Partially Composite Higgs in Supersymmetry

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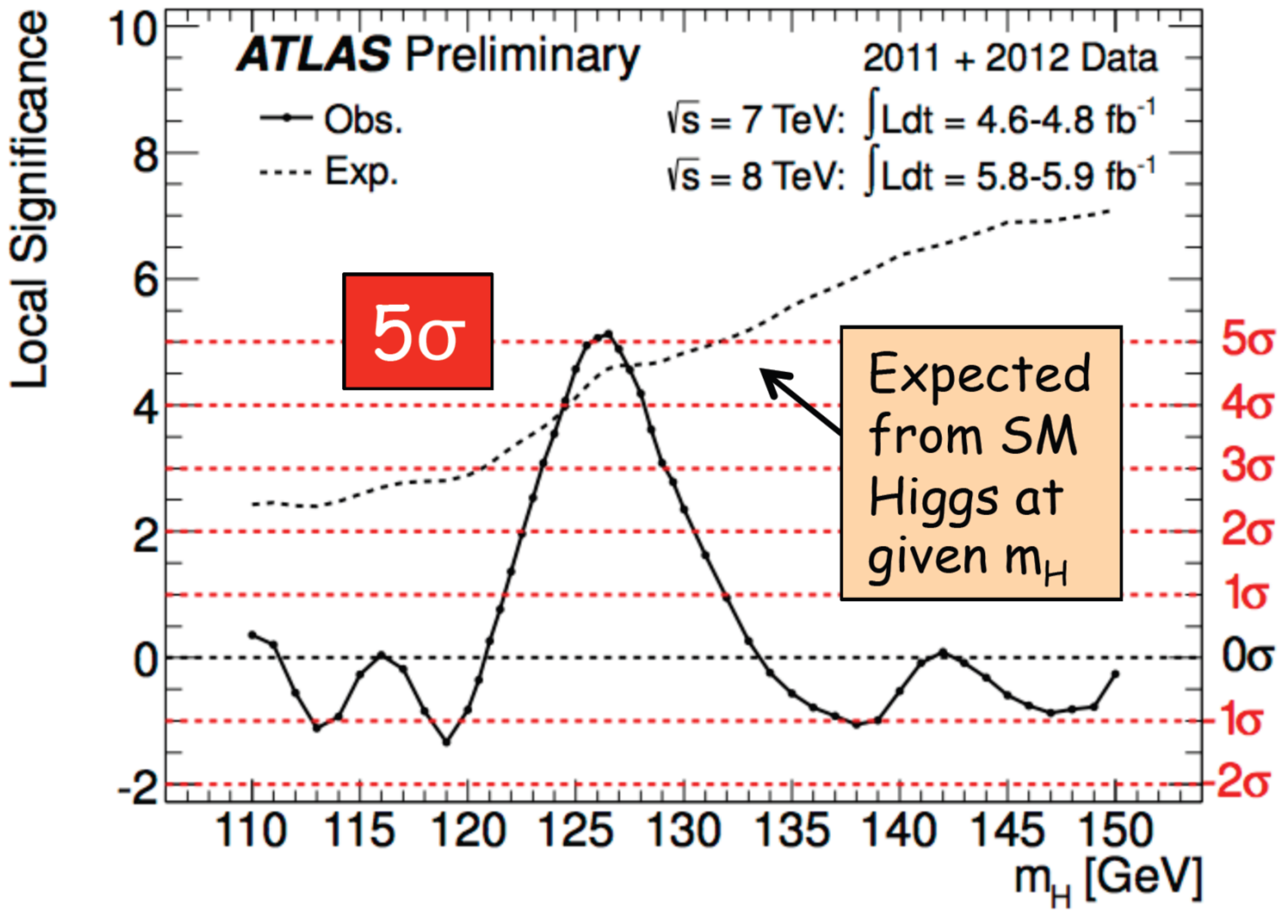
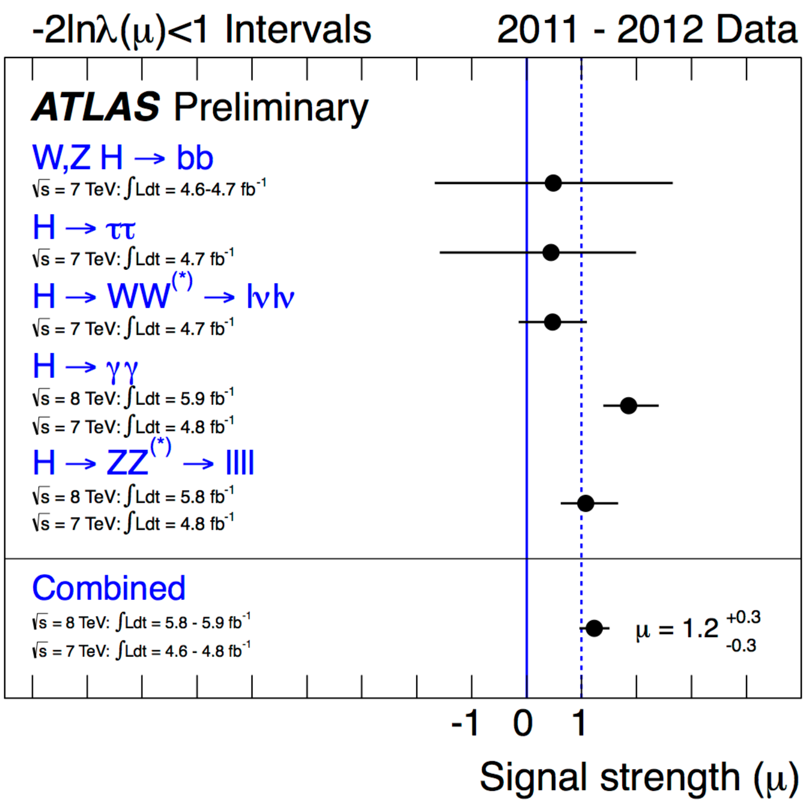
R. Kitano, M. Luty and Y. N., arXiv:1206.4053.

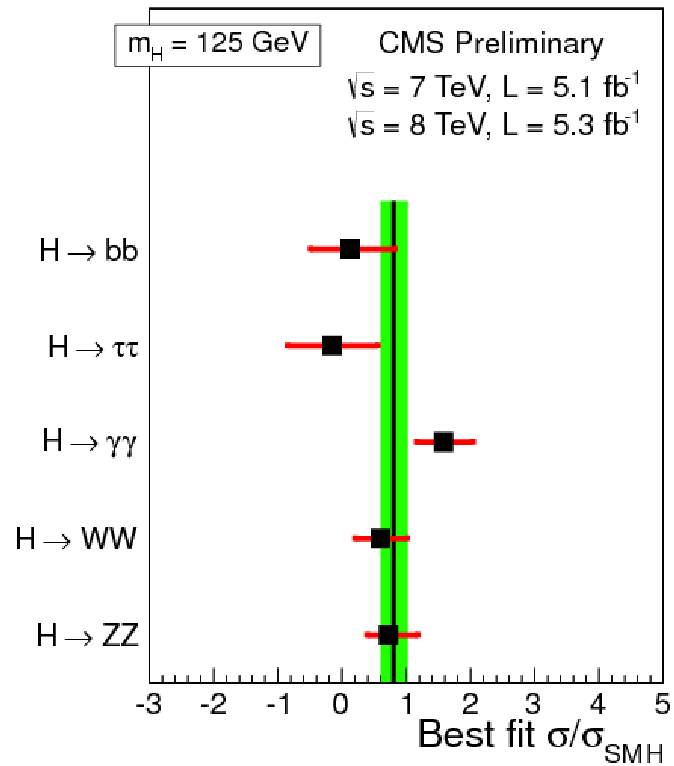
Higgs has been discovered !!



F. Gianotti (ATLAS Collaboration)

The Higgs era





SM Higgs or BSM Higgs ?

We have enough motivations to expect BSM Higgs sector !!

The SM Higgs sector provides no dynamical explanation for the EW breaking.

⇓

We need Physics beyond the SM !

Strong dynamics like Technicolor ?

Radiative breaking like MSSM ?

…

125 GeV Higgs is light, but not so light …

SUSY ? *(good for naturalness !)*

Significant radiative correction is needed in MSSM.

$$\Delta\lambda_H \sim \frac{y_t^4 N_c}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}, \quad N_c = 3$$

A Large quadratic term is also generated.

$$\Delta m_H^2 \sim \frac{y_t^2 N_c}{16\pi^2} m_{\tilde{t}}^2 \ln \frac{M^2}{m_{\tilde{t}}^2}$$

➡ **Fine tuning is required in MSSM.**

Generating a large quartic without fine-tuning

$$\Delta\lambda_H \propto y_t^4, \qquad \Delta m_H^2 \propto y_t^2$$

⇨ We need Higgs interactions stronger than typical perturbative ones.

Composite Higgs is favored ?

⇧

Sizable top Yukawa coupling is difficult to obtain …

Semi-perturbative interaction is enough for 125 GeV Higgs.

So, maybe …

Higgs is partially composite !!

We also have a new dynamics of ~~EW~~ with semi-perturbative couplings to a strong sector.

We here consider a partially composite Higgs scenario such as …

MSSM + CFT

Higgs doublets $H_{u,d}$ *couple to a CFT operator* $\mathcal{O}_{u,d}$:

(dimension d)

$$W = \kappa_u^{2-d} H_u \mathcal{O}_d + \kappa_d^{2-d} H_d \mathcal{O}_u$$

κ : coupling constant (*dimension one*)

⇧

near *the EW scale* ⇦ naturally explained by a generalization of *the Giudice-Masiero mechanism*

$\not{\text{EW}}$ and $\not{\text{CFT}}$: Higgs bootstrap

The conformal breaking is provided by the Higgs vev.

Breaking scale : $\Lambda^{3-d} \sim 4\pi\kappa^{2-d} v$

Higgs is only partially composite

$$\Lambda < 4\pi v \simeq 2\,\mathrm{TeV}$$

The Higgs vev is provided by the conformal breaking.

The minimal model

$SU(2)$ *gauge theory with **8** doublets* :

$$SU(2)_S \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$(Y = T_{3R} + B - L)$$

$$\Psi_i \sim (2,2,1)_b$$

$$\tilde{\Psi}_i \sim (2,1,2)_{-b} \qquad i = 1, 2$$

⇨ **The middle of *"conformal window"***

With superconformal symmetry , …

$$D = 1 + \frac{\gamma}{2} = \frac{3}{2} R$$

⇨ Dimension of $\mathcal{O}_{u,d}$: $d = 3/2$

<u>Higgs potential</u> *(after the decoupling of the CFT sector)*

The CFT sector gives important contributions to the Higgs potential.

$$V_{\rm Higgs} = V_{\rm tree} + V_{\rm dyn} + V_A + V_{\rm soft}$$

Dynamically generated supersymmetric potential ($V_{\rm dyn}$)

Dynamically generated non-supersymmetric potential (V_A, $V_{\rm soft}$)

Two parts are balanced and EW breaking is realized !!

Tree-level Higgs mass terms :

$$V_{\rm tree} = m_{Hu}^2 |H_u|^2 + m_{Hd}^2 |H_d|^2 + B\mu(H_u H_d + {\rm h.c.}) \sim m_H^2 H^2$$

The supersymmetric contribution :

$$\Delta W_{\rm dyn} \sim \frac{\Lambda^3(H)}{16\pi^2}, \qquad \Lambda^{6-2d}(H) \sim 16\pi^2 \kappa_u^{2-d} \kappa_d^{2-d} H_u H_d$$

μ-term is generated !

$$\mu_{\rm dyn} \sim \frac{\partial^2 W}{\partial H^2} \sim \frac{\Lambda^3}{(4\pi v)^2}$$

$$\Rightarrow \quad V_{\rm dyn} \sim \frac{|\Lambda(H)|^6}{(4\pi)^4} \frac{H_u^\dagger H_u + H_d^\dagger H_d}{|H_u H_d|^2} \sim H^{2d/(3-d)}$$

The A-term contribution :

$$\Delta \mathcal{L} = \kappa_u^{2-d} A_u H_u \mathcal{O}_d + \kappa_d^{2-d} A_d H_d \mathcal{O}_u + \text{h.c.}$$

$$\Rightarrow \quad V_A \sim \frac{\Lambda^3(H)}{16\pi^2}(A_u + A_d) + \text{h.c.} \sim H^{3/(3-d)}$$

The contribution of SUSY breaking in the CFT sector :

Not directly expressible in terms of the holomorphic scale $\Lambda(H)$:

$$V_{\rm soft} \sim \frac{1}{16\pi^2} m_{\rm soft}^2 (4\pi\kappa^{2-d} H)^{2/(3-d)}$$

cf. Perturbative case : $W = \sum_i y_i H \tilde{Q}^i Q^i$

$$V_{1-\rm loop} = \sum_i {\rm tr} \left\{ \frac{y_i^2}{(4\pi)^2} (m_i^2 + \tilde{m}_i^2) |H|^2 \left(\ln \frac{y_i^2 |H|^2}{\mu^2} - 1 \right) \right\} + O(m^4)$$

➡ Nonzero even if $\sum_i (m_i^2 + \tilde{m}_i^2) = 0$ for a generic set of y_i

The vacuum

Which two parts are balanced ?

(2)

$$V_{\text{Higgs}} = V_{\text{tree}} + V_{\text{dyn}} + V_A + V_{\text{soft}}$$

(1)

...

(1) V_{dyn} and V_{tree} $\left(\frac{3}{2} < d < 2\right)$

At the vacuum , $V_{\text{tree}} \sim V_{\text{dyn}} \sim m_h^2 v^2$

$$\Rightarrow \quad m_H^2 v^2 \sim \frac{\Lambda^6}{(4\pi)^4 v^2} \sim m_h^2 v^2 \quad \left(\frac{\mu_{\text{dyn}}}{m_h} \sim 1\right)$$

$$m_h \simeq 125\ \text{GeV} \quad \Rightarrow \quad \Lambda \sim 800\ \text{GeV} \quad \left(\frac{\Lambda}{4\pi v} \sim 0.4\right)$$

(2) V_A and $V_{\rm tree}$ $\left(1 < d < \frac{3}{2}\right)$

At the vacuum , $V_{\rm tree} \sim V_A \sim m_h^2 v^2$

$$m_H^2 v^2 \sim \frac{A\Lambda^3}{(4\pi)^2} \sim m_h^2 v^2 \qquad \left(\frac{\mu_{\rm dyn}}{m_h} \sim \left(\frac{m_h}{4\pi v}\right)^{1/2} \left(\frac{A}{\Lambda}\right)^{-3/4} \lesssim 1\right)$$

$$m_h \simeq 125 \text{ GeV} \quad \Rightarrow \quad \Lambda \sim 500 \text{ GeV} \times (A/\Lambda)^{-1/4}$$

...

In all cases , ...

The Higgs VEVs are the dominant source of conformal breaking.

The spectrum of the CFT sector is almost supersymmetric !!

Precision Electroweak Tests

T Parameter

The custodial symmetry is generically broken in the CFT sector.

Degree of tuning : $\delta_C = \frac{1}{2}\frac{\kappa_u^{2-d} v_u - \kappa_d^{2-d} v_d}{\kappa_u^{2-d} v_u + \kappa_d^{2-d} v_d}$

$$\Rightarrow \quad \Delta T \simeq \frac{N(\Delta m)^2}{12\pi s_W^2 c_W^2 m_Z^2} \sim 0.4\left(\frac{N}{4}\right)\left(\frac{\delta_C}{0.1}\right)^2$$

~10% tuning

S Parameter

$$\Delta S \sim \frac{N}{6\pi} \sim 0.2\left(\frac{N}{4}\right)$$

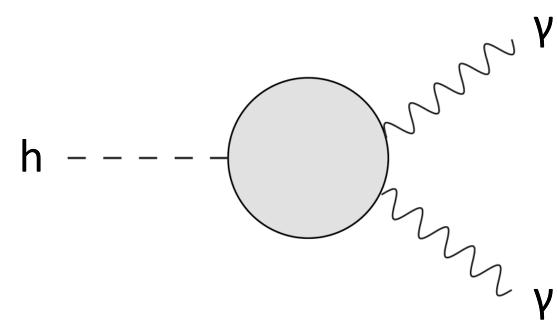
LHC signatures

Two photon decay

The effective interaction at 1-loop

⇧

NSVZ beta function



$$\Gamma(h \to \gamma\gamma) \propto \left| A_{\rm SM} + \frac{1}{2}\left(\sum_r Q_r^2\right)\frac{\cos(\alpha+\beta)}{\sin 2\beta}\right|^2$$

$$A_{\rm SM} \simeq -6.5$$

The minimal model : $\sum_r Q_r^2 = 8(1+4b^2)$

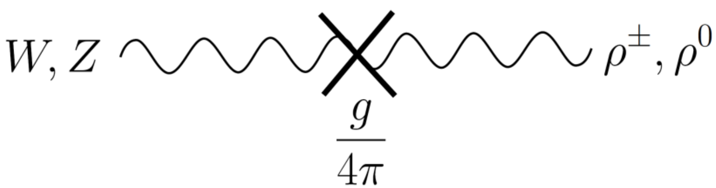
Either an increase or decrease is possible !

TeV Resonances

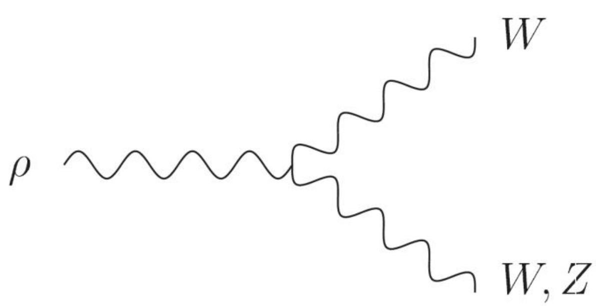
The CFT sector has hadronic resonances at the scale $\Lambda \sim 800 \text{ GeV}$

The CFT sector is almost supersymmetric

e.g. *vector resonances*



Drell-Yan production



$$\mathcal{M} \sim \frac{\Lambda^3}{4\pi v^2}$$

The discovery of resonances can happen soon !!

NMSSM + CFT

$$\Delta W = \kappa_S^{2-d} S \mathcal{O}_S$$ ➡ *Electroweak preserving masses*

$$\Lambda_0^{3-d} \sim 4\pi \kappa_S^{2-d} \langle S \rangle$$

Dynamically generated potential :

$$V \propto \left[1 + c_1 \frac{H_u H_d}{\langle S \rangle^2} + c_2 \left(\frac{H_u H_d}{\langle S \rangle^2} \right)^2 + \cdots \right]$$

A small quadratic term requires fine tuning : $\delta_H \sim \left(\frac{v}{\langle S \rangle} \right)^2 \lesssim 1$

$$\Delta T \simeq \frac{13}{480\pi s_W^2 c_W^2 m_Z^2} \frac{N \Delta m^4}{\Lambda_0^2} \sim 1.2 \left(\frac{N}{4} \right) \left(\frac{\delta_H}{0.1} \right)$$

A model with unification

$SU(3)$ *gauge theory with **6** flavors* :

$$SU(3)_S \times SU(5)_{\rm SM} \quad \left[\begin{array}{ll} \Psi \sim (3,5) & \Sigma \sim (3,1) \\ \tilde{\Psi} \sim (\bar{3},\bar{5}) & \tilde{\Sigma} \sim (\bar{3},1) \end{array} \right.$$

$$\boxed{W = \lambda_u H_u \tilde{D} \Sigma + \lambda_d H_d D \tilde{\Sigma} + \lambda_\Sigma S \tilde{\Sigma} \Sigma + \lambda_D S \tilde{D} D + \lambda_T S \tilde{T} T}$$

$$\Psi = (D, T) \quad \tilde{\Psi} = (\tilde{D}, \tilde{T})$$

Custodial symmetry is maximally broken !

Summary

Partially composite Higgs in supersymmetry !

Fine tuning is relaxed.

The μ-term is generated by the strong dynamics.

Higgs decay property can change.

We can observe new hadrons in LHC.

Thank you !

Extra slides

The Giudice-Masiero Machanism

X : SUSY breaking field with $\langle F_X \rangle$

➡ *Visible sector SUSY breaking* : $M_{\mathrm{SUSY}} \sim \dfrac{\langle F_X \rangle}{M}$

M : Mediation scale

Adding another field Y , $\langle Y \rangle \sim \langle F_X \rangle^{1/2}$

$$W'' = k_1 X + \frac{k_2}{M} Y^4$$

$$\boxed{W' \sim \frac{1}{M^{1/2}} Y H \psi_i \bar{\psi}_i}$$ ➡ $\kappa \sim M_{\mathrm{SUSY}}$

Naïve Dimensional Analysis (NDA)

Λ : The dynamical scale , $g\,(\sim 4\pi)$: The typical size of couplings

$$S_\Lambda = \frac{\Lambda^4}{g^2}\int d^4x\,\mathcal{L}\left(\frac{g\phi}{\Lambda},\frac{g\psi}{\Lambda},\frac{gV}{\Lambda},\frac{\partial}{\Lambda}\right)$$

e. g.) $\partial^\mu\phi^\dagger\partial_\mu\phi = \frac{\Lambda^4}{g^2}\left(\frac{\partial^\mu}{\Lambda}\right)\left(\frac{g\phi^\dagger}{\Lambda}\right)\left(\frac{\partial_\mu}{\Lambda}\right)\left(\frac{g\phi}{\Lambda}\right)$

S-parameter $\Delta\mathcal{L}_{\rm eff} = \frac{gg'S}{16\pi}W^3_{\mu\nu}B^{\mu\nu}$

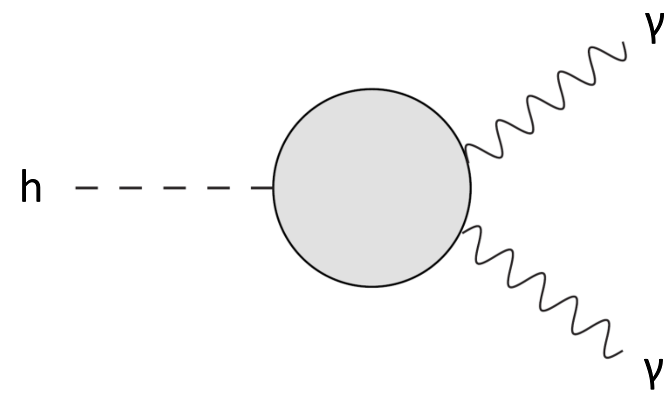
$$\Delta\mathcal{L}_{\rm eff} \sim \frac{\Lambda^4}{16\pi^2}\left(\frac{D}{\Lambda}\right)^4 \sim \frac{gg'}{16\pi^2}W^3_{\mu\nu}B^{\mu\nu} \Rightarrow \Delta S \sim \frac{1}{\pi}$$

The Higgs decay to two photons

The effective interaction at 1-loop

⇧

NSVZ beta function



Example $SU(2)$ *gauge theory with 8 doublets*

Electric charges : $\pm 1/2$

Photon kinetic term

$$\mathcal{L}_{\rm kin} = -\frac{1}{4 g_e^2(v)} F_{\mu\nu} F^{\mu\nu}$$

g_e : QED gauge coupling

→ *Extract Higgs – photon interaction .*

NSVZ beta function

$$\beta(g_e) = \frac{\partial g_e}{\partial \log \mu} \simeq \frac{g_e^3}{16\pi^2} F(1-\gamma)$$

$F = 4$, $\gamma = -1/2$

$$\Rightarrow \quad \frac{1}{g_e^2(v)} \simeq -\frac{6}{8\pi^2} \int_{\log \mu_0}^{\log \Lambda} d \log \mu \quad \Rightarrow \quad \frac{d}{dv}\left(\frac{1}{g_e^2(v)}\right) = -\frac{6}{8\pi^2} \frac{d}{dv} \log \Lambda$$

$$\Rightarrow \quad \mathcal{L}_{\text{int}} = \frac{g_e^2}{(4\pi)^2} \cdot 2 \cdot \frac{1}{v} \cdot h F_{\mu\nu} F^{\mu\nu}$$

Matrix element of two photon decay

$$|\mathcal{M}|^2 = \frac{g^2 m_h^4}{32\pi^2 m_W^2} \left|\alpha_e \cdot ((\text{SM contributions}) + 4)\right|^2$$