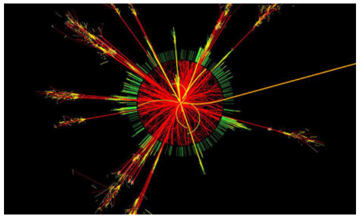

# If there is no Higgs particle, what then?


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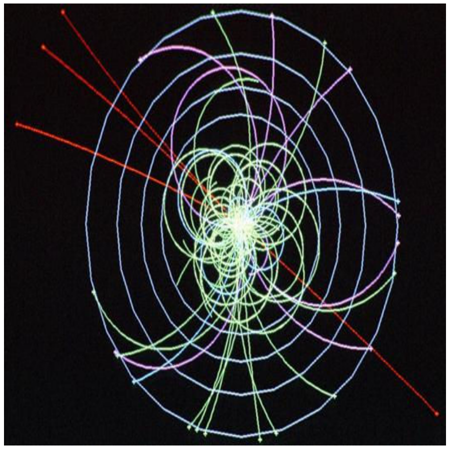
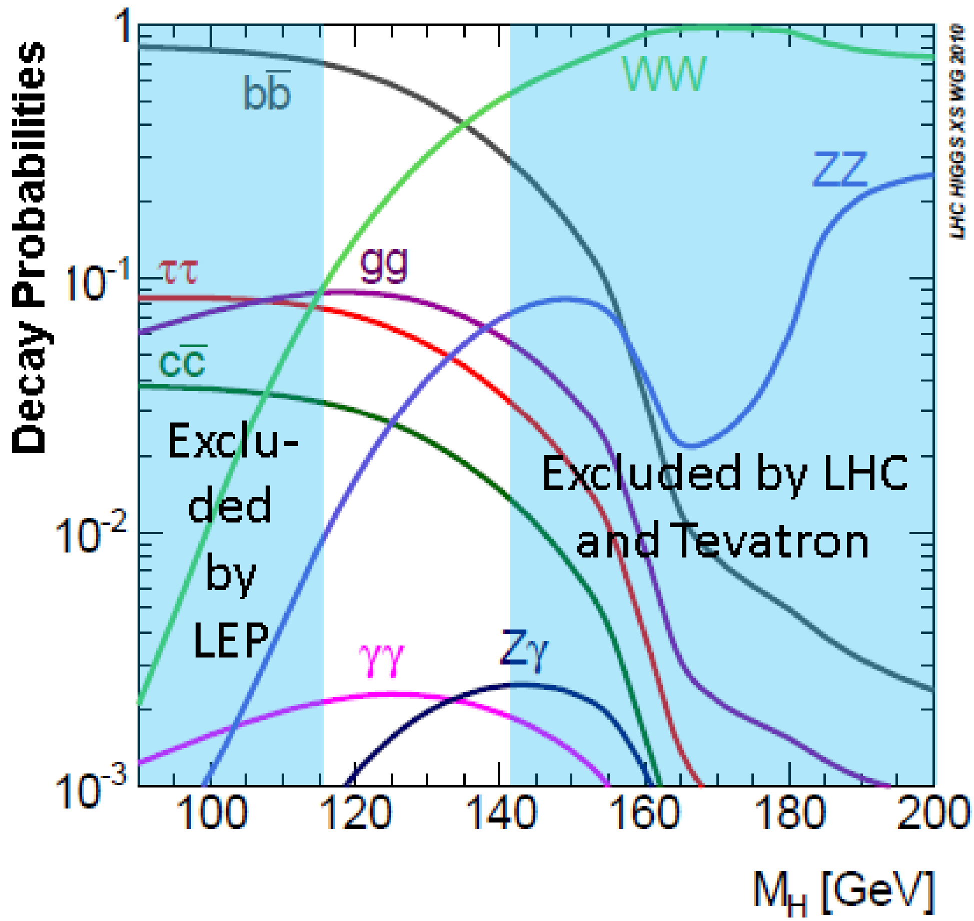


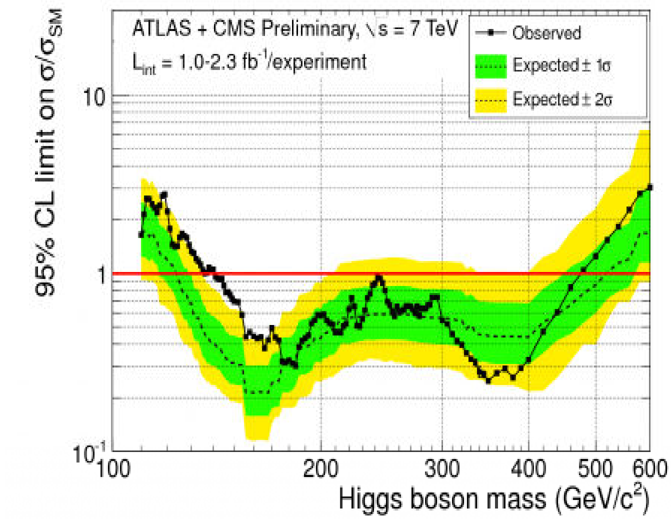
"In the room 3σ bumps come and go
Talking of Michelangelo."

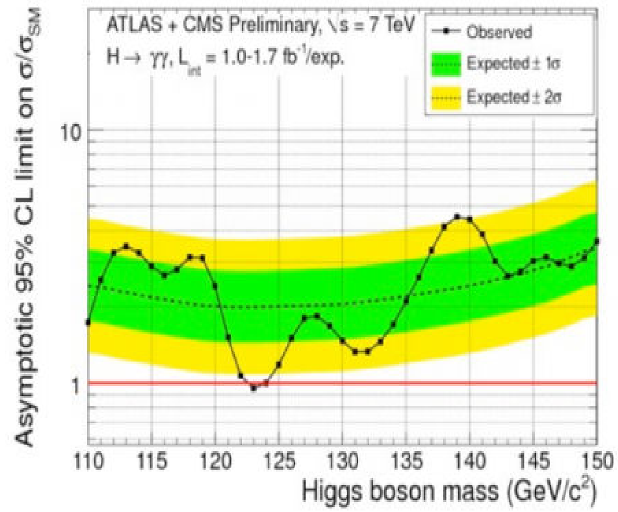
Paraphrased from "Love Song of J. Alfred Prufrock": T. S. Elliot

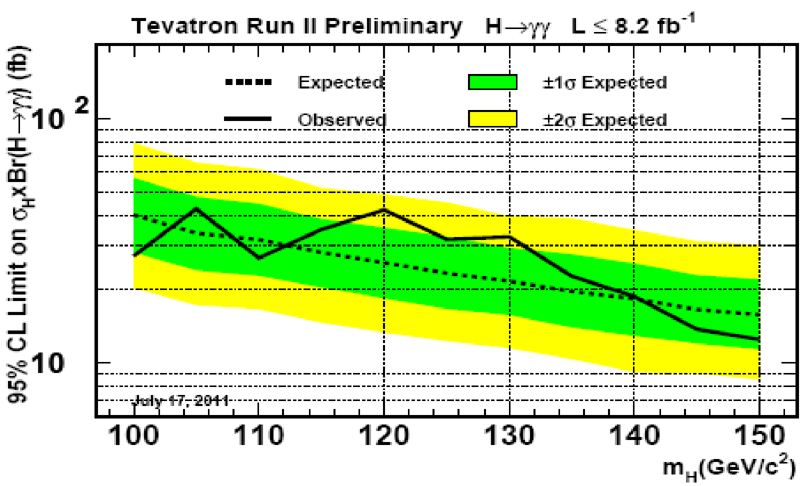
# 1. Present Status of the Higgs Particle Search

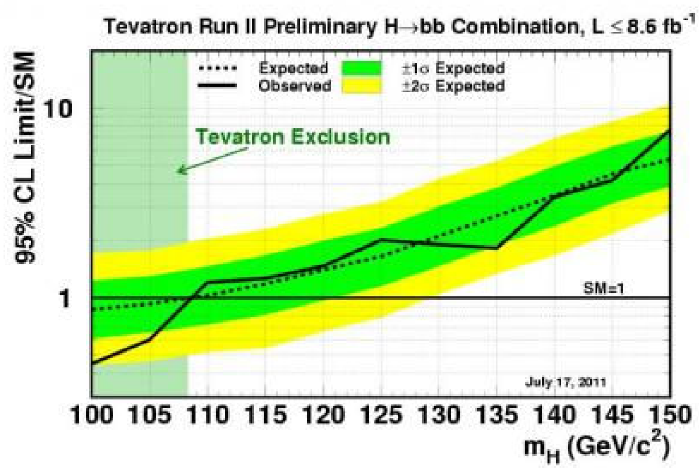


Experimental progress of Higgs particle search: Summer 2011: TEVATRON Group and LHC, CERN Group

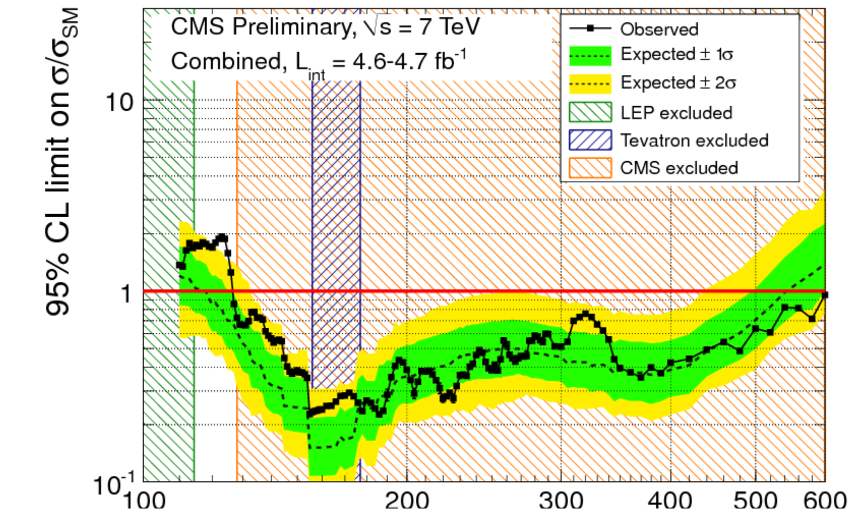


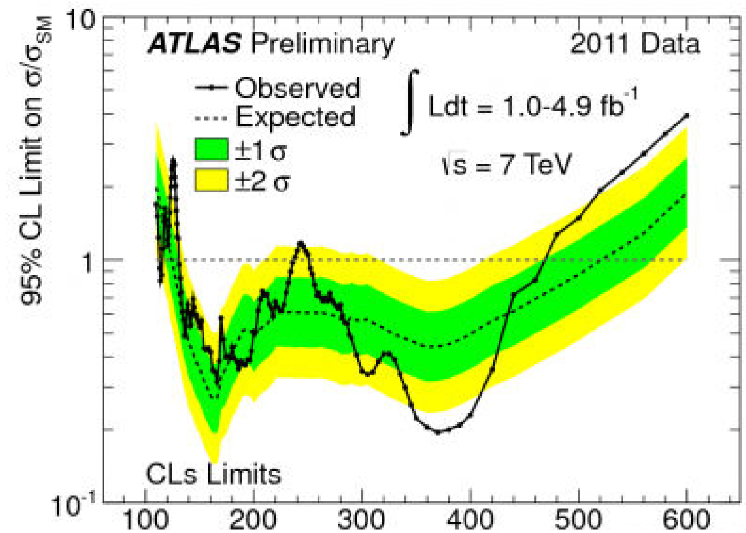



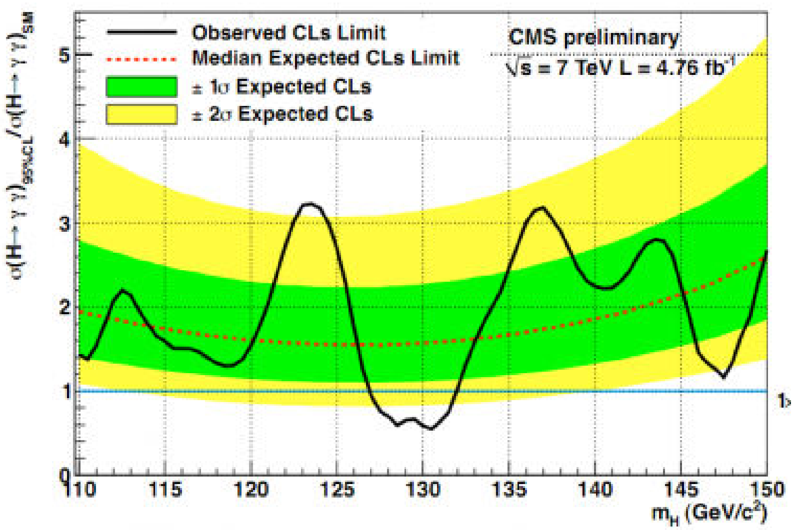



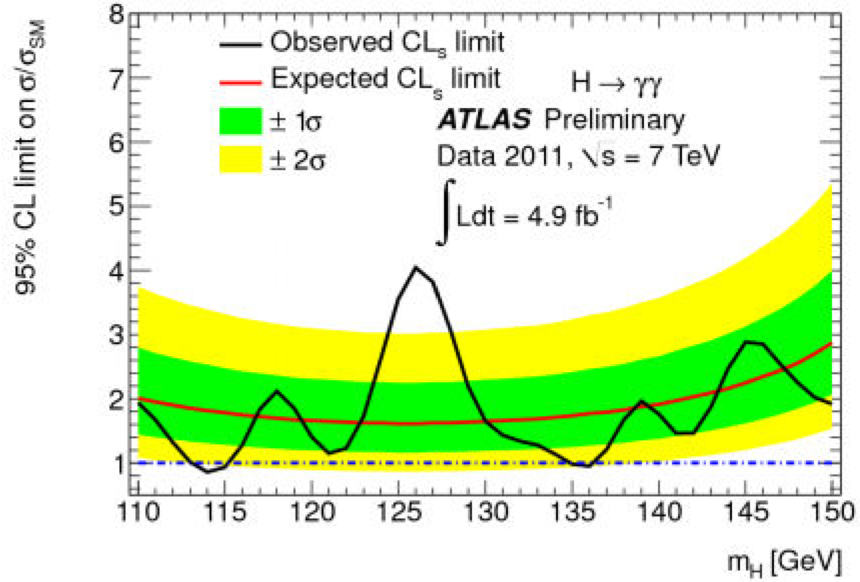



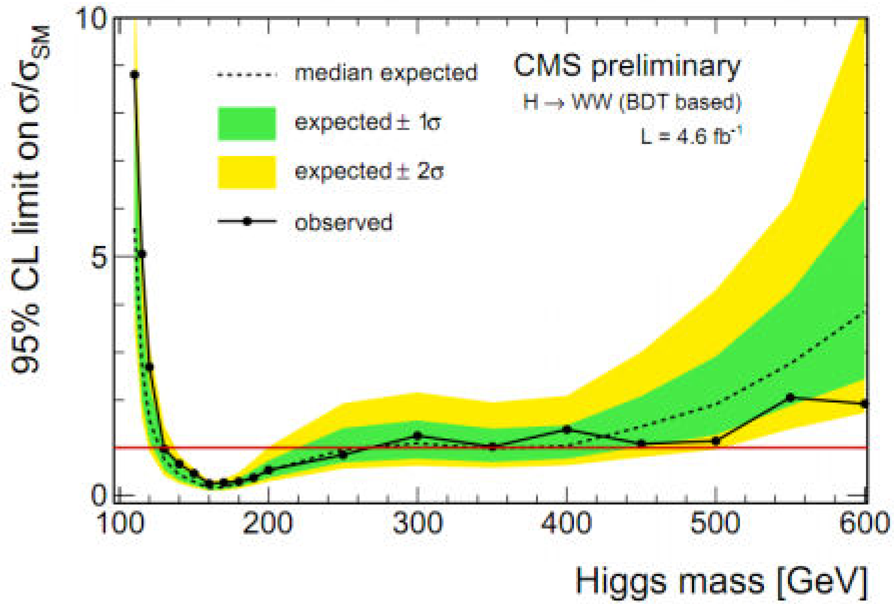
F. Gianotti (for ATLAS) and G. Tonelli (for CMS), talks given at the CERN seminar on update on the Standard Model Higgs searches, CERN,13/12/2011;https://indico.cern.ch/conferenceDisplay.py?confId=164890.

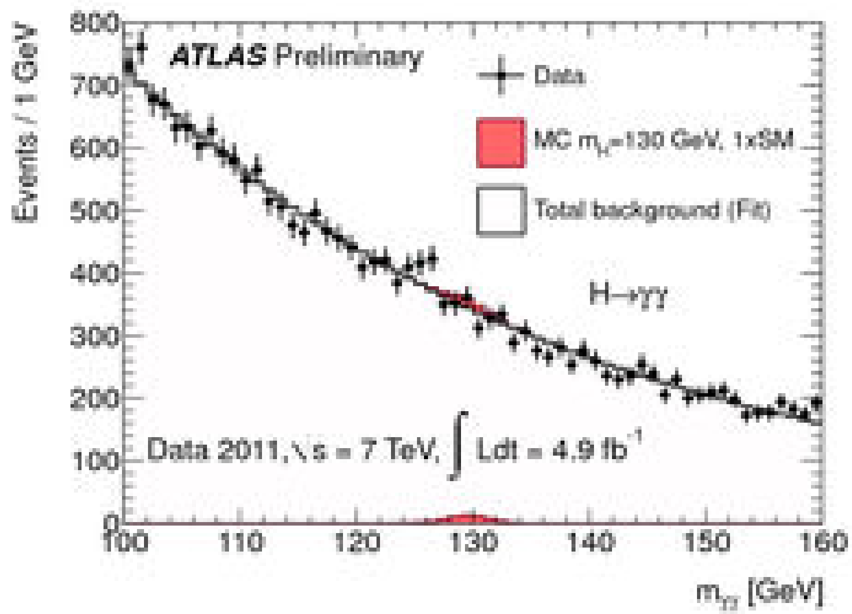



95% CL limit on σ/σ_SM
median expected
expected ± 1σ
expected ± 2σ
observed
CMS preliminary
H → WW (BDT based)
L = 4.6 fb-1
Higgs mass [GeV]


Events / 1 GeV
ATLAS Preliminary
Data
MC m_H=130 GeV, 1xSM
Total background (Fit)
H→γγ
Data 2011, √s = 7 TeV, ∫ Ldt = 4.9 fb-1
m_γγ [GeV]

• The 2010 – July 2011 ATLAS+CMS data for the golden channel H -> γγ for √s=7 TeV and L=1.0-1.7 $fb^{-1}$ shows a 2σ excess (bump) at $m_H$~ 140 GeV that was potentially identified as a Higgs particle. Later data in 2011 excluded this signal and showed that it was due to a statistical fluctuation.

• The 2011 data from CMS for the channel H -> γγ at √s = 7 TeV and L = 4.7 $fb^{-1}$ shows a 2.3σ excess (bump) at $m_H$ ~ 123 GeV which is reduced to 1.9σ with LEE (look elsewhere effect). However, there is another ~ 2σ excess (bump) at $m_H$~ 136 GeV and a 2.4σ dip at $m_H$~ 130 GeV. Whereas the excess events at $m_H$ ~ 123 GeV could be the signal for a Higgs particle, the bump at $m_H$ ~ 136 GeV is also a likely candidate. However, these bumps and the dip can also be interpreted as statistical fluctuations in the data.

• The 2011 ATLAS data for H -> γγ at √s = 7 TeV and L = 4.9 $fb^{-1}$ shows a 2.3σ excess of events (bump) at $m_H$ ~ 126 GeV which could be identified with the Higgs particle. Note that this ATLAS bump is located about $m_H$ ~ 3 GeV away from the CMS bump for this decay channel. This signal can also be interpreted as a statistical fluctuation in the data.

• The allowed range of Higgs mass is now 114.4 GeV < $m_H$ < 130 -136 GeV.

• The 2011 plot for H -> γγ for ATLAS Events/1 GeV versus the invariant $m_{\gamma\gamma}$ , shows a 2 bin excess of events at $m_H$ ~ 126 GeV. However, this should be compared to the MC SM calculation of the expected Events/1 GeV for a Higgs particle at $m_H$ ~ 130 GeV. The significant excess of events in the comparison with the expected events may again be due to this signal being a statistical fluctuation.

• The CMS data for the dominant channel H -> WW at √s=7 TeV and L = 4.6 $fb^{-1}$ does not show any excess of events above 1σ at $m_H$ ~ 126 GeV.

• The TEVATRON data for 2010 and 2011 for H -> γγ at √s=2 TeV and L = 8.2 TeV does not show any excess of events above 1σ at $m_H$ ~ 126 GeV. The same is true for the TEVATRON data for H -> bb at L = 8.6 $fb^{-1.}$

• We conclude that as of December 2011, the search for the Higgs particle at the LHC and TEVATRON colliders is inconclusive. Hopefully, in 2012 more definite results can be obtained with increased luminosity at the LHC.

Global fits to EW precision data yield the best fit :

ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, LEP Electroweak Working Group, Tevatron Electroweak Working Group, LD Electroweak, Heavy Flavour Groups, arXiv:0911.2604[hep-ex].
The TEVNPH Working Group of the CDF, D0 Collaborations, arXiv:1007.4587 [hep-ex]; B. Kilminster, ICHEP, Paris, France, July 2010.

$$m_H = 87^{+35}_{-26}\,\mathrm{GeV}.$$

The present fits to EW data and flavor changing neutral current constraints favor a light fundamental (elementary) SM Higgs particle.

A lower bound on the Higgs mass $m_H > 114.4$GeV has been established by direct searches at the LEP accelerator

LHC data have excluded a Higgs mass $m_H \sim 130 - 600$ GeV to 95% confidence level (2011).

# 2. Alternatives to the Weinberg-Salam Standard Model.

Possible alternatives to the Standard Electroweak Model (SEM) are:

1. Technicolor. Composite model with the scalar spin 0 Higgs particle composed of fermions as a strongly bound state. Equivalent to the BCS model of superconductivity. For a review see e.g., J. R. Anderson et al. arXiv:1104.125.

2. Adding new spin 1 resonances above 1 – 2 TeV. See e.g., A. Falkowski, C. Grojean, A. Kaminska, S. Pokorski and A. Weiler, JHEP 1111, 028 (2011) [arXiv:1108.1183 [hep-ph]].

3. Top-antitop quark resonances. See e.g., P. Ferrario and G. Rodrigo, arXiv:0906.5541 [hep-ph].

4. Supersymmetric partners with 5 – (?) Higgs particles. See e.g., G. Aad *et al. [The ATLAS Collaboration], arXiv:0901.0512 [hep-ex].*

5. Extra dimensions – Kaluza-Klein excitations (new resonances above 1 – 2 TeV) See e.g., C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D 69, 055006 (2004) [arXiv:hep-ph/0305237].

The scattering amplitude matrix elements for the process $W_L^+ + W_L^- \rightarrow W_L^+ + W_L^-$ is given in the SM by

$$i\mathcal{M}_W = ig^2 \left[ \frac{\cos\theta + 1}{8M_W^2} s + \mathcal{O}(1) \right]$$

The Higgs exchange contribution cancels the bad high energy behavior:

$$i\mathcal{M}_H = -ig^2 \left[ \frac{\cos\theta + 1}{8M_W^2} s + \mathcal{O}(1) \right]$$

It can be proved that spontaneous symmetry breaking of the vacuum for $SU_L(2) \times U_Y(1) \rightarrow U_{em}(1)$ with an Anderson, Brout, Englert, Higgs, Guralnik, Hagen, Kibble (ABEHGHK) mechanism is necessary and sufficient to guarantee renormalizability and tree graph unitarity (‘t Hooft 1971; ‘t Hooft-Veltman 1971-74; Llewllyn-Smith 1973; Cornwall, Levin, Tiktopoulos, 1974, others).

The Higgs field pervades all of space and is claimed to generate the masses of the elementary quarks, leptons W and Z bosons, keeping the photon massless.

An alternative to the electroweak model (EM) is to envisage a significant overhaul of QFT. This would allow for a finite QFT that avoids the problem of UV renormalizability and retains unitarity. Most QFTs are not renormalizable e.g. scalar field theory with $V(\phi)=\mu^2(\partial\phi)^2+\lambda\phi^n$ ($n > 4$) and quantum gravity.

A UV complete EW theory can be constructed that begins with a dynamically broken SU(2) X U(1) (JWM, Eur. Phys. J. Plus (2011) 126: 53, arXiv: 1006.1859 [hep-ph]; arXiv:1103.0979 [hep-ph]; arXiv:1104.5706 [hep-ph]). The EW model with running coupling constants described by an energy dependent entire function is UV complete and avoids unitarity violations for energies above 1 TeV. The action contains no physical scalar fields and no Higgs particle and the physical fields are local and satisfy microcausality. The W and Z masses are compatible with a symmetry breaking $SU(2)_L\times U(1)_Y \rightarrow U_{em}(1)$, which retains a massless photon. The nonlocal vertex couplings possess an energy scale $\Lambda_W > 1\text{-}2$ TeV predicting scattering amplitudes that can be tested at the LHC.

In our nonlocal interaction EW model, the tree graph unitarity violation is canceled by the high-energy behavior of g(s). The amplitude is now

$$i\mathcal{M}_W = i\bar{g}^2(s)\left[\frac{\cos\theta + 1}{8M_W^2}s + \mathcal{O}(1)\right].$$

The EW coupling constants are defined by

$$\bar{g}(x) = g\mathcal{E}(\Box(x)/\Lambda_W^2), \qquad \bar{g}'(x) = g'\mathcal{E}(\Box(x)/\Lambda_W^2).$$

Here, $\mathcal{E}(\Box(x)/\Lambda_W^2)$ is an entire function of $\Box(x)/\Lambda_W^2$ .

We require that for √s > 1-2 TeV, g(s) decreases as ~ 1/√s or faster, resulting in the cancelation of the unitarity violating contribution. We expect that a consistent choice of the entire function $\mathcal{E}(\Box(x)/\Lambda_W^2)$ will lead to a different prediction for the $W_L + W_L \rightarrow W_L + W_L$ scattering amplitude for √s > 1-2 TeV compared to the Higgs EW model, providing an experimental test of our model.

Can EW theory without the Higgs particle be renormalizable and unitary?

The only unique renormalizable EW model that is unitary is the spontaneously broken standard model with a Higgs particle, but the mass of the Higgs must satisfy $m_H < 600$ -800 GeV, otherwise the perturbation theory breaks down and Born tree graph unitarity is violated. Moreover if $m_H < 120$ GeV the theory is vacuum unstable and breaks down as $\sqrt{s} \rightarrow \infty$. The standard Higgs model also suffers from the Higgs mass radiative correction instability (Higgs mass hierarchy problem) , the potential triviality problem and a very large and physically unacceptable vacuum energy density..

A necessary and sufficient condition for renormalizability of a local QFT is gauge invariance. This can be a “hidden” gauge invariance as occurs in the SM Higgs Weinberg-Salam model.

An alternative gauge symmetry can be invoked using the Stueckelberg formalism (E. C. G. Stueckelberg, Helv. Phys. Acta. 11, 225 (1938).)

An effective EW model is based on a gauge invariant action with *local interactions* using a Stueckelberg formalism . The gauge invariance of the Lagrangian leads to a renormalizable EW theory, provided the scalar fields in the Lagrangian decouple at high energies rendering a scalar spin-0 boson undetectable at present accelerator energies. The model contains only the observed particles, namely, 12 quarks and leptons, the charged *W boson, the neutral Z boson and the massless photon and gluon without* the Higgs particle.

In our EW theory, there is no attempt to explain the origin of masses. This is particularly true for the *W and $Z^0$ bosons. The gauge invariant Lagrangian is given by*

$$\mathcal{L}_{\mathrm{EW}} = \sum_f \bar{f} i \not{D}^W f + \sum_f \bar{f} i \not{D}^Z f + \sum_f \bar{f} i \not{D}^A f - \frac{1}{2} W^{+\mu\nu} W^-_{\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$
$$+ \frac{1}{2}(M_Z Z_\mu - \partial_\mu \beta)(M_Z Z^\mu - \partial^\mu \beta) + (M_W W^+_\mu - P\partial_\mu \sigma)(M_W W^{-\mu} - P\partial^\mu \sigma) + \mathcal{L}_{m_f},$$

where *$\beta$ and $\sigma$ are scalar gauge fields and P is a function of $\sigma$.*

The Lagrangian is invariant under the infinitesimal gauge transformations

$$Z_\mu \to Z_\mu + \partial_\mu \nu, \quad \beta \to \beta + M_Z \nu, \quad W_\mu \to W_\mu + \mathcal{D}^W_\mu \chi, \quad \sigma \to \sigma + Q\chi.$$

$$W^+_{\mu\nu} = D^W_\mu W^+_\nu - D^W_\nu W^+_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$$

The fermion mass Lagrangian is

$$\mathcal{L}_{m_f} = - \sum_{\psi^i_L, \psi^j_R} m^f_{ij} (\bar{\psi}^i_L \psi^j_R + \bar{\psi}^i_R \psi^j_L),$$

We have not included in the Lagrangian the standard scalar field Higgs contribution:

$$\mathcal{L}_\phi = |(i\partial_\mu - gT^a W^a_\mu - g' \frac{Y}{2} B_\mu)\phi|^2 - V(\phi), \quad V(\phi) = \mu^2_H \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2$$

The *W and Z* masses are the experimental masses. We do not begin with a massless Lagrangian and then break the *SU(2)* symmetry through a spontaneous symmetry breaking of the vacuum. The Stueckelberg gauge invariance is a dynamical “hidden" symmetry.

Our effective EW theory is not ultraviolet (UV) complete. We have to demand that we apply the theory in the restricted energy region $E_s < \mu = \sqrt{\lambda} M_W$ *in which there are no scalar bosons in either the initial or final state of the S matrix. Thus, the* non-renormalizable scalar field interactions are decoupled from the non-Abelian *W interactions. This decoupling* of the scalar field interactions follows automatically for the neutral $Z^0$ *boson Abelian interactions and this U(1) sector of the theory is renormalizable and unitary. For a sufficiently large λ parameter the scalar* boson has a $\mu = \sqrt{\lambda} M_W$ *that makes is heavy enough to avoid detection by LHC experiments. In the* restricted effective energy range the S matrix is unitary $S^\dagger = S^{-1}$.

In our EW model the standard Higgs mechanism generated by spontaneous symmetry breaking of the vacuum is absent, and we do not have a Higgs boson contribution. Moreover, the scalar bosons do not contribute to the S matrix in our restricted energy range $E_s < \sqrt{\lambda} M_W$, *so we* solve the unitarity problem by asserting that we have (JWM & V. T. Toth, arXiv:0812.1994v6 [hep-th]):

$$\mathcal{M}(W_L W_L \to W_L W_L) = g^2_{\rm eff}(s)\left[\frac{\cos\theta + 1}{8m^2_W}s + \mathcal{O}(1)\right] \qquad g_{\rm eff}(s) = g\left[1 + (\sqrt{s}/M)^n\right]^{-1}.$$

Here, *g is the low energy weak coupling constant, M is a parameter that determines the energy scale of the* running of the effective $g_{eff}(s)$ *and* $n \geq 1$. $g_{eff}(s)$ *decreases fast enough , so that a* unitarity violation can be avoided for the tree graph approximation and the scattering amplitude and the cross section can remain below the unitarity bound for *M > 1-2 TeV. This behavior of weak scattering* amplitudes and cross sections implies that the vector bosons *W and Z satisfy a form of asymptotic safety.*

In our local model without the scalar boson interactions in the restricted energy range $E_s < \sqrt{\lambda} M_W$ *for* which the scalar boson mass *is sufficiently heavy to avoid detection by the LHC, the effective EW theory will be both* renormalizable and unitary.

In composite models of weak interactions such as technicolor and the postulate of heavy resonances at energies above 1 TeV , the weak interactions are predicted to become strong, positing a unitarization of the strongly bound state particles. In these models we are faced with attempting to calculate cross sections for strongly coupled bound states.

Experiments conducted at the LHC can test the predictions of our EW model and alternative models by measuring the EW cross sections and determining whether they in fact do grow weaker than predicted in the standard Weinberg-Salam model, or whether they grow stronger as in composite bound state models.

# 3. Conclusions

Various alternative EW models can be formulated in the event that a SM Higgs particle is not detected at the LHC. Composite models of the Higgs particle generate strong interactions at energies 1-2 TeV, and predict the existence of new as yet undetected particles.

It will be important for the LHC to measure cross sections in the energy range 1-3 TeV where unitarity becomes a significant issue in EW models.

The latest LHC experimental data have ruled out sequential Z' bosons up to an energy ~ 1-3 TeV. Extra dimensions have been excluded up to energies 2-3.8 TeV. Low energy supersymmetric particles have been excluded to an energy ~ 800 GeV-1 TeV. As of December 2011, the search for a fundamental Higgs boson remains inconclusive.