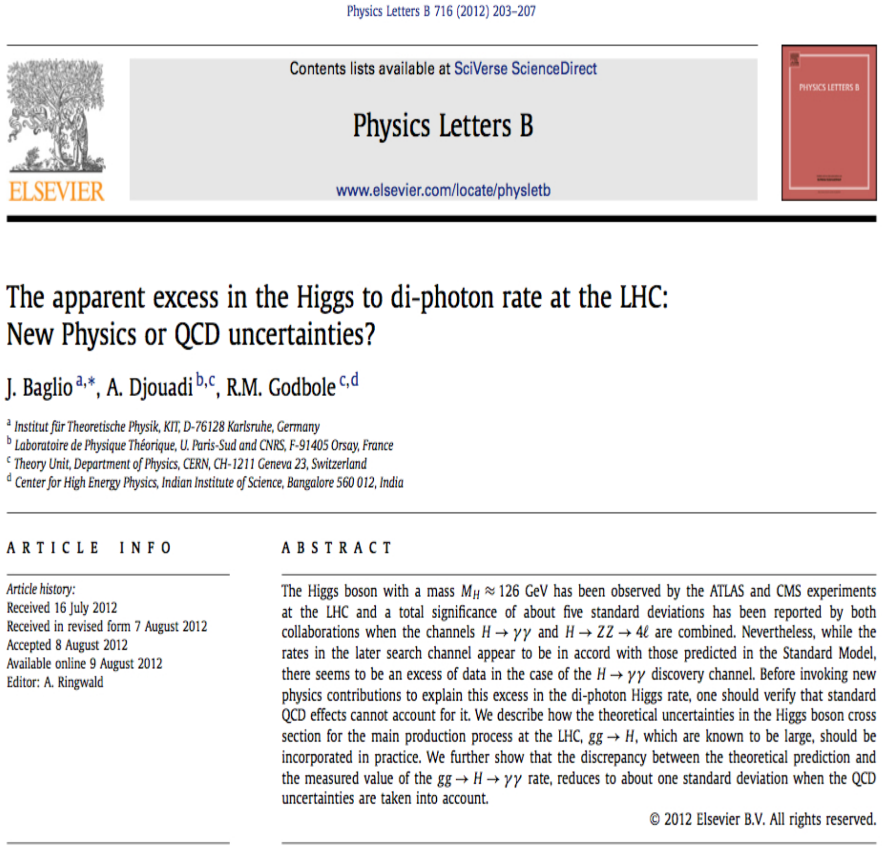
ATLAS: $R_{\gamma\gamma} = 1.90 \pm 0.5\,, \quad R_{ZZ} = 1.3 \pm 0.6\,,$

CMS: $R_{\gamma\gamma} = 1.56 \pm 0.43\,, \quad R_{ZZ} = 0.7 \pm 0.5\,,$

ATLAS⊕CMS: $R_{\gamma\gamma} = 1.71 \pm 0.33\,, \quad R_{ZZ} = 0.95 \pm 0.4\,.$

To confirm that the new boson IS a HIGGS boson one needs to confirm that values of R for all channels are close to one!

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The apparent excess in the Higgs to di-photon rate at the LHC: New Physics or QCD uncertainties?

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ABSTRACT

The Higgs boson with a mass $M_H \approx 126$ GeV has been observed by the ATLAS and CMS experiments at the LHC and a total significance of about five standard deviations has been reported by both collaborations when the channels $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ are combined. Nevertheless, while the rates in the later search channel appear to be in accord with those predicted in the Standard Model, there seems to be an excess of data in the case of the $H \to \gamma\gamma$ discovery channel. Before invoking new physics contributions to explain this excess in the di-photon Higgs rate, one should verify that standard QCD effects cannot account for it. We describe how the theoretical uncertainties in the Higgs boson cross section for the main production process at the LHC, $gg \to H$, which are known to be large, should be incorporated in practice. We further show that the discrepancy between the theoretical prediction and the measured value of the $gg \to H \to \gamma\gamma$ rate, reduces to about one standard deviation when the QCD uncertainties are taken into account.

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The paper on the right appeared in the same issue of Physics Lett. B which carried the announcement of the discovery of the new boson!