A Light Composite Higgs

Marco Serone, SISSA, Trieste

In collaboration with David Marzocca and Jing Shu, based on 1205.0770

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Plan

Introduction on Composite Higgs Models

General Set-Up and Generalized Weinberg Sum Rules

Minimal Higgs Potential (MHP) Hypothesis and Higgs Mass

A Possible Issue for Partial Compositeness

Conclusions

Introduction on Composite Higgs Models (CHM)

A composite Higgs coming from some strongly coupled theory can solve the hierarchy problem. At some scale the Higgs compositeness appears and the quadratic divergence is naturally cut-off

The Higgs field might or might not be a pseudo Nambu-Goldstone boson (pNGb) of a spontaneously broken global symmetry. Models where the **Higgs is a pNGB are** the most promising

The spontaneously broken global symmetry has also to be explicitly broken (by SM gauge and Yukawa couplings), otherwise the Higgs remains massless

Whole Higgs potential is radiatively generated

The symmetry breaking pattern is closely related to the QCD case

The $SU(2)_L \times SU(2)_R$ global symmetry is replaced by

$$G_f \supset SU(2)_L \times U(1)_Y$$

The SM gauge group arises as a weak gauging of G_f

The SM gauge fields are the analogue of the photon.
The Higgs field is the analogue of the pions

Important difference: fermion fields must now be added (no QCD analogue)

Implementations in concrete models hard (calculability, flavour problems)

Recent breakthrough: the composite Higgs paradigm is **holographically** related to theories in extra dimensions!

Extra-dimensional models have allowed a tremendous progress

The Higgs becomes the fifth component of a gauge field, leading to

Gauge-Higgs-Unification (GHU) models
a.k.a. Holographic Composite Higgs models

Not only relatively weakly coupled description of CHM, Higgs potential fully calculable, but the key points of how to go in model building have been established in higher dimensions

Main lesson learned from extra dimensions reinterpreted in 4D

$$\mathcal{L}_{tot} = \mathcal{L}_{el} + \mathcal{L}_{comp} + \mathcal{L}_{mix}$$

Elementary sector: SM particles but Higgs (and possibly top quark)

Composite sector: unspecified strongly coupled theory with unbroken global symmetry $G \supset G_{SM}$

Mixing sector: mass mixing between SM fermion and gauge fields and spin 1 or 1/2 bound states of the composite sector

Crucial ingredient in such constructions is the notion of

Partial Compositeness

SM fields get mass by mixing with composite fields:
the more they mix the heavier they are
(4D counterpart of 5D wave function overlap)

$$m \propto \epsilon_L \epsilon_R v_H$$

Light generations are automatically screened by new physics effects

Natural mechanism to suppress dangerous FCNC

Independently of the nature of composite sector, the pNGB Higgs dynamics can be parametrized by using the Callan-Coleman-Wess-Zumino (CCWZ) construction [Giudice,Grojean,Pomarol,Rattazzi,2007]

The composite sector might be intrinsically strongly coupled, with no small expansion parameter (e.g. some CFT), or admit some weakly coupled description in terms of free fields (e.g. mesons in large N)

We assume the second case, where simple parametrizations are possible

[Barbieri,Bellazzini,Rychkov,Varagnolo,2007;Anastasiou,Furlan,Santiago, 2009;Gripaios,Pomarol,Riva,Serra,2009;Mrazek et al,2011;Panico,Wulzer, 2011;Curtis,Redi,Tesi,2012; ...]

The Higgs potential is generally incalculable in these models

One can impose a collective symmetry breaking mechanism on moose-type models, deconstructed versions of 5D models

Considerable progress, but models still too close to their 5D parents

Is it possible to build more general CHM, not directly related to the 5D holographic models and yet with a calculable Higgs potential ?

This requires a symmetry principle, alternative to collective symmetry breaking, to protect the Higgs potential

or

we might look for the generic constraints a model should have

Our aim

Construct 4D pNGB composite Higgs models, not directly related by deconstruction to 5D models, where the Higgs mass can at least be assumed to be calculable, and characterize the main properties these models should have in order to give rise to a Higgs mass at 125 GeV

We assume that a given number of spin 1 and 1/2 resonances of the composite sector are lighter than the cut-off Λ of the theory and appear in the low-energy effective action and impose generalized Weinberg sum rules to make the Higgs potential calculable

Weinberg sum rules

In QCD, for $SU(2)_V \times SU(2)_A \to SU(2)_V$

$$\langle V^a_\mu(q) V^b_\nu(-q)\rangle \equiv P^t_{\mu\nu}\delta^{ab}\Pi_{VV}(q^2)$$

$$\langle A^a_\mu(q) A^b_\nu(-q)\rangle \equiv P^t_{\mu\nu}\delta^{ab}\Pi_{AA}(q^2)$$

$\Pi_{LR} = \Pi_{VV} - \Pi_{AA}$ is such that

$$\lim_{p_E^2\to\infty} \Pi_{LR}(-p_E^2) = 0$$ First sum rule (I)

$$\lim_{p_E^2\to\infty} p_E^2\Pi_{LR}(-p_E^2) = 0$$ Second sum rule (II)

(I) consequence of symmetry restoration
(II) assumes UV asymptotically free theory

[S. Weinberg, 1967]

At leading order in $1/N_c$

$$\Pi_{VV}(p_E^2) = p_E^2 \sum_n \frac{f_{\rho_n}^2}{p_E^2 + m_{\rho_n}^2}$$

$$\Pi_{AA}(p_E^2) = f_\pi^2 + p_E^2 \sum_n \frac{f_{a_n}^2}{p_E^2 + m_{a_n}^2}$$

$SU(2)_L \times SU(2)_R$ is explicitly broken by electromagnetic interactions

mass splittings among charged and neutral pions expected

If one assumes that only first vector and axial resonance contribute to the form factors and impose rules I and II, the pion potential becomes calculable

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha_{em}}{4\pi} \frac{m_\rho^2 m_a^2}{m_a^2 - m_\rho^2} \log\left(\frac{m_a^2}{m_\rho^2}\right)$$

Good theoretical prediction of pion mass difference

General Set-Up

Assume composite sector with global symmetry

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

Gauge $\quad SU(2)_L \times U(1)_Y \subset SO(4) \times U(1)_X \qquad Y = T_{3R} + X$

NGB matrix: $\quad U = \exp\left(i\sqrt{2}\frac{h}{f}\right)$

$$\mathcal{L}_{\sigma_g} = -\frac{1}{4} W^{aL}_{\mu\nu} W^{aL\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{f^2}{4} \mathrm{Tr}\left(\hat{d}_\mu \hat{d}^\mu\right)$$

$$iU^\dagger D_\mu U = \hat{d}_\mu + \hat{E}_\mu \qquad \begin{cases} \hat{d}_\mu = & -\frac{\sqrt{2}}{f}(D_\mu h) + \ldots \\ \hat{E}_\mu = & g_0 A_\mu + \frac{i}{f^2}(h \overleftrightarrow{D}_\mu h) + \ldots \end{cases}$$

[CCWZ notation]

$$m_W = \frac{gf}{2} \sin\frac{\langle h \rangle}{f} \equiv \frac{gv}{2}\,. \qquad s_h = \sin\frac{\langle h \rangle}{f}, \qquad \xi \equiv s_h^2$$

Include Spin 1 resonances

It is known how to add spin 1 resonances in a chiral Lagrangian [Ecker et al,1989]

Consider fields in the $SU(2)_L \times SU(2)_R$ representations

ρ_L: $(\mathbf{3},\mathbf{1})$ ρ_R: $(\mathbf{1},\mathbf{3})$

``Vector Resonances''

a: $(\mathbf{2},\mathbf{2})$

``Axial Resonances''

$$\mathcal{L}_g = \mathcal{L}^v + \mathcal{L}^a$$

$$\mathcal{L}^v = \sum_{i=1}^{N_{\rho_L}} \Big(-\frac{1}{4}\rho^{i,2}_{\mu\nu} + \frac{f_\rho^2}{2}\left(g_\rho \rho^i - \hat{E}\right)^2 + \sum_{j<i} \frac{f^2_{\mathrm{mix}_{ij}}}{2} g_\rho^2 \left(\rho^i - \rho^j\right)^2 \Big),$$

$$\mathcal{L}^a = \sum_{i=1}^{N_a} \Big(-\frac{1}{4}a^{i,2}_{\mu\nu} + \frac{f_a^2}{2\Delta_i^2}\left(g_a a^i - \Delta_i \hat{d}\right)^2 \Big).$$

$$\rho^i_{\mu\nu} = \partial_\mu \rho^i_\nu - \partial_\nu \rho^i_\mu - i g_{\rho^i}[\rho^i_\mu, \rho^i_\nu], \quad a_{\mu\nu} = \nabla_\mu a_\nu - \nabla_\nu a_\mu, \quad \nabla = \partial - i\hat{E}$$

$$m^2_{\rho^i} = f^2_{\rho^i} g^2_{\rho^i} \qquad\qquad m^2_{a_i} = \frac{f^2_{a_i} g^2_{a_i}}{\Delta_i^2}$$

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ρ-SM gauge mass mixing terms

$$\rho^i_{\mu\nu} = \partial_\mu \rho^i_\nu - \partial_\nu \rho^i_\mu - i g_{\rho^i}[\rho^i_\mu, \rho^i_\nu], \quad a_{\mu\nu} = \nabla_\mu a_\nu - \nabla_\nu a_\mu, \quad \nabla = \partial - i\hat{E}$$

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Spin 1/2 resonances

Fermion resonances S and Q in singlet and fundamental SO(4) representations

Let us introduce explicit breaking terms, transforming in SO(5) representations

$$\mathcal{L} \;\; = \bar{q}_L i\hat{D} q_L + \bar{t}_R i\hat{D} t_R + \sum_{i=1}^{N_S} \bar{S}_i (i\hat{\nabla} - m_{iS}) S_i + \sum_{j=1}^{N_Q} \bar{Q}_j (i\hat{\nabla} - m_{iQ}) Q_j +$$

$$\sum_{i=1}^{N_S} \left(\frac{\epsilon^i_{tS}}{\sqrt{2}} \bar{\xi}_R P_L U S_i + \epsilon^i_{qS} \bar{\xi}_L P_R U S_i \right) + \sum_{j=1}^{N_Q} \left(\frac{\epsilon^j_{tQ}}{\sqrt{2}} \bar{\xi}_R P_L U Q_i + \epsilon^j_{qQ} \bar{\xi}_L P_R U Q_i \right) + h.c.,$$

$$\xi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix}, \qquad \xi_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

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$$\sum_{i=1}^{N_S} \left(\frac{\epsilon^i_{tS}}{\sqrt{2}} \bar{\xi}_R P_L U S_i + \epsilon^i_{qS} \bar{\xi}_L P_R U S_i \right) + \sum_{j=1}^{N_Q} \left(\frac{\epsilon^j_{tQ}}{\sqrt{2}} \bar{\xi}_R P_L U Q_i + \epsilon^j_{qQ} \bar{\xi}_L P_R U Q_i \right) + h.c.,$$

Spin 1/2 resonance -SM fermion mass mixing terms

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Minimal Higgs Potential (MHP) hypothesis

Assume that the Higgs potential is saturated at one-loop by the contributions given by the SM and spin 1, 1/2 resonances, made calculable by imposing generalized Weinberg sum rules

Strong, but reasonable, assumption, because

any CHM (within our construction) where a symmetry mechanism is at work to have a calculable Higgs potential will fall into this class

Generalized Weinberg sum rules in our context

Analogue of Π_{LR} in gauge sector

$$\Pi_1(p^2) = g_0^2 f^2 + 2 g_0^2 p^2 \left[\sum_{i=1}^{N_a} \frac{f_{a_i}^2}{(p^2 - m_{a_i}^2)} - \sum_{j=1}^{N_\rho} \frac{f_{\rho^j}^2}{(p^2 - m_{\rho^j}^2)} \right]$$

$$\lim_{p_E^2 \to \infty} g_0^{-2} \Pi_1(-p_E^2) = f^2 + 2 \sum_{i=1}^{N_a} f_{a_i}^2 - 2 \sum_{j=1}^{N_\rho} f_{\rho^j}^2 \equiv 0 \,. \quad \text{(I)}$$

$$\lim_{p_E^2 \to \infty} g_0^{-2} p_E^2 \Pi_1(-p_E^2) = 2 \sum_{i=1}^{N_a} f_{a_i}^2 m_{a_i}^2 - 2 \sum_{j=1}^{N_\rho} f_{\rho^j}^2 m_{\rho^j}^2 \equiv 0. \quad \text{(II)}$$

Sum rule (I) requires at least one vector resonance.

Sum rule (II) requires at least one axial resonance.

Similar sum rules in fermion sector

$$\sum_{i=1}^{N_S} |\epsilon^i_{tS}|^2 - \sum_{j=1}^{N_Q} |\epsilon^j_{tQ}|^2 = 0 \qquad \sum_{i=1}^{N_S} |\epsilon^i_{qS}|^2 - \sum_{j=1}^{N_Q} |\epsilon^j_{qQ}|^2 = 0. \qquad \text{(III)}$$

$$\sum_{i=1}^{N_S} m^2_{iS}\left(|\epsilon^i_{tS}|^2 - |\epsilon^i_{qS}|^2\right) - \sum_{j=1}^{N_Q} m^2_{jQ}\left(|\epsilon^j_{tQ}|^2 - |\epsilon^j_{qQ}|^2\right) = 0\,. \qquad \text{(IV)}$$

Typically in moose-models one has $N_S = N_Q$

$$|\epsilon^i_{tS}| = |\epsilon^i_{tQ}| \qquad |\epsilon^i_{qS}| = |\epsilon^i_{qQ}|$$

Much more constrained choice

Higgs Mass

The Higgs boson is finally a reality

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$$m_H \sim \quad ?$$ with partial compositeness additional states and scales complicate the analysis

Higgs Potential

Calculable Higgs potential is a crucial portal for new physics.

Let first consider the top quark.

The top must be semi-composite

$$m_t \sim \frac{\epsilon^2}{M_f} \frac{v}{f} \sim v \quad \Rightarrow \quad \epsilon^2 \sim M_f f$$

The top mixing largest explicit symmetry breaking terms

Within the MHP hypothesis, Higgs mass related to new resonances masses

For $s_h \ll 1$ $\qquad V(h) = V_g(h) + V_f(h)$

$$V_g(h) = -\gamma_g s_h^2 + \beta_g s_h^4 \qquad\qquad V_f(h) = -\gamma_f s_h^2 + \beta_f s_h^4$$

Non-trivial minimum at $s_h^2 = \xi = \frac{\gamma}{2\beta}$

$$m_h^2 = \frac{8\beta}{f^2}\xi\,(1-\xi)\,. \qquad \beta \simeq \beta_f \propto \frac{\epsilon^4 N_c}{16\pi^2}$$

$$m_H^2 \sim \frac{\epsilon^4 N_c}{2\pi^2 f^2}\xi \simeq \frac{N_c}{2\pi^2}\frac{m_t^2 M_f^2 f^2}{v^2 f^2}\frac{v^2}{f^2}$$

$$\boxed{m_H \simeq \sqrt{\frac{N_c}{2\pi^2}}\,\frac{m_t M_f}{f}}$$

Direct relation between Higgs and resonance masses and

a light Higgs implies light fermion resonances

[A. Wulzer, talk at ICTP workshop, Jan 2012]

[Matsedonskyi, Panico and Wulzer, 1204.6333; Redi and Tesi, 1205.0232; Pomarol and Riva, 1205.6434; Panico, Redi, Tesi, Wulzer, 1210.7114]

Argument can be made more precise

Consider $N_\rho = N_a = N_Q = N_S = 1$

When the sum rules (I-IV) are imposed

one mass scale in gauge sector: m_ρ

three mass scales in fermion sector: m_Q, m_S and ϵ

$$m_L = \min\left(m_0, m_{1/6}, m_{7/6}\right)$$

is the lightest fermion resonance

Fine-tuning requires $\gamma = \gamma_g + \gamma_f \simeq 0$

$$\Rightarrow \quad m_L \leq \frac{\sqrt{2}\pi f}{\sqrt{N_c} m_{top}} m_H \qquad m_\rho \simeq \frac{\pi f}{\sqrt{2} m_W} m_H$$

$$\boxed{\text{It is important to distinguish } m_\rho \text{ from } m_L}$$

For a 125 GeV Higgs, vector resonances not heavy enough to get viable S parameter

With more vector and/or fermion resonances, parameter space greatly enlarged

The tree level S can be accommodated either by
heavier vector resonances or mild tuning

The implication light Higgs $\longrightarrow$ light fermion resonances continue to hold,

with one exception only, based on a chiral composite sector (fully composite RH top)

The converse

light fermion resonances $\longrightarrow$ light Higgs does **not** always hold

Notice that we might also relax the second sum rule. In this way **EWSB no longer calculable, but Higgs mass still predicted**

Counter-example: a Light Higgs and Heavy Resonances

The RH top is fully composite and arises as a chiral massless bound state

In principle the simplest model of all: $N_\rho = N_Q = 1,\ N_a = N_S = 0!$

$$\mathcal{L} = \bar{q}_L i\hat{D} q_L + \bar{t}_R i\hat{\nabla} t_R + \bar{Q}(i\hat{\nabla} - m_Q)Q + \epsilon_{qS}\bar{\xi}_L U P_S t_R + \epsilon_{qQ}\bar{\xi}_L U P_Q Q_R + h.c.$$

Sum rule (III) requires $|\epsilon_{qS}| = |\epsilon_{qQ}| = \epsilon$

Sum rule (IV) would require $\epsilon = 0$

Relax (IV) and keep a log. div. Higgs potential

$$m_H \simeq \sqrt{\frac{N_c}{2\pi^2}}\frac{m_{top}^2}{v}\sqrt{\log\frac{m_{1/6}^2}{m_{top}^2} - 1} \simeq 36\sqrt{\log\frac{m_{1/6}^2}{m_{top}^2} - 1}\ \mathrm{GeV}.$$

(Too) Light Higgs and heavy fermion resonances

Collider Signatures

The deviations to SM couplings might be too small to be detected at the LHC

On the other hand, the light sub-TeV fermion resonances, necessary to explain a 125 GeV Higgs, seem a generic and clear prediction for CHM

LHC already puts significant constraints on the parameter space of CHM, particularly when the lightest fermion resonance has Q=5/3

[Matsedonskyi, Panico and Wulzer, 1204.6333; De Simone,Matsedonskyi,Rattazzi,Wulzer,1211.5663]

Roughly one has

$$m_{2/3} \gtrsim 400 \quad \text{GeV}$$

$$m_{5/3} \gtrsim 600 \quad \text{GeV}$$

Comment on Light Fermion Bound States and Partial Compositeness

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But baryons are not light !

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One possibility is to assume they are meson-like, made by 1 fermion and 1 scalar

Scalar is unnatural ⇨ Assume composite sector is supersymmetric

In this case, UV completions of CHM have recently been constructed

[Caracciolo,Parolini,MS,1211.7290]

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SM gauge couplings develop unacceptably low Landau poles
if one assumes partial compositeness for **all** SM fermions

Conclusions

Holographic CHM represent interesting, calculable and viable models for BSM physics but it is important to go beyond them and look for a wider class of models

Based on the MHP hypothesis, more general CHM leading to a calculable Higgs potential can be constructed

For generic non-chiral composite sectors, a 125 GeV Higgs seems to imply the presence of light, sub TeV, colored fermion resonances

Light fermion states are also welcome from EWPT considerations, because of possible sizable and positive contributions to the T parameter

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The end

Back-up Slides

$$\text{Example: } N_Q = N_S = 1$$

$$Q = (Q_1, Q_7), \quad Y = \frac{1}{6}, \quad Y = \frac{7}{6}$$

Before EWB, LH and RH top mix with doublet Q_1 and singlet S

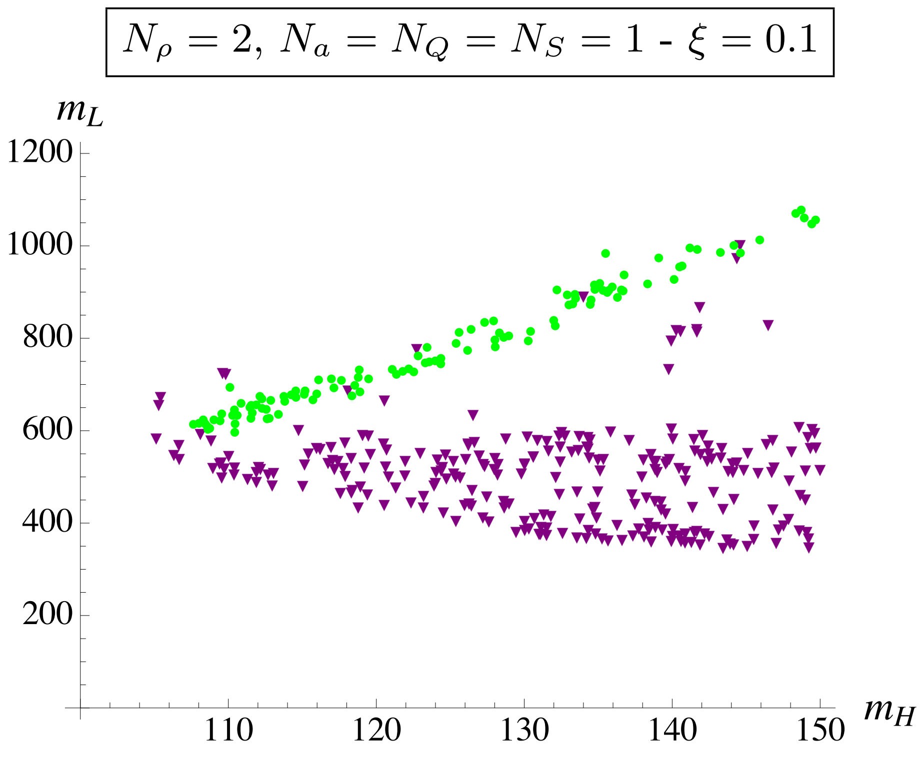
Degree of compositeness measured by the angles

$$\tan\theta_L = \frac{|\epsilon_{qQ}|}{m_Q}, \quad \tan\theta_R = \frac{|\epsilon_{tS}|}{\sqrt{2}m_S}$$

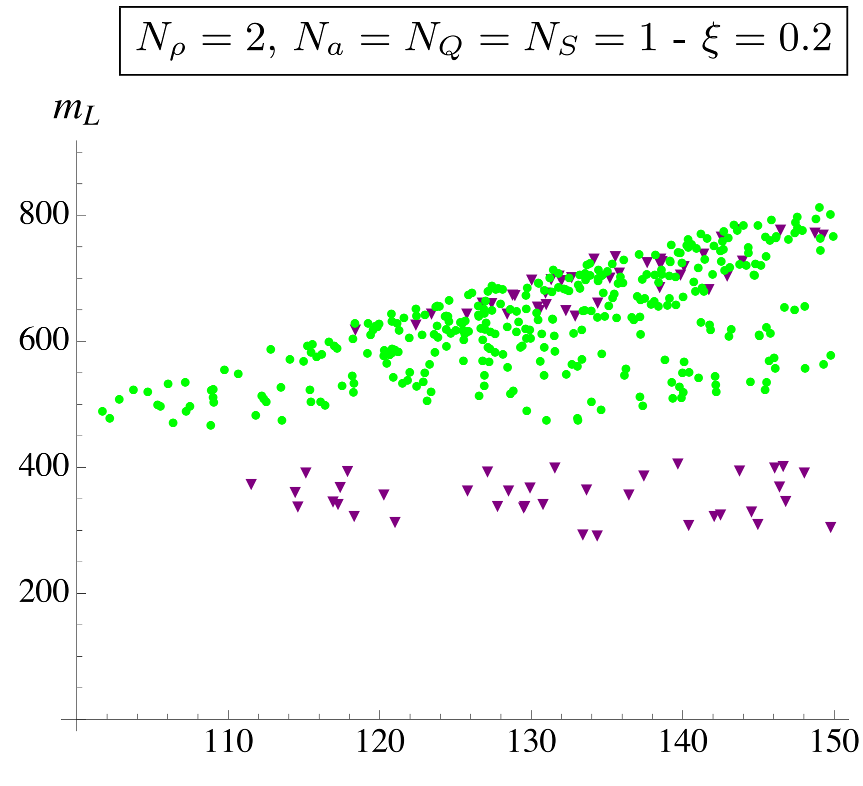
[Contino et al, 2007]

$$m_{top} \simeq \frac{\sin\theta_L \sin\theta_R}{\sqrt{2}} \left| \frac{\epsilon_{qS}}{\epsilon_{qQ}} m_Q - \frac{\epsilon_{tQ}}{\epsilon_{tS}} m_S \right| s_h$$

$$m_0 = \frac{m_S}{\cos\theta_R}, \quad m_{1/6} = \frac{m_Q}{\cos\theta_L}, \quad m_{7/6} = m_Q$$

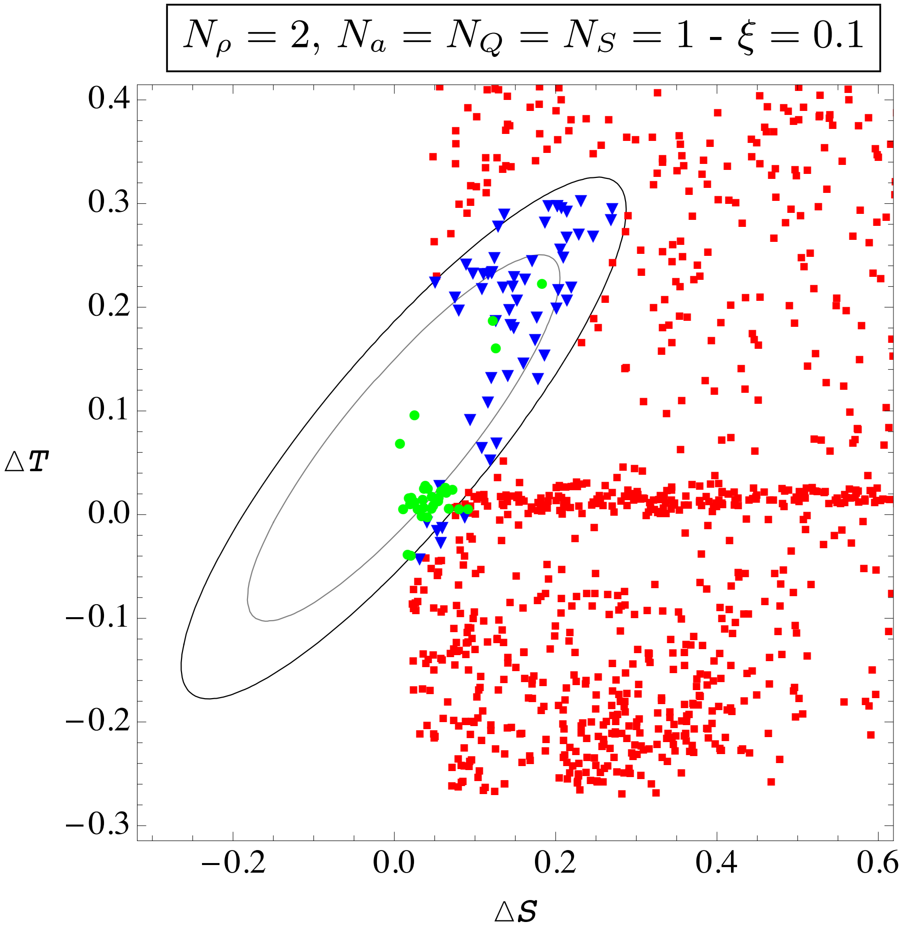


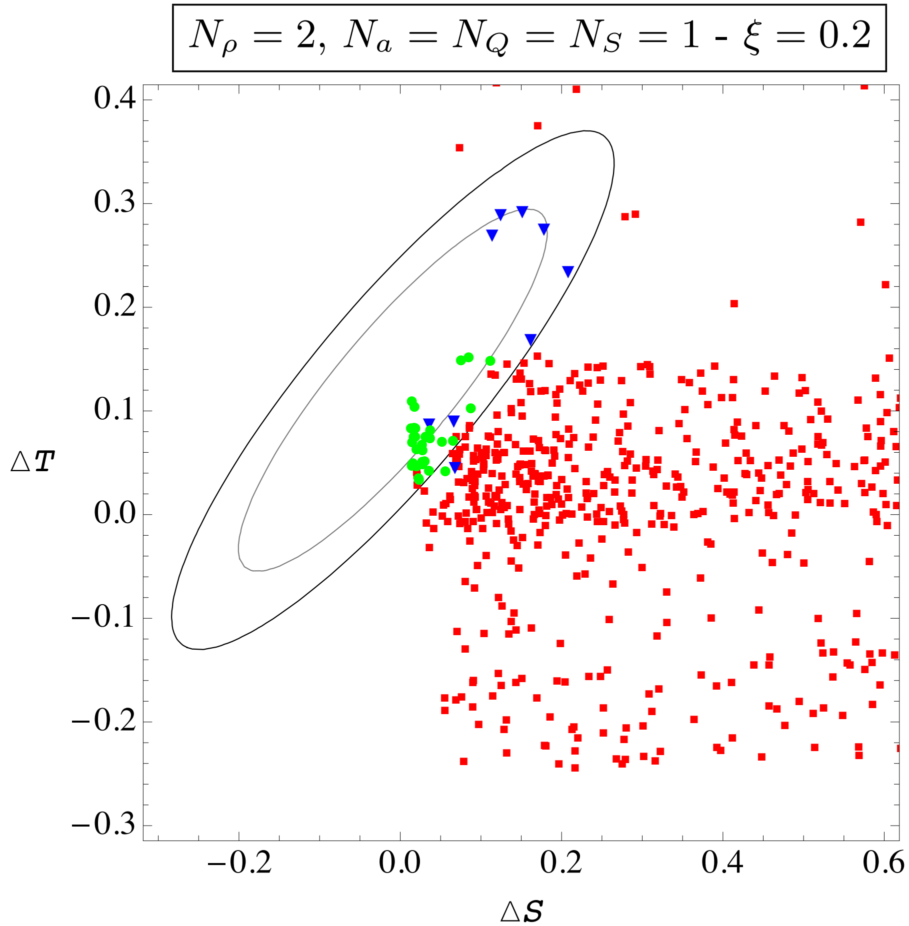
(a)



(b)

Mass of the lightest composite fermion (in GeV), before EWSB, as a function of the Higgs mass (in GeV). The green circles represent the singlet while the purple triangles represent the Q=5/3 state





The green circles are the points which pass both EWPT and the direct bound, the blue triangles pass EWPT but are ruled out by the direct bound and the red squares don't pass EWPT.