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

Shaouly Bar-Shalom
shaouly@physics.technion.ac.il

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 …)

SUSY Higgs?
BUT: where is SUSY ?

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DEWSB from heavy fermions

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Nambu,report#89-08,1989(unpublished); Bardeen,Hill,Lindner, PRD41,1647,1990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: $\langle \bar{q}' q' \rangle \neq 0$ …

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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* top-condensation $\langle \bar{t} t \rangle \neq 0$ doesn't work
- m_t (dynamical) ~ 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 Λ**

and

- **TRADE ignorance for effective couplings + boundary conditions @ Λ**

NJL mechanism

DEWSB with the NJL mechanism

NJL mechanism: Nambu,Jona-Lasinio,PR122,345,1961

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

$$L_{NJL} = G_{\psi}\left(\overline{\psi}_L \psi_R\right)\left(\overline{\psi}_R \psi_L\right)$$

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

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

- **EW symmetry can be broken**
- **the field ψ acquires a mass**
- **the low-energy theory contains a scalar bound state: S ~ $<\psi\,\psi>$!**

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:

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

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Then, below the cutoff Λ, 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** $G_{\psi} = \frac{\left(g_0^{\psi}\right)^2}{m_0^2}$

⇒ H is interpreted as a bound state: H ~ <ψψ> …

More generally (& naturally):

should expect multiple bound states

e.g., ⟨t' t'⟩ , ⟨b' b'⟩ …

⇒ 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,Kephart,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; Hernandez,Dib,Neill,Zewekh,JHEP1202,132,2012;

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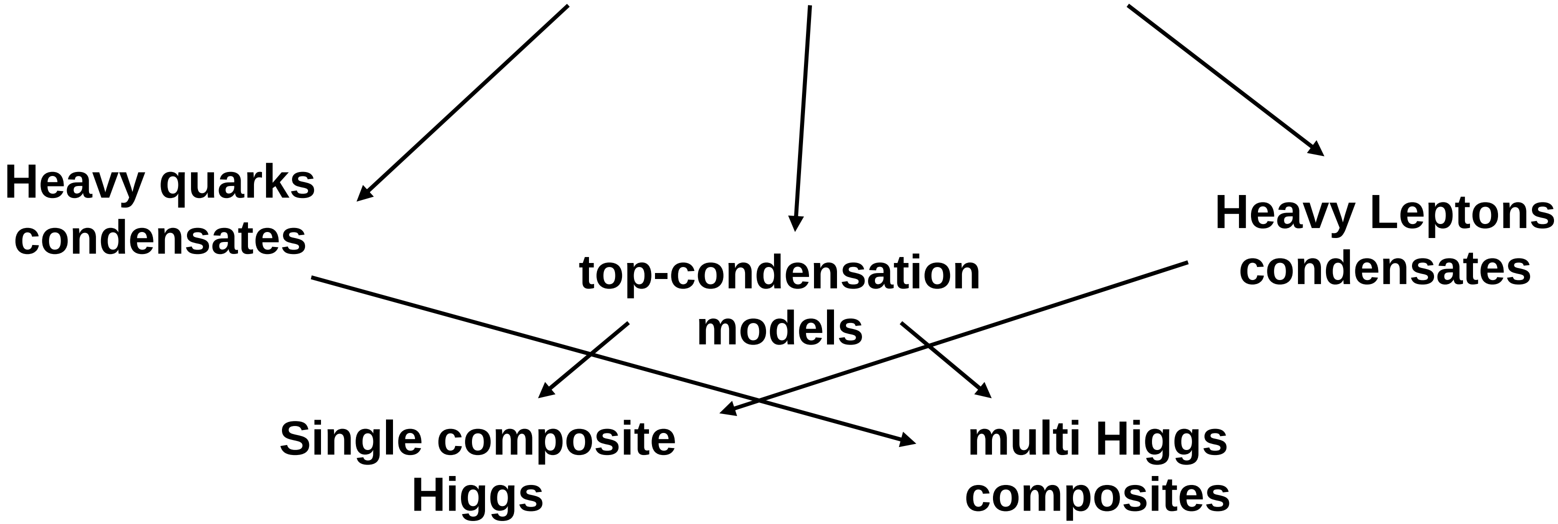
Heavy fermions + multiple Higgs also more favorable when confronted with the data …

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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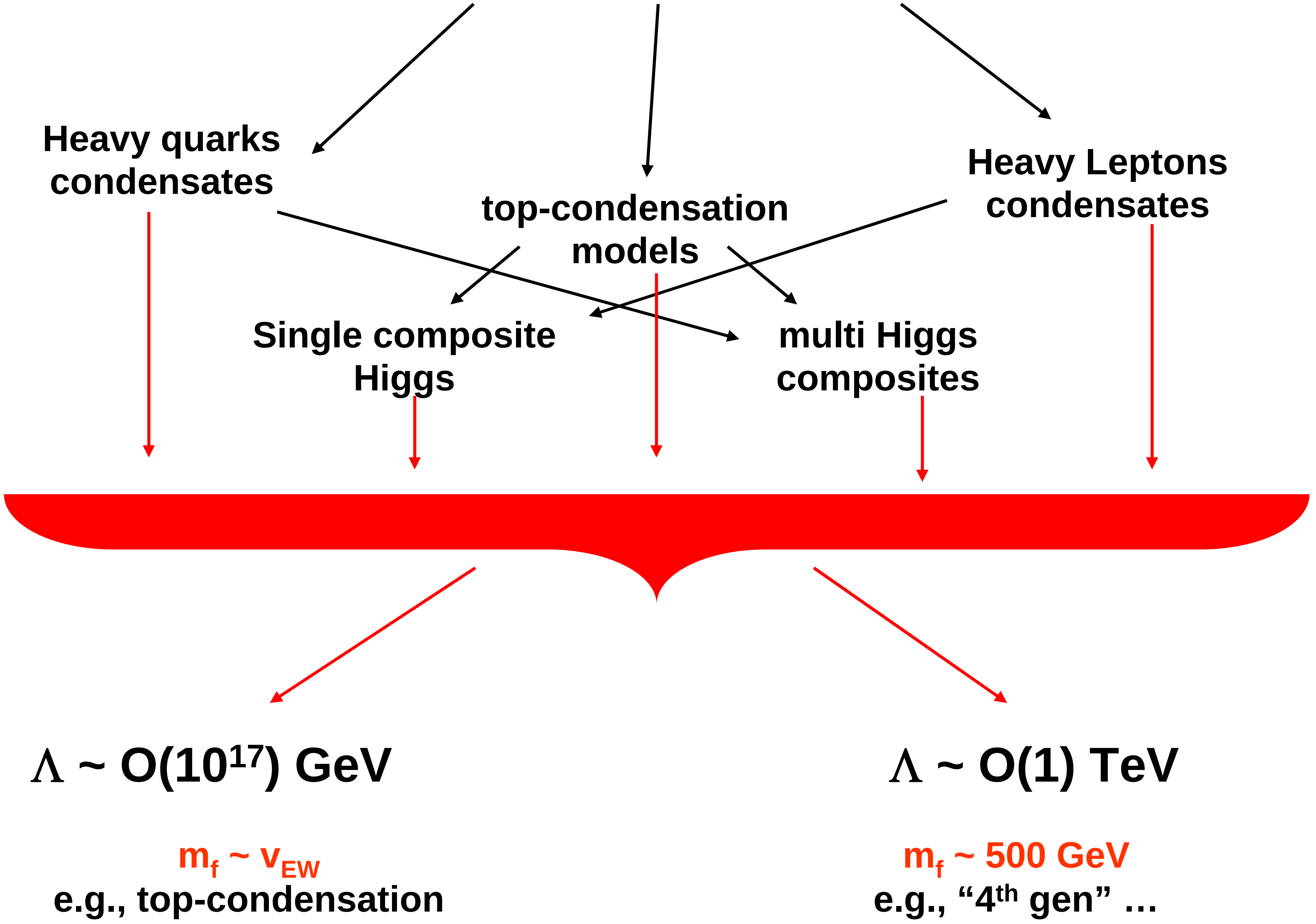

A major caveat:

In the “conventional” NJL models for DEWSB the typical mass of the composite H ~ <ψψ> tends to lie in the range:

$$m_\psi < m_{<\bar{\psi}\psi>} < 2m_\psi$$

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

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

Hybrid setup with heavy quarks [& Λ ~ O(1) TeV] :

add an unconstrained scalar ("fundamental", ϕ_l) at the compositeness scale, where the super-critical 4-Fermi operators form an additional heavy composite ϕ_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 4th gen. doublet, assumed to be charged under some new strong interaction that dynamically break EW symmetry:***

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

The bare SM Lag. at Λ **(with ϕ_l)**

At the compositeness scale Λ :

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

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The above Lag/theory can be reproduced by introducing at Λ an auxiliary Higgs doublet ϕ_h which couples ONLY to the 4th gen. quarks:

$$\mathcal{L}_{q'}(\Lambda) = g^0_{b'}\left(\bar{Q}'_L \Phi_h b'_R + h.c.\right) + g^0_{t'}\left(\bar{Q}'_L \tilde{\Phi}_h t'_R + h.c.\right) - (\mu^0_h)^2 \Phi^\dagger_h \Phi_h$$

The full theory at Λ is then described by:

$$\mathcal{L}(\Lambda) = \mathcal{L}_{SM}(\Lambda) + \mathcal{L}_{q'}(\Lambda) + (\mu^0_{h\ell})^2\left(\Phi^\dagger_h \Phi_\ell + h.c.\right)$$

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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 ϕ_h, recovers the 4-Fermi Lag with:

$$G_{t'} = \frac{(g^0_{t'})^2}{(\mu^0_h)^2}\,,\quad G_{b'} = \frac{(g^0_{b'})^2}{(\mu^0_h)^2}\,,\quad G_{t'b'} = -\frac{g^0_{t'} g^0_{b'}}{(\mu^0_h)^2}$$

Hybrid DEWSB with heavy quarks and the 125 GeV Higgs

ϕ_h - couples to new heavy quarks & leptons – composite

$\Rightarrow$ Q' have purely dynamical masses …

ϕ_l - mass of SM fermions & CKM falvor structure – "fundamental"/unconstrained

"fundamental" = unconstrained at Λ
e.g., pseudo-Goldstone of the underlying theory

Hybrid DEWSB with heavy quarks and the 125 GeV Higgs

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At energies below Λ:

"fundamental" = unconstrained at Λ
e.g., pseudo-Goldstone of the underlying theory

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

$\lambda_h \propto$

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

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

The low-energy Hybrid 4G2HDM (h4G2HDM)

$\rightarrow Z_\phi(\Lambda) \rightarrow 0$

$\rightarrow$ now dynamical: $Z_\phi |D\phi|^2$

$\rightarrow$ from the f'-loops

$$V_{h4G2HDM}(\Phi_h,\Phi_\ell) = \mu_\ell^2 \Phi_\ell^\dagger \Phi_\ell + \mu_h^2 \Phi_h^\dagger \Phi_h - \mu_{h\ell}^2 \left(\Phi_h^\dagger \Phi_\ell + h.c.\right) + \frac{1}{2}\lambda_\ell \left(\Phi_\ell^\dagger \Phi_\ell\right)^2 + \frac{1}{2}\lambda_h \left(\Phi_h^\dagger \Phi_h\right)^2 + \lambda_3 \left(\Phi_h^\dagger \Phi_h\right)\left(\Phi_\ell^\dagger \Phi_\ell\right) + \lambda_4 \left(\Phi_h^\dagger \Phi_\ell\right)\left(\Phi_\ell^\dagger \Phi_h\right)$$

Matching the 4-Fermi theory to the h4G2HDM at Λ:

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

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

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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Higgs mass parameters (minimizing the potential):

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

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

$t_\beta = \frac{v_h}{v_\ell}$

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$\mu_{h\ell}(m_W) \sim m_W$

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RGE & spectrum

$\mathcal{D} \equiv 16\pi^2 \mu \frac{d}{d\mu}$

Relevant new RGE (rest is SM-like …)

(& $\lambda_{3,4}$ << λ_h, λ_l)

$$\boxed{\begin{aligned} \mathcal{D} g_{q'} &\approx 6 g_{q'}^3 \,, \\ \mathcal{D}\lambda_h &\approx 4\lambda_h \left(3\lambda_h + 6 g_{q'}^2\right) - 24 g_{q'}^4 \end{aligned}}$$

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

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

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

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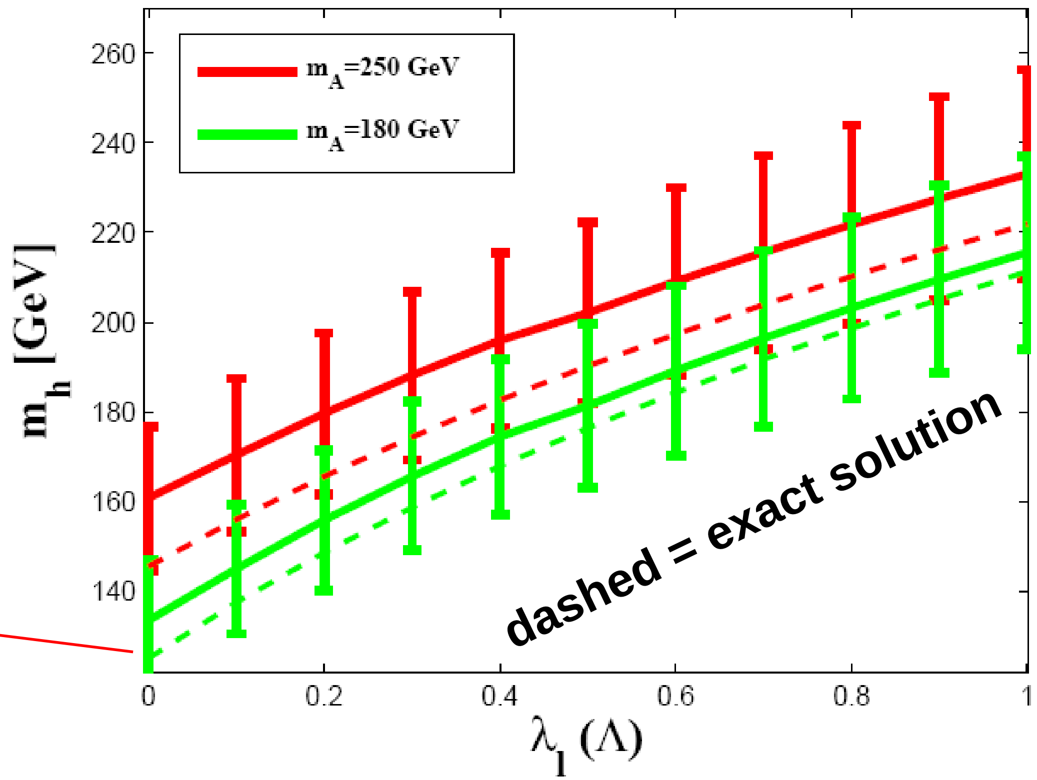
Recall: the top-condensate scenario had a severe fine-tuning problem:

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

Higgs masses

A light Higgs **requires** $\lambda_l(\Lambda)\to 0$**:**

$$m_h \xrightarrow{\lambda_l(\Lambda)\to 0\,\&\,\tan\beta\sim O(1)} \frac{m_A}{\sqrt{2}}$$



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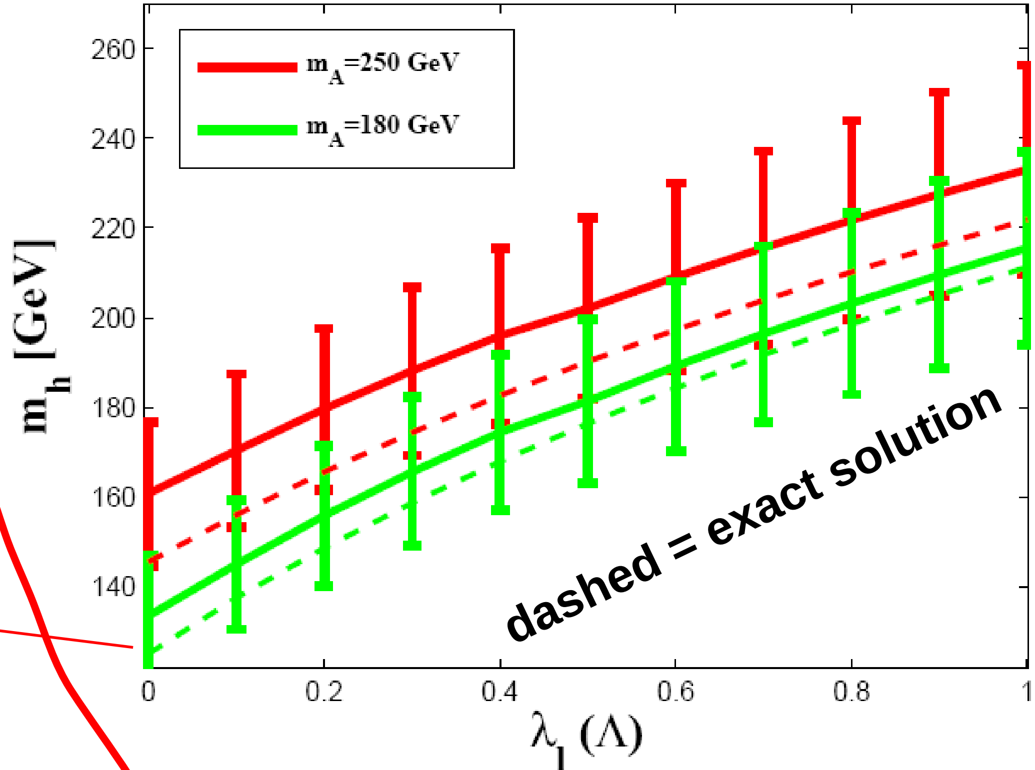

pseudo - Goldstone!!!

$\lambda_l(\Lambda)\to 0$

$\Leftrightarrow \lambda_l(m_W) \ll \lambda_h(m_W)$

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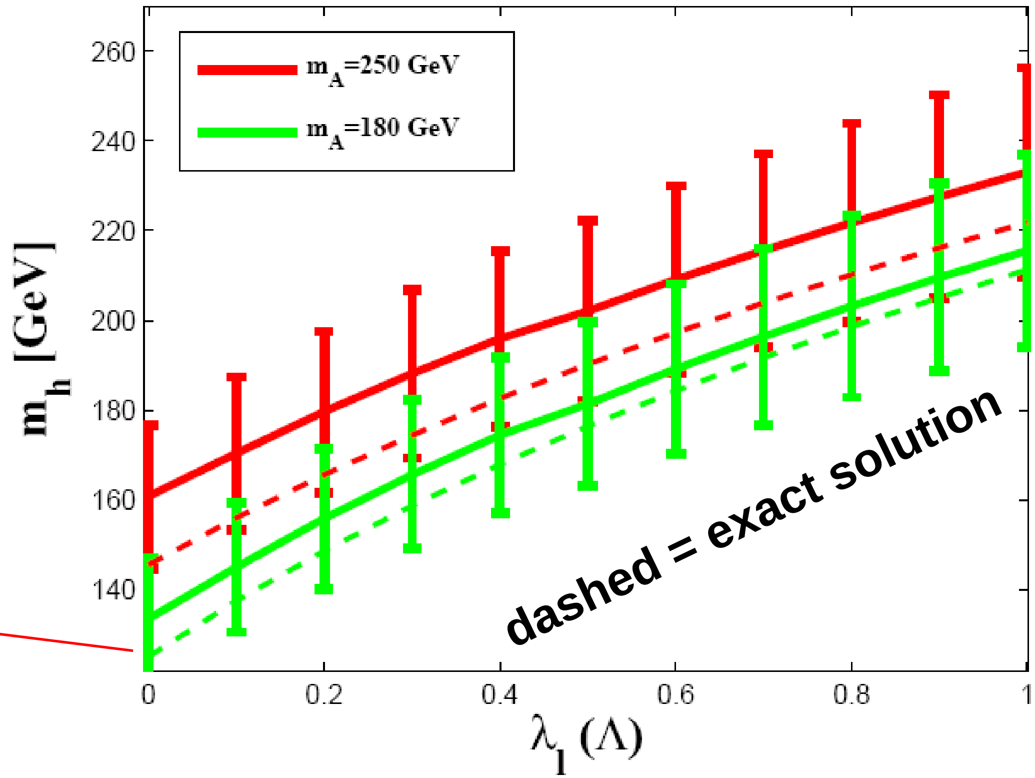
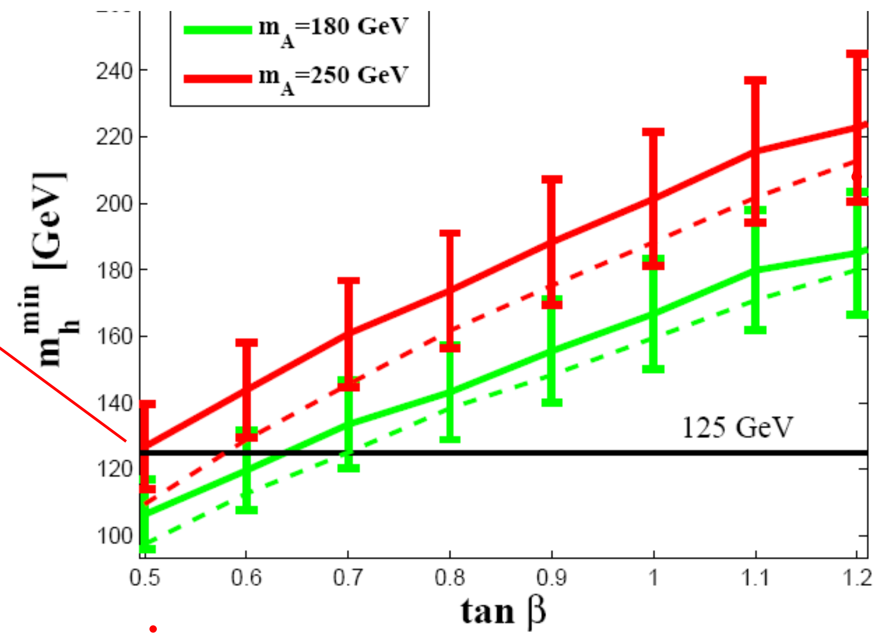


$$m_h \sim 125\,GeV\,(\pm 10\%)$$

Requires:

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



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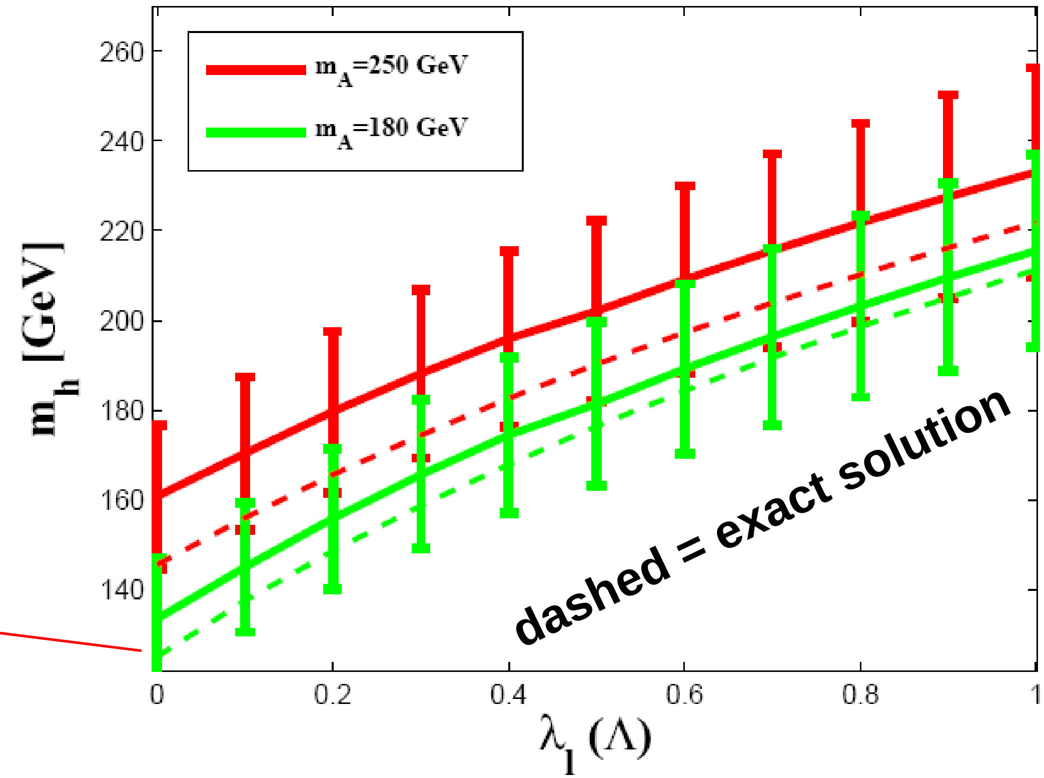

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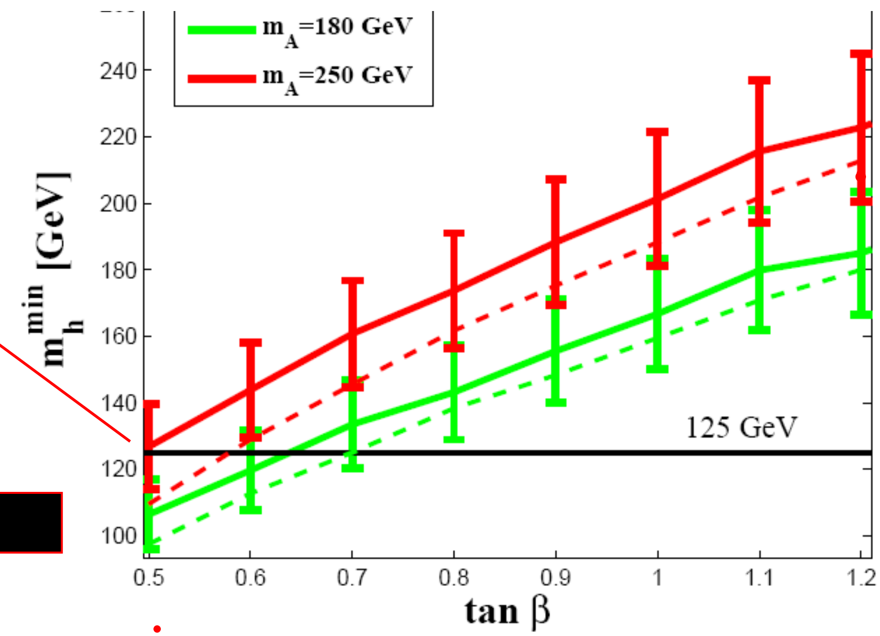

Reproduces all observed Higgs signals, see M. Geller's poster

Higgs masses cont.

Heavy CP-even Higgs is mostly composite:

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Higgs masses cont.

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Higgs mixing angle ~ O(10⁰)

$$\begin{aligned} h &= \cos\alpha \cdot \mathrm{Re}(\Phi_\ell^0) - \sin\alpha \cdot \mathrm{Re}(\Phi_h^0) \\ H &= \cos\alpha \cdot \mathrm{Re}(\Phi_h^0) + \sin\alpha \cdot \mathrm{Re}(\Phi_\ell^0) \end{aligned}$$

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

SUSY Higgs? - where is it ?

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

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

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

Needs heavy fermions !

The h4G2HDM

- **New heavy quarks with $y_{q'}$ (Λ~TeV)$\rightarrow\infty$**
  $\Rightarrow$ New physics scale: $\Lambda \sim \mathit{O}$(TeV)

- **q' $\in$ strong dynamics $\Rightarrow$ composite ϕ_h**
- **$m_{q'}$ $\in$ dynamical origin**
- **SM fermions + flavor $\in$ "fundamental" ϕ_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: $m_{H+} \sim m_A < 250$ GeV, $m_H \sim 500$ GeV**