

# Dynamical Origin for the 125 GeV Higgs (a hybrid setup)

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## Based on:

1. *“Hybrid dynamical EW symmetry breaking with heavy quarks and the 125 GeV Higgs”*,  
M. Geller, SBS, A. Soni, arXiv:1302.2915 (PRD2013)
2. *“125 GeV Higgs in the context of four generations with two Higgs doublets”*,  
M. Geller, SBS, G. Eilam, A. Soni, PRD86, 115008 (2012)

## Need to account for the recently discovered 125 GeV Higgs-like ...

SM Higgs? So far looks like it but makes no sense:  
where is the new physics? (hierarchy problem ...)

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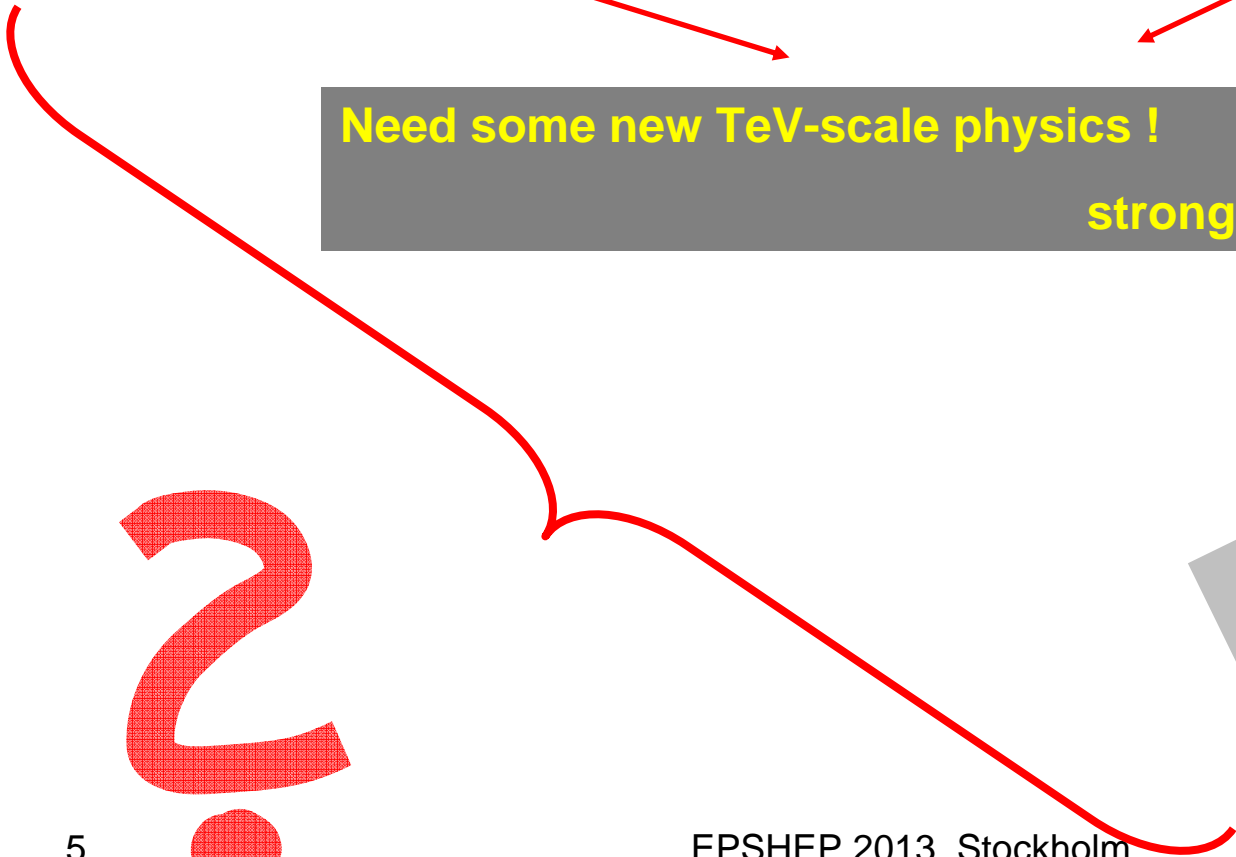
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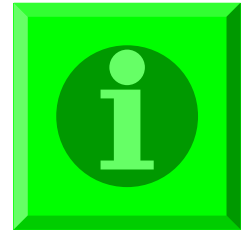


An “old” idea: heavy fermions may be the agents for a Dynamical EWSB

Miransky, Tanabashi, Yamawaki, PLB221,177,1989 & PLA4,1043,1989;  
Nambu, report#89-08,1989(unpublished); Bardeen, Hill, Lindner, PRD41,1647,1990

no need to introduce an elementary Higgs:  $\langle \bar{q}' q' \rangle \neq 0 \dots$

e.g., 4th generation fermions/quarks can trigger  
DEWSB through their condensations



Holdom, PRL57, 2496, 1986 & JHEP,0608,076,2006; King, PLB234,108,1990; Luty, PRD41,2893,1990;  
Hill, Luty, Paschos, PRD43,3011, 1991; Hung, Isidori, PLB402,122,1997; Burdman, Da Rold,  
JHEP,0712,086,2007; Hung, Xiong, NPB848,288,2011 & PLB694,430,2011; Mimura, Hou, Kohyama,  
arXiv:1206.6063; Hashimoto, Miransky, arXiv:0912.4453

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no need to introduce an elementary Higgs:  $\langle \bar{q}' q' \rangle \neq 0 \dots$

\* top-condensation  $\langle \bar{t} t \rangle \neq 0$  doesn't work  
-  $m_t$  (dynamical)  $\sim 230$  GeV  
-  $\Lambda \sim 10^{17}$  GeV  $\Rightarrow$  fine tuning ...

Bardeen, Hill, Lindner, PRD41,1647,1990

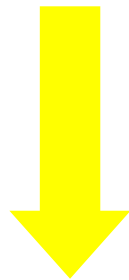
# Adopt a simple logic ...

**Be modest (no explicit model building ...):**

- **ASSUME** a strongly interacting fermionic sector above  $\Lambda$

and

- **TRADE** ignorance for effective couplings + boundary conditions @  $\Lambda$



***NJL mechanism***



At the compositeness scale,  $\Lambda$ , physics is described by an effective (attractive) 4-Fermi interaction of the strongly coupled fermions:

$$L_{NJL} = G_{\psi} (\bar{\psi}_L \psi_R) (\bar{\psi}_R \psi_L)$$

Solve the Gap equation (keeping only fermion loops – bubble diagrams):

If  $G$  is greater than some critical value,  $G_{\psi} > G_{\text{critical}}$ , then:

- **EW symmetry can be broken**
- **the field  $\psi$  acquires a mass**
- **the low-energy theory contains a scalar bound state:  $S \sim \langle \psi \psi \rangle$  !**

Bardeen, Hill, Lindner, PRD41,1647,1990

# DEWSB with the NJL mechanism & “matching”

To get a realistic framework;

use an auxiliary field H which reproduces the 4-Fermi interaction when it is integrated out:

$$L_{aux} = g_0^\psi (\bar{\psi}_L \psi_R H + H.c) - m_0^2 H^+ H \xrightarrow{\text{integrate } H} L_{NJL} = \frac{(g_0^\psi)^2}{m_0^2} (\bar{\psi}_L \psi_R)(\bar{\psi}_R \psi_L)$$

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Then, below the cutoff  $\Lambda$ , H develops kinetic terms and quatric interactions (from the fermion loops) in the effective action

- H becomes a dynamical field
- the theory containing H is exactly equivalent to the theory written in terms of fermions, i.e., in terms of  $L_{NJL}$  with  $G_\psi = \frac{(g_0^\psi)^2}{m_0^2}$

⇒ H is interpreted as a bound state:  $H \sim \langle \psi \psi \rangle \dots$

***More generally (& naturally):***

**should expect multiple bound states**

**e.g.,  $\langle t' t' \rangle$ ,  $\langle b' b' \rangle$  ...**

**$\Rightarrow$  multiple Higgs bosons below the compositeness scale**

**Luty,PRD41,2893,1990; Hill,Luty,Paschos,PRD43,3011,1991; Burdman,Da Rold, JHEP,0712,086,2007;  
Hung,Xiong,NPB848,288,2011 & NPB847,160,2011 & PLB694,430,2011;  
Ho,Hung,Kepart,JHEP1206,45,2012; Burdman,de Lima,Matheus,PRD83,035012,2011;  
Burdman,Haluch,JHEP1112,038,2011; Holdom,arXiv:1301.0329;Smetana,arXiv:1301.1554; Burdman,Da  
Rold,Eboli,Matheus,PRD79,075026,2009; Hashimoto,Miransky,PRD81,055014,2010;  
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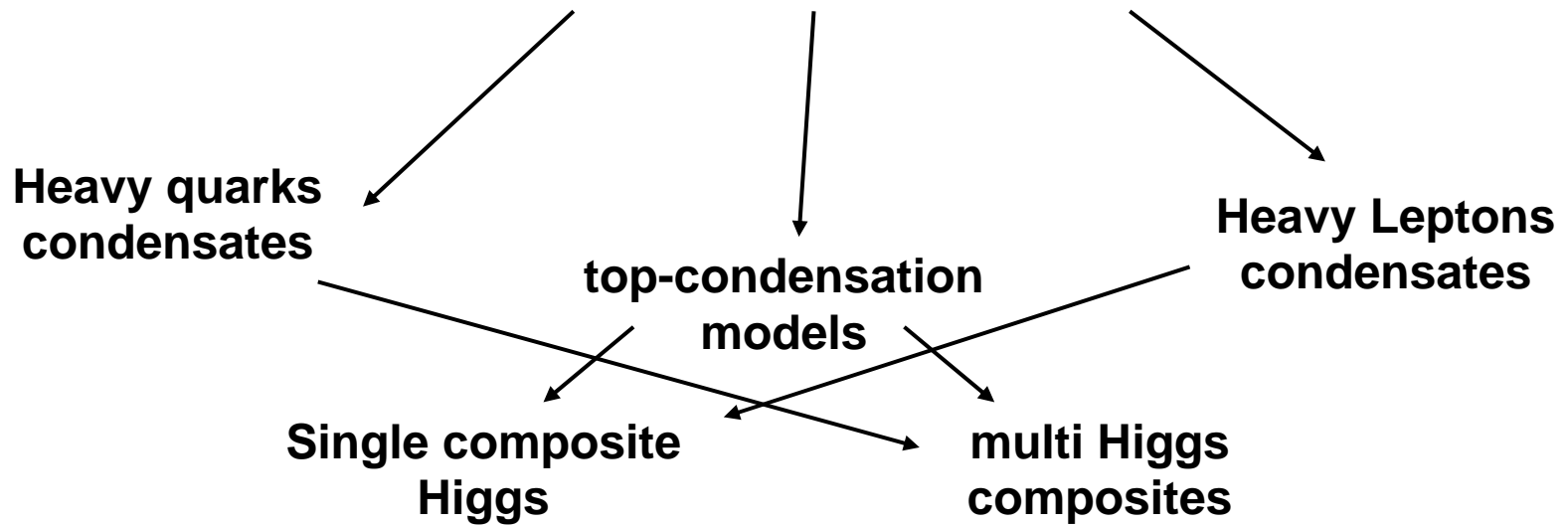
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**Heavy fermions + multiple Higgs also more favorable when confronted with the data ...**

M. Geller, SBS, G. Eilam, A. Soni, PRD86, 115008 (2012)  
SBS, S. Nandi, A. Soni, PRD84, 035009 (2011)

SBS, M. Geller, S. Nandi, A. Soni, arXiv:1208.3195, in: "Advances in High Energy Physics" V2013

# The DEWSB/NJL “spectrum”



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Heavy quarks  
condensates

top-condensation  
models

Heavy Leptons  
condensates

Single composite  
Higgs

multi Higgs  
composites

$\Lambda \sim O(10^{17}) \text{ GeV}$

$m_f \sim v_{EW}$   
e.g., top-condensation

$\Lambda \sim O(1) \text{ TeV}$

$m_f \sim 500 \text{ GeV}$   
e.g., “4<sup>th</sup> gen” ...

## A major caveat:

In the “conventional” NJL models for DEWSB the typical mass of the composite H  $\sim \langle \psi\psi \rangle$  tends to lie in the range:

$$m_\psi < m_{\langle \bar{\psi}\psi \rangle} < 2m_\psi$$



**Too heavy to account for the recently observed 125 GeV Higgs-like particle**



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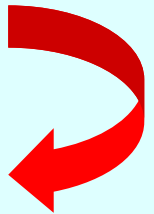


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Our proposed HYBRID “solution” leads to  $m_H \sim O(m_W)$

Hybrid setup with heavy quarks [ &  $\Lambda \sim O(1)$  TeV ] :

add an unconstrained scalar (“fundamental”,  $\phi_l$ ) at the compositeness scale, where the super-critical 4-Fermi operators form an additional heavy composite  $\phi_h$



# Hybrid DEWSB with heavy quarks and the 125 GeV Higgs

M. Geller, SBS, A. Soni, arXiv:1302.2915

As a “toy framework”: use a chiral 4<sup>th</sup> gen. doublet, assumed to be charged under some new strong interaction that dynamically break EW symmetry:

At the compositeness scale  $\Lambda$ : *The bare SM Lag. at  $\Lambda$  (with  $\phi_1$ )*

$$\mathcal{L} = \mathcal{L}_{SM}(\Lambda) + G_{t'} \bar{Q}'_L t'_R \bar{t}'_R Q'_L + G_{b'} \bar{Q}'_L b'_R \bar{b}'_R Q'_L + G_{t'b'} (\bar{Q}'_L b'_R \bar{t}'_R i\tau_2 Q'^e_L + h.c.)$$

$$Q'_L = (t'_L \ b'_L)^T$$

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The above Lag/theory can be reproduced by introducing at  $\Lambda$  an auxiliary Higgs doublet  $\phi_h$  which couples **ONLY** to the 4th gen. quarks:

$$\mathcal{L}_{q'}(\Lambda) = g_{b'}^0 (\bar{Q}'_L \Phi_h b'_R + h.c.) + g_{t'}^0 (\bar{Q}'_L \tilde{\Phi}_h t'_R + h.c.) - (\mu_h^0)^2 \Phi_h^\dagger \Phi_h$$

The full theory at  $\Lambda$  is then described by:  $\mathcal{L}(\Lambda) = \mathcal{L}_{SM}(\Lambda) + \mathcal{L}_{q'}(\Lambda) + (\mu_{he}^0)^2 (\Phi_h^\dagger \Phi_e + h.c.)$

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$$\phi_h \sim g_{t'} \langle \bar{Q}'_L t'_R \rangle + g_{b'} \langle \bar{Q}'_L b'_R \rangle$$

Integrating out  $\phi_h$ , recovers the 4-Fermi Lag with:

$$G_{t'} = \frac{(g_{t'}^0)^2}{(\mu_h^0)^2}, \quad G_{b'} = \frac{(g_{b'}^0)^2}{(\mu_h^0)^2}, \quad G_{t'b'} = -\frac{g_{t'}^0 g_{b'}^0}{(\mu_h^0)^2}$$

# Hybrid DEWSB with heavy quarks and the 125 GeV Higgs

$\phi_h$  - couples to new heavy quarks & leptons – **composite**

⇒ Q' have purely dynamical masses ...

$\phi_l$  - mass of SM fermions & CKM flavor structure – **“fundamental”/unconstrained**

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At energies below  $\Lambda$ :

$\phi_h$  acquires a kinetic term as well as LARGE self interactions from the heavy fermion loops ( $\phi_l$  quartic do not receive such large corrections !)



$\Rightarrow$  the theory behaves like a 2HDM below  $\Lambda$

*(specifically: like the 4G2HDM of SBS, Nandi, Soni PRD2011)*

# The low-energy Hybrid 4G2HDM (h4G2HDM)

$$\begin{aligned}
 V_{h4G2HDM}(\Phi_h, \Phi_\ell) = & \mu_\ell^2 \Phi_\ell^\dagger \Phi_\ell + \mu_h^2 \Phi_h^\dagger \Phi_h - \mu_{h\ell}^2 (\Phi_h^\dagger \Phi_\ell + h.c.) \\
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 \end{aligned}$$

$\hookrightarrow$  how dynamical:  $Z_\phi \sim |\phi|^2$   
 $Z_\phi(\Lambda) \rightarrow 0$

$\hookrightarrow$  from the  $f'$ -loops

## Matching the 4-Fermi theory to the h4G2HDM at $\Lambda$ :

$\Rightarrow$  Solve RGE of the h4G2HDM with the compositeness boundary conditions :

$$g_{q'}(\Lambda) \rightarrow \infty, \quad \lambda_{h,3,4}(\Lambda) \rightarrow \infty, \quad \frac{\lambda_h(\Lambda)}{g_{q'}^4(\Lambda)} \rightarrow 0, \quad \frac{\lambda_{3,4}(\Lambda)}{g_{q'}^2(\Lambda)} \rightarrow 0$$

i.e., the composite theory is effectively a strongly coupled

Higgs-Yukawa and Higgs-quartic systems ...

**While**  $\lambda_\ell(\mu \rightarrow \Lambda) \rightarrow \lambda_\ell^{(0)}$ , where  $\lambda_\ell^{(0)}$  is a free parameter

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**While**  $\lambda_\ell(\mu \rightarrow \Lambda) \rightarrow \lambda_\ell^{(0)}$ , where  $\lambda_\ell^{(0)}$  is a free parameter

## Higgs mass parameters (minimizing the potential):

$$\mu_\ell^2 \simeq \frac{\mu_{h\ell}^2}{t_\beta} - \frac{v^2}{2} c_\beta^2 \lambda_\ell, \quad \mu_h^2 \simeq t_\beta \mu_{h\ell}^2 - \frac{v^2}{2} s_\beta^2 \lambda_h$$



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$t_\beta = \frac{s_\beta}{c_\beta}$

# RGE & spectrum

Relevant new RGE (rest is SM-like ...)  
(&  $\lambda_{3,4} \ll \lambda_h, \lambda_1$ )

$$D \equiv 16\pi^2 \mu \frac{d}{d\mu}$$
$$Dg_{q'} \approx 6g_{q'}^3,$$
$$D\lambda_h \approx 4\lambda_h (3\lambda_h + 6g_{q'}^2) - 24g_{q'}^4$$

$$g_{q'}(\mu) = \sqrt{\frac{4\pi^2}{3\ln\frac{\Lambda}{\mu}}}, \quad \lambda_h(\mu) = \frac{4\pi^2}{3\ln\frac{\Lambda}{\mu}}$$

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The compositeness scale ( $m_{q'} = v_h g_{q'}(\mu = m_{q'}) / \sqrt{2}$ ):

$$\Lambda \approx m_{q'} \cdot \exp\left(\frac{2\pi^2 (s_\beta v)^2}{3m_{q'}^2}\right) \xrightarrow{m_{q'} \sim O(500 \text{ GeV}), t_\beta \sim O(1)} \Lambda \sim 1 - 1.5 \text{ TeV}$$

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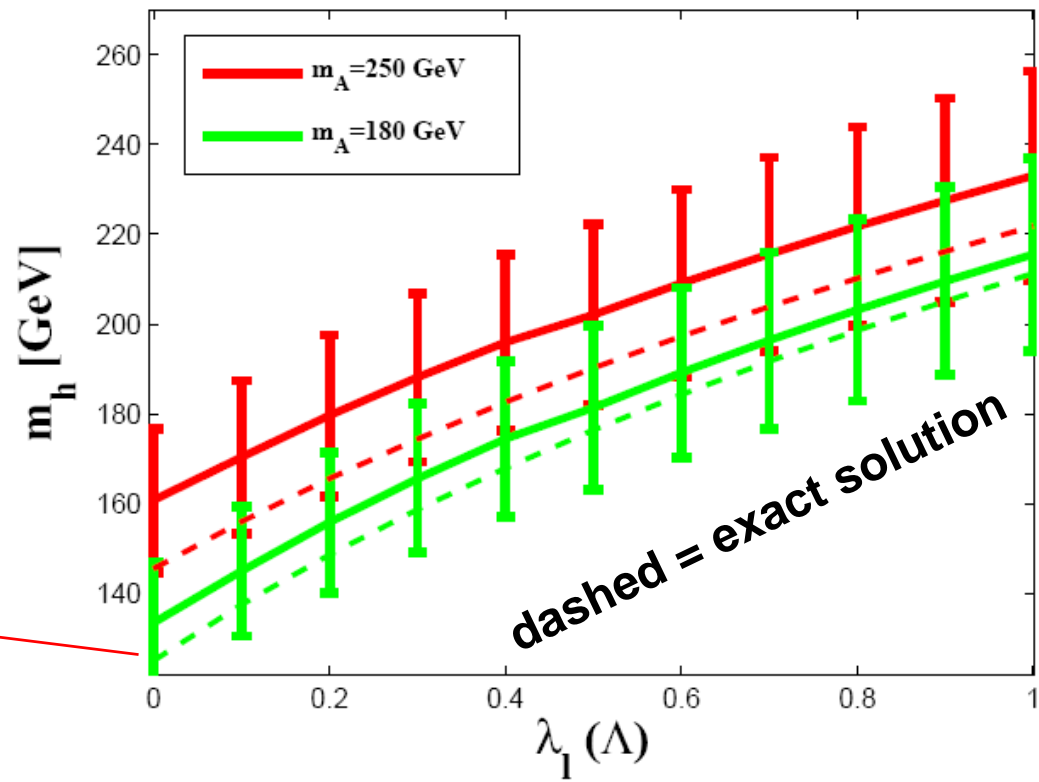
Recall: the top-condensate scenario had a severe fine-tuning problem:

$$\Lambda \sim m_t \cdot \exp\left(\frac{16\pi^2 v^2}{9m_t^2}\right) \sim 10^{17} \text{ GeV} \quad \text{!!!}$$

# Higgs masses

A light Higgs **requires**  $\lambda_1(\Lambda) \rightarrow 0$ :

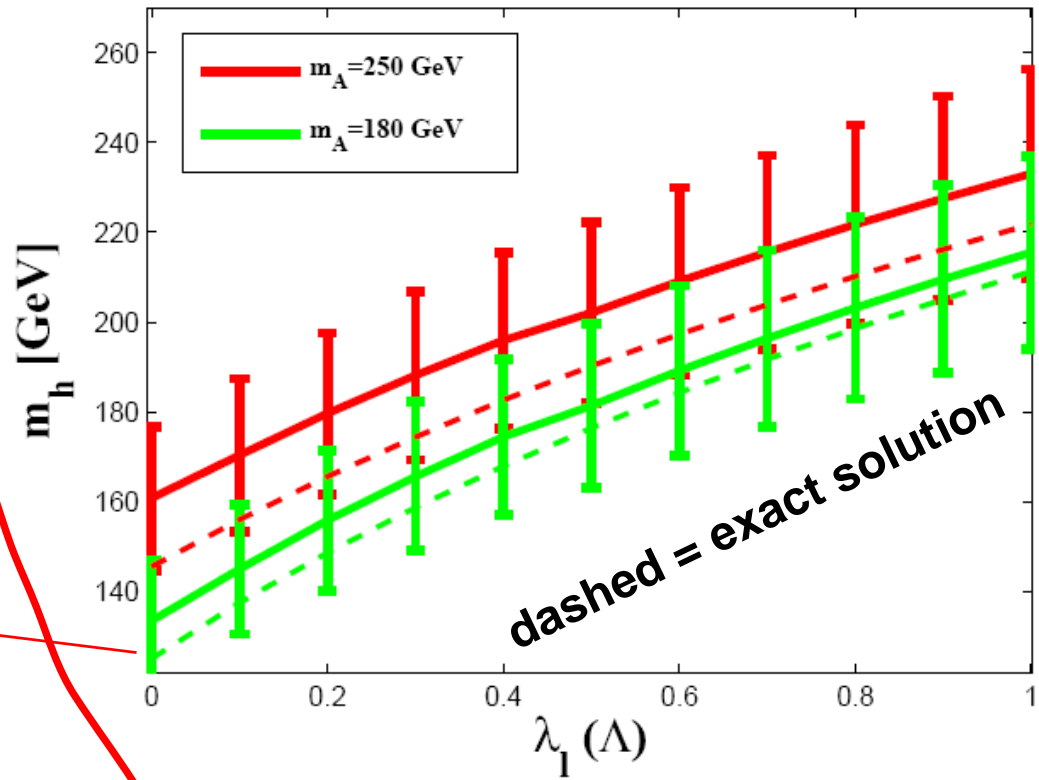
$$m_h \xrightarrow{\lambda_1(\Lambda) \rightarrow 0 \text{ \& \; } \tan \beta \sim O(1)} \frac{m_A}{\sqrt{2}}$$



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$\rightarrow$  pseudo - Goldstone!!

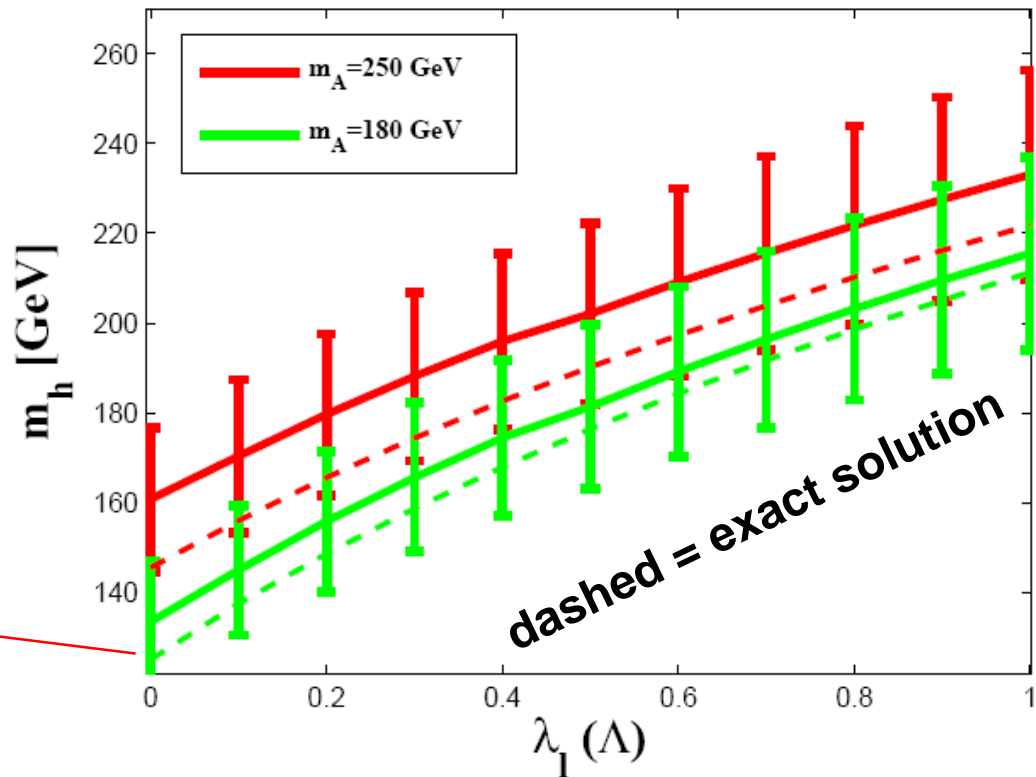
$\rightarrow \lambda_2(\Lambda) \rightarrow 0$

$\hookrightarrow \lambda_2(m_{UV}) \ll \lambda_h(m_{UV})$

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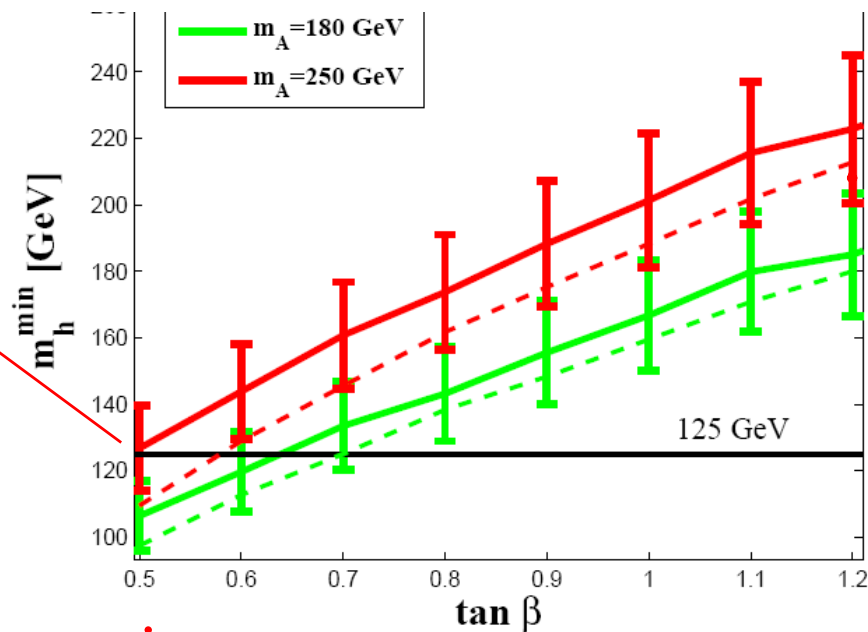
$$m_h \xrightarrow{\lambda_1(\Lambda) \rightarrow 0 \text{ \& \; } \tan \beta \sim O(1)} \frac{m_A}{\sqrt{2}}$$



$$m_h \sim 125 \text{ GeV } (\pm 10\%)$$

**Requires:**

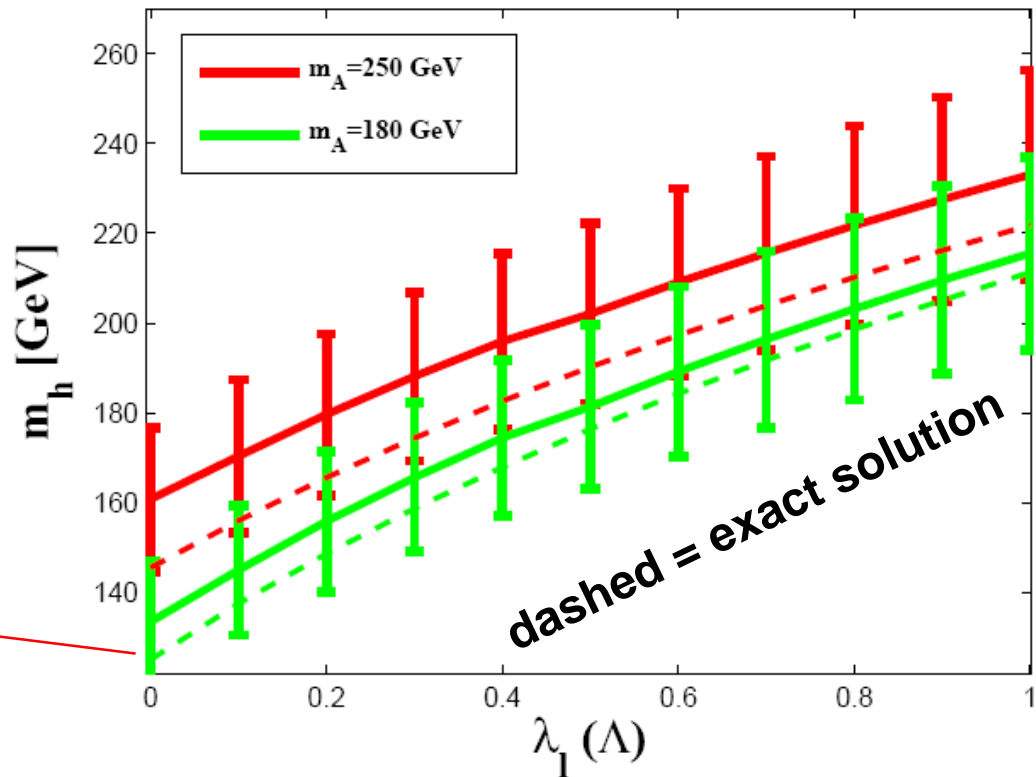
$$\tan \beta \lesssim 0.7 \text{ and } m_A \lesssim 250 \text{ GeV}$$



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A light Higgs **requires**  $\lambda_1(\Lambda) \rightarrow 0$ :

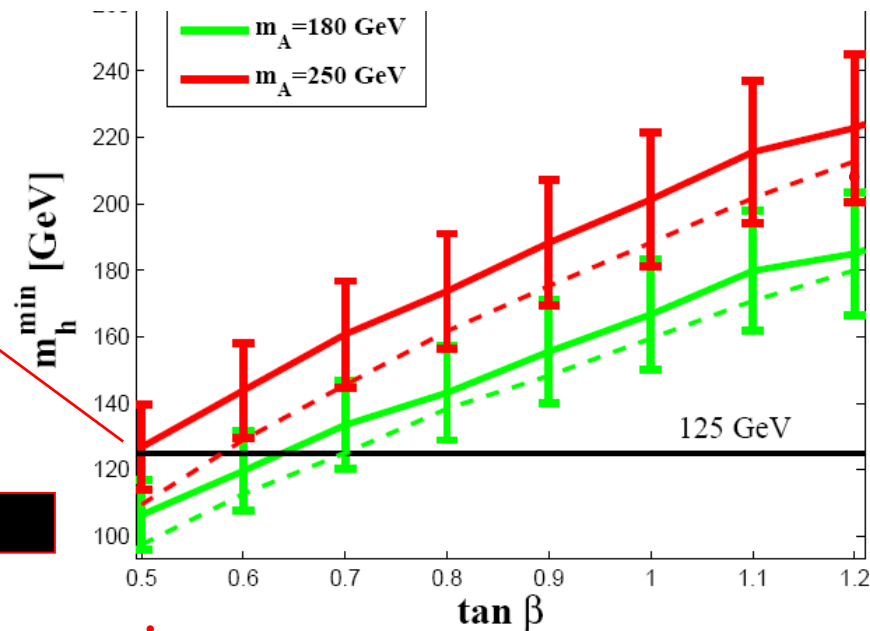
$$m_h \xrightarrow{\lambda_1(\Lambda) \rightarrow 0 \text{ \& \; } \tan \beta \sim O(1)} \frac{m_A}{\sqrt{2}}$$



$$m_h \sim 125 \text{ GeV } (\pm 10\%)$$

**Requires:**

$$\tan \beta \lesssim 0.7 \text{ and } m_A \lesssim 250 \text{ GeV}$$



Reproduces all observed Higgs signals, see M. Geller's poster



# Higgs masses cont.

Heavy CP-even Higgs is **mostly composite**:

$$m_H \approx v \cdot \sqrt{\frac{\lambda_h}{2}} \xrightarrow{m_{q'} \sim O(500 \text{ GeV})} \sim 500 \pm 100 \text{ GeV}$$



# Higgs masses cont.

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Higgs mixing angle  $\sim O(10^\circ)$

$$h = \cos \alpha \cdot \text{Re}(\Phi_\ell^0) - \sin \alpha \cdot \text{Re}(\Phi_h^0)$$

$$H = \cos \alpha \cdot \text{Re}(\Phi_h^0) + \sin \alpha \cdot \text{Re}(\Phi_\ell^0)$$

Light Higgs mostly "fundamental"

$$\tan 2\alpha \simeq \left( \cot 2\beta - \frac{v^2}{2\mu_{h\ell}^2} \cdot (s_\beta^2 \lambda_h - c_\beta^2 \lambda_\ell) \right)^{-1}$$

# Summary & concluding remarks

SM Higgs – makes no sense:  
where is the new physics? (hierarchy problem ...)

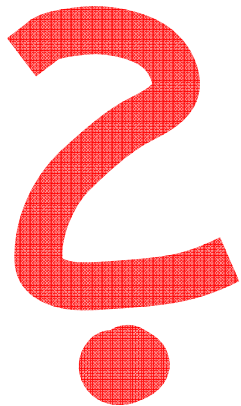
SUSY Higgs? - where is it ?

Need some new TeV-scale physics !

strong dynamics?

Difficult to realize with a  
light composite Higgs ...

Light Higgs may be  
pseudo-Goldstone ?



# Summary & concluding remarks

SM Higgs – makes no sense:  
where is the new physics? (hierarchy problem ...)

SUSY Higgs? - where is it ?

Need some new TeV-scale physics !

strong dynamics?

Hybrid setup:  
"fundamental" + composite scalars at TeV-scale



Needs heavy fermions !

Difficult to realize with a  
light composite Higgs ...

Light Higgs may be  
pseudo-Goldstone ?

# The $h4G2HDM$

- New heavy quarks with  $y_{q'}$ ,  $(\Lambda \sim \text{TeV}) \rightarrow \infty$   
 $\Rightarrow$  New physics scale:  $\Lambda \sim \mathcal{O}(\text{TeV})$
  - $q' \in$  strong dynamics  $\Rightarrow$  composite  $\phi_h$
  - $m_{q'} \in$  dynamical origin
  - SM fermions + flavor  $\in$  “fundamental”  $\phi_l$  (@TeV)
- 
- GET: a viable 125 GeV Higgs candidate - mostly fundamental  
(protected from large  $q'$  loops)
  - consistent with all currently measured 125 Higgs signals
  - Other Higgs states:  $m_{H^\pm} \sim m_A < 250 \text{ GeV}$ ,  $m_H \sim 500 \text{ GeV}$