— 26th Rencontres de Blois, 18-23 May 2014 —

Higgs and EW precision data

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SCUOLA NORMALE SUPERIORE

INFN

mainly based on

Barbieri, T 1311.7493 , Barbieri, Buttazzo, Kannike, Sala, T 1304.3670

DISCLAIMER

I will only consider the impact of Higgs and EW measurements in the case of Natural New Physics.

I will consider explicit models

Natural SUSY	Composite Higgs
weak	strong

- What is the present scenario?
- Higgs couplings vs. EWPT

[D'Agnolo, Kuflik, Zanetti; Gupta, Montull, Riva; Gupta, Rzehak, Wells; ...]

THE PARTICLE PHYSICISTS VIEW OF THE WORLD

[from D.B. Kaplan '97]

Natural SUSY

Cohen et al '94

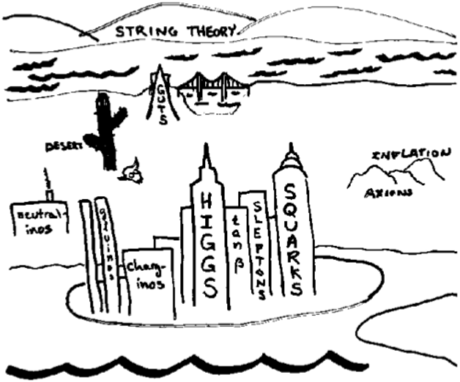
Dimopoulos, Giudice '95

...

Barbieri, Pappadopulo '09

Papucci et al '11

...



Light higgsinos, stops and gluinos **vs.** 126 GeV

$$-\frac{m_Z^2}{2} \simeq |\mu|^2 + m_{Hu}^2, \qquad m_h^2 \simeq m_Z^2 + \Delta_t^2$$

$\downarrow$

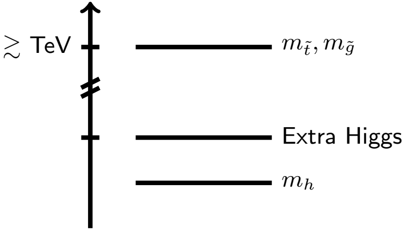
NMSSM as the best motivated option for Natural SUSY,

$$W \supset \lambda S H_d H_u + f(S)$$

- * Less sensitive to stop-top sector

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta_{mix}^2 + \Delta_t^2$$

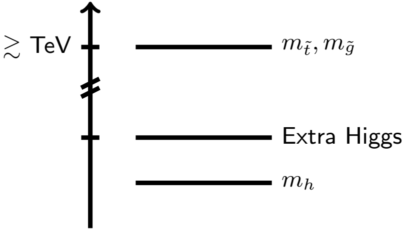
- * Small tuning $\Delta \lesssim 10$ for small $\tan\beta$ and $\lambda \simeq 1$ [Gherghetta et al '12]
- * It allows the lightest particle to be an extra Higgs: $\tilde{m} \longrightarrow \frac{\lambda}{g}\tilde{m}$



[Hall,Pinner, Ruderman '11],[Gherghetta et al '12]

This spectrum allows us to focus only on the Higgs sector

$$c_V = \cos\gamma\cos\delta, \quad c_t = \cos\gamma(\cos\delta + \sin\delta\cot\beta), \quad c_b = \cos\gamma(\cos\delta - \sin\delta\tan\beta)$$



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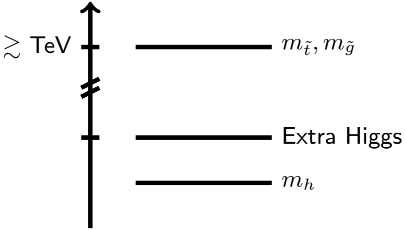
NMSSM with light singlet, $\delta \equiv 0$. Universal rescaling with $\cos\gamma$



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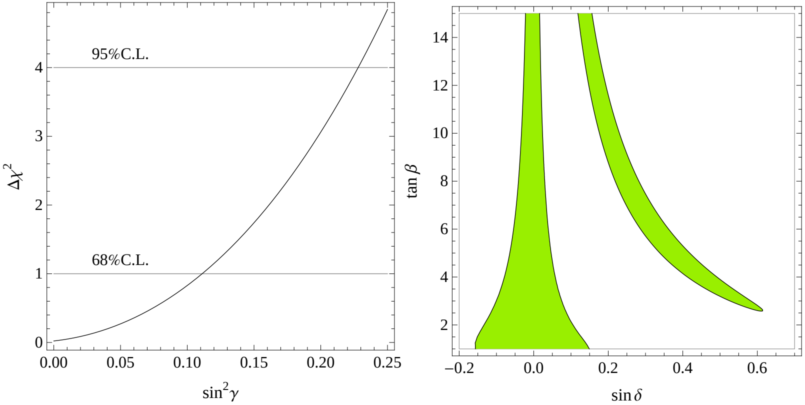
MSSM $\gamma \equiv 0$

Fitting the Higgs



We used the code of [Giardino, Kannike, Masina, Raidal, Strumia, 13]

NMSSM with light-singlet, $\sin^2\gamma \lesssim 22\%$ $\boxed{\rightarrow c_V \sim 10\%}$

MSSM, $\sin\delta|_{\tan\beta=10} \lesssim 5\%$ $\boxed{\rightarrow c_V \sim .1\%}$

NMSSM with light singlet

- Phenomenology similar to singlet extension of the SM
- Peculiar potential from SUSY

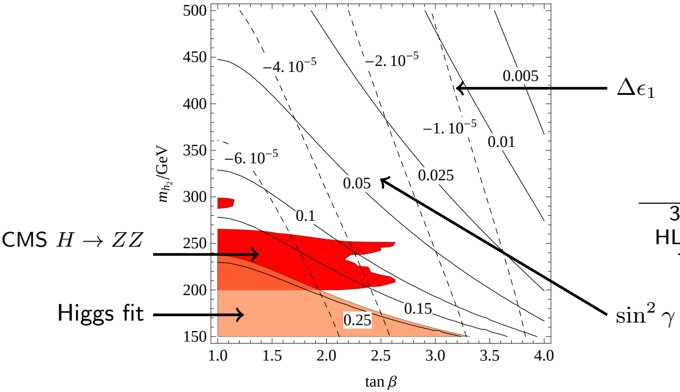
Once $\boxed{\lambda = 0.8}$ and $\boxed{\Delta_t \lesssim 75 \text{ GeV}}$ have been chosen, just two parameters

Higgs Couplings

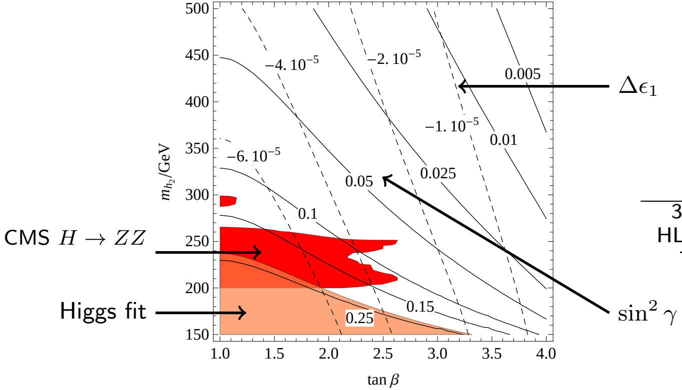
$$\sin^2\gamma = \frac{1}{m_{h_2}^2 - m_h^2}\left[\frac{2{t_\beta}^2}{(1+{t_\beta}^2)^2}\lambda^2 v^2 + \Delta_t^2 + m_Z^2\left(\frac{1-{t_\beta}^2}{1+{t_\beta}^2}\right)^2 - m_h^2\right]$$

ElectroWeak parameters (fully computable)

$$\Delta\varepsilon_1 = -\sin^2\gamma\,\frac{3\alpha}{8\pi c_w^2}\left[\log\frac{m_{h_2}}{m_h} + c_1(m_h) + O\left(\frac{m_Z^2}{m_{h_2}^2}\right)\right] \simeq -10^{-5}$$



	$\sin^2\gamma$
300/fb	15%
HL-LHC	5%
TLEP	$< 1\%$



	$\sin^2\gamma$
300/fb	15%
HL-LHC	5%
TLEP	$< 1\%$

This is a natural region poorly constrained by precision measurements

In the allowed region most interesting channel BR$(h_2 \to hh)$

[CMS looked for it $X \to hh \to b\bar{b}\gamma\gamma$, CMS-PAS-HIG-13-032]

MSSM

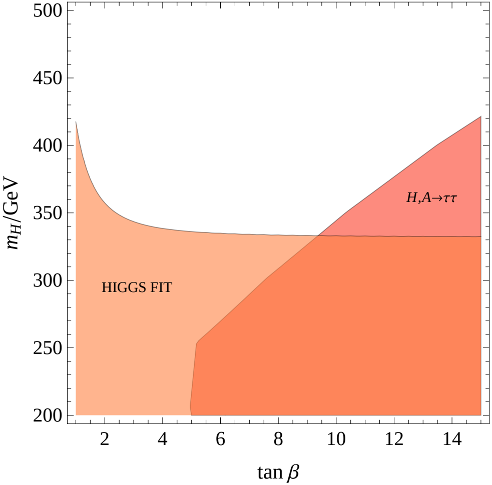
EWPT never relevant

Absence of log-enhancement (suppressed by m_W^4/m_H^4),
but custodial breaking in quartics leads to

$$\widehat{T} = \frac{\alpha}{48\pi s_w^2}\frac{m_W^2 - \Delta m^2}{m_H^2} + O(\frac{m_W^4}{m_H^4})$$

Numerically very small $\longrightarrow$ $\boxed{\widehat{T} \sim 10^{-6}}$

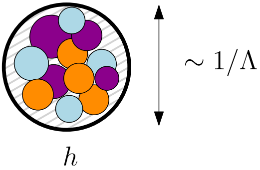
Higgs couplings powerful constraint



- LHC8, $m_H > 350$ GeV @ 95% CL
- @ large-$\tan\beta$ direct searches $H, A \to \tau\tau$ important

Composite Higgs

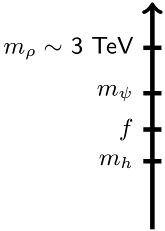
Georgi, Kaplan '84
Agashe, Contino, Pomarol '04
Contino, Da Rold, Pomarol '06
...



Effective description
below the compositeness scale

Why light and natural?

Higgs as pseudo-GB of a strong sector with SO(5)/SO(4) symmetry



- Predictive power of "chiral" expansion
- Separation of scales $f > v$
- Custodial in the strong sector
- Composite fermions $m_\psi = g_\psi f$ needed to trigger EWSB
- Higgs mass set by top yukawa and g_ψ

$$m_h^2 = C \frac{N_c m_t^2}{2\pi^2} g_\psi^2$$

- Tuning (for 126 GeV Higgs)

$$\Delta \sim \frac{m_\psi^2}{v^2} \geq \frac{f^2}{v^2}$$

Top partners have been actively searched for: $m_\psi > 700\ \mathrm{GeV}$

Composite Higgs couplings

Precise prediction from symmetry of the "chiral" lagrangian.
Important tree-level effects mainly sensitive to v/f

$$c_V = \sqrt{1 - \frac{v^2}{f^2}}, \quad c_\psi = \frac{1 - 2\frac{v^2}{f^2}}{\sqrt{1 - \frac{v^2}{f^2}}}$$

From the previous Higgs fit we get

$$f^2 \gtrsim 5v^2$$

Full complementary with direct searches $\boxed{m_\psi > 1.5 \text{ TeV}\left(\frac{g_\psi}{3}\right)}$

Target precision on c_V from Higgs fit $c_V \sim 10\%$

EWPT & strong coupling

When the Higgs is a pGB, general prediction [Barbieri et al '07]

$$\widehat{S} = \frac{g^2}{96\pi^2}(1 - c_V^2)\log\frac{\Lambda}{m_h}, \qquad \widehat{T} = -(1 - c_V^2)\frac{3\alpha}{8\pi c_w^2}\log\frac{\Lambda}{m_h}$$

Assuming no other contribution **precision on $c_V \sim 5\%$**

[Ciuchini, Franco, Mishima, Silvestrini '13]

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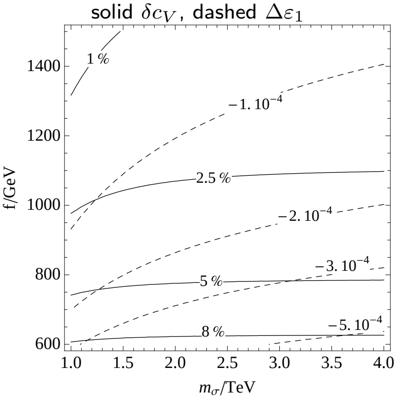
At present, Composite Higgs has natural islands allowed by precision tests

We can simulate the physics of Composite Higgs by a (computable) LΣM

$$1 - c_V^2 = \sin^2\theta = \xi - \frac{m_h^2}{m_\sigma^2} + O(\xi \frac{m_h^2}{m_\sigma^2})$$

$$\Delta\varepsilon_1 = -\sin^2\theta \frac{3\alpha}{8\pi c_w^2}\left[\log\frac{m_\sigma}{m_h} + c_1(m_h) + O(\frac{m_Z^2}{m_\sigma^2})\right]$$



Both Higgs couplings and EW can have strong impact

300/fb	$c_V < 6\%$
HL-LHC	$c_V < 2 \div 3\%$
TLEP	$c_V < 1\%$
TLEP	$\Delta\epsilon_1 < 10^{-4}$ [Mishima]

Complementary info on top-partners mass: $m_\psi \gtrsim 3 \times f \times (\frac{g_\psi}{3})$

Conclusions

Higgs couplings already useful tool

- LHC8 powerfully constrained 2HDM type-II (MSSM)
- Competitive with direct searches in the MSSM (at moderate $\tan\beta$)

NMSSM with light singlet motivated option for SUSY

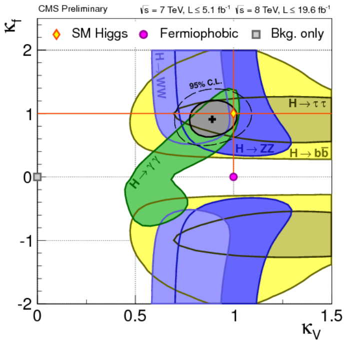
- Poorly constrained by direct and indirect searches
- EWPT never relevant

Higgs couplings seem the best places to see effects in future

EWPT play a role only in strongly coupled scenarios

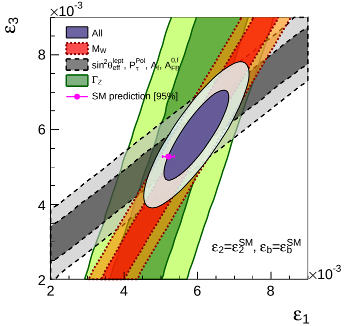
Backup

Experimental status: fit



Agreement with SM within 1σ.
In principle room for sizeable deviations

$$\delta c_V \lesssim 15\%, \quad \delta c_f \lesssim 20\%$$



[Ciuchini, Franco, Mishima, Silvestrini '13]
New fit after Higgs discovery

$$\Delta\varepsilon_1 = (5 \div 8)10^{-4}$$

In the “near” future (2022) 300/fb @LHC14

	ATLAS	CMS
$h \to \gamma\gamma$	0.16	0.15
$h \to ZZ$	0.15	0.11
$h \to WW$	0.30	0.14
$Vh \to Vb\bar{b}$	–	0.17
$h \to \tau\tau$	0.24	0.11
$h \to \mu\mu$	0.52	–

w/ theoretical uncertainties included

...and in the far (203*)

HL-LHC (3000/fb)	TLEP (240→ 350 GeV)	TLEP (90→ 160 GeV)
$\delta c_V \lesssim 4 \div 5\%$	$\delta\sigma_{hZ} \leftrightarrow \delta c_V < 1\%$	$\Delta\varepsilon_1 \lesssim 10^{-4}$
[ATLAS & CMS twiki]	[1308.6176]	[Mishima]

The 3 parameters of EW sector fixed in terms of the most precise observables

$$g, g', v \longleftarrow \alpha, G_F, M_Z$$

Many others (derived) observables depends on these input parameters

$$O_i = O_i(\alpha, G_F, M_Z), \quad O_i = \{\Gamma_Z, A^{(l,b,\tau)}_{Z-pole}, M_W\}$$

We can extract 3 parameters in terms of measured quantities, M_W, g_V, g_A.

$$\begin{aligned}\Delta r &= 1 - s^2 c^2 [(1 - \frac{M_W^2}{M_Z^2})\frac{M_W^2}{M_Z^2}]^{-1} \\ \Delta\rho &= -2(1 + 2g_A) \\ \Delta k &= (1 - g_V/g_A)/(4s^2) - 1\end{aligned}$$

$$\begin{aligned}\varepsilon_1 &= \Delta\rho \\ \varepsilon_2 &= c^2\Delta\rho + s^2/(c^2 - s^2)\Delta r - 2s^2\Delta k \\ \varepsilon_3 &= c^2\Delta\rho + (c^2 - s^2)\Delta k\end{aligned}$$

[Altarelli, Barbieri '91]

ε-parameters

In terms of 1-loop corrections, [Barbieri, Caravaglios, Frigeni '92]

$$\begin{aligned}
\varepsilon_1 &= e_1 - e_5 - \delta G_{V,b}/G_F - 4\delta g_A, \\
\varepsilon_2 &= e_2 - s^2 e_4 - c^2 e_5 - \delta G_{A,b}/G_F - \delta g_V - 3\delta g_A, \\
\varepsilon_3 &= e_3 + c^2 e_4 - c^2 e_5 + (c^2 - s^2)/(2s^2)\delta g_V - (1+2s^2)/(2s^2)\delta g_A
\end{aligned}$$

where e_i encodes oblique corrections,

$$\Pi_{ij}^{\mu\nu}(q^2) = -i\eta^{\mu\nu}[\Pi_{ij}(0) + q^2 F_{ij}(q^2)] + (q^\mu q^\nu \cdots)$$

$$e_1 = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{M_W^2}, \qquad e_2 = F_{WW}(M_W^2) - F_{33}(M_Z^2), \qquad e_3 = \frac{c}{s} F_{30}(M_Z^2),$$

$$e_4 = F_{\gamma\gamma}(0) - F_{\gamma\gamma}(M_Z^2), \qquad e_5 = M_Z^2 F'_{ZZ}(M_Z^2),$$

- Often $\Delta\varepsilon_i \equiv \varepsilon_i - \varepsilon_i^{\text{SM}}$ depends only on oblique corrections Δe_i.
- Sometimes $F_{ij}(q^2)$ has a mild dependence on q^2.

In 'many' cases, we can expand

$$\begin{aligned}
\Pi_{WW}(q^2) &= \Pi_{WW}(0) + q^2\left[\Pi'_{WW}(0) + \frac{q^2}{2!}\Pi''_{WW}(0) + \cdots\right], \\
\Pi_{33}(q^2) &= \Pi_{33}(0) + q^2\left[\Pi'_{33}(0) + \frac{q^2}{2!}\Pi''_{33}(0) + \cdots\right], \\
\Pi_{BB}(q^2) &= \Pi_{BB}(0) + q^2\left[\Pi'_{BB}(0) + \frac{q^2}{2!}\Pi''_{BB}(0) + \cdots\right], \\
\Pi_{3B}(q^2) &= \Pi_{3B}(0) + q^2\left[\Pi'_{3B}(0) + \frac{q^2}{2!}\Pi''_{3B}(0) + \cdots\right],
\end{aligned}$$

$\Pi' \to$ [Peskin, Takeuchi '91]
$\Pi'' \to$ [Barbieri, Pomarol, Rattazzi, Strumia '04]

Up to order q^4 we have

$$12 - \underbrace{3}_{g,g',v} - \underbrace{2}_{U(1)_{QED}} = 7 \text{ coefficients}$$

[Barbieri, Pomarol, Rattazzi, Strumia '04]

Adimensional form factors			operators	custodial	SU(2)$_L$
$g^{-2}\widehat{S}$	$=$	$\Pi'_{3B}(0)$	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}/gg'$	$+$	$-$
$g^{-2} M_W^2 \widehat{T}$	$=$	$\Pi_{33}(0) - \Pi_{WW}(0)$	$\lvert H^\dagger D_\mu H \rvert^2$	$-$	$-$
$-g^{-2}\widehat{U}$	$=$	$\Pi'_{33}(0) - \Pi'_{WW}(0)$		$-$	$-$
$2g^{-2} M_W^{-2} V$	$=$	$\Pi''_{33}(0) - \Pi''_{WW}(0)$		$-$	$-$
$2g^{-1} g'^{-1} M_W^{-2} X$	$=$	$\Pi''_{3B}(0)$		$+$	$-$
$2g'^{-2} M_W^{-2} Y$	$=$	$\Pi''_{BB}(0)$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$	$+$	$+$
$2g^{-2} M_W^{-2} W$	$=$	$\Pi''_{33}(0)$	$(D_\rho W^a_{\mu\nu})^2/2g^2$	$+$	$+$

$$\delta e_1 = \widehat{T}\,,$$

$$\delta e_2 \simeq \widehat{U} - V - \frac{s^2}{c^2} W\,, \qquad e_4 \simeq -\frac{s^2}{c^2} W - \frac{2s}{c} X - Y\,,$$

$$\delta e_3 \simeq \widehat{S} + \frac{X}{sc}\,, \qquad e_5 \simeq W - 2\frac{s}{c} X + \frac{s^2}{c^2} Y,$$

$$\begin{aligned}
\delta\varepsilon_1 &\simeq \widehat{T} - W + 2X\frac{s}{c} - Y\frac{s^2}{c^2},\\
\delta\varepsilon_2 &\simeq \widehat{U} - W + 2X\frac{s}{c} - V\,,\\
\delta\varepsilon_3 &\simeq \widehat{S} - W + \frac{X}{sc} - Y.
\end{aligned}$$

We can simulate the physics of Composite Higgs by a simple LΣM

$$\mathcal{L} = \frac{1}{2}(D_\mu \Phi)^2 - \lambda(\Phi^2 - f_0^2)^2 - V(\varphi, \varphi_5),$$

The limit $\lambda \gg 1$ reproduces the usual constraint $\Phi^2 = f^2$
$V(\varphi, \varphi_5)$ breaks SO(5) explicitly: φ (fourplet), φ_5 (SM singlet)

$$V_{\mathbf{5}}(\varphi, \varphi_5) = \alpha f_0^2 \varphi^2 - \beta \varphi^2 \varphi_5^2$$

$m_\sigma \sim \sqrt{\lambda} f < 4\pi f$

$\sin\theta$, mixing $(h, \sigma) \leftrightarrow (\varphi, \varphi_5)$

f

m_h

All determined by m_σ and f

If one accepts this model, then all become calculable.
IR-logs in EWPT are then cut-off by m_σ.