# *Softening Higgs Naturalness*
## *an EFT Analysis*

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**Shaouly Bar-Shalom**
**Technion, Israel**

**(shaouly@physics.technion.ac.il)**

**"EFT naturalness: an effective field theory analysis of Higgs naturalness"**

**arXiv/1405.2924 [hep-ph]**

**SBS (Technion), A. Soni (BNL) & J. Wudka (UCR)**

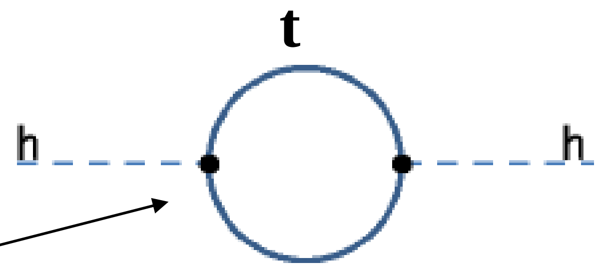
# outline


- **Naturalness …**

- **"EFT naturalness": conditions for the heavy underlying theory** ***that can soften the little hierarchy up to $\Lambda$***

- **Constraints, signals of EFT naturalness & concluding remarks**

# Naturalness




The **“master equation”:**

$$\delta m_h^2(\mathrm{SM}) = \frac{\Lambda^2}{16\pi^2}\left[24x_t^2 - 6\left(2x_W^2 + x_Z^2 + x_h^2\right)\right] \sim 8.2\frac{\Lambda^2}{16\pi^2} \quad , \quad x_i \equiv \frac{m_i}{v} \quad (v \simeq 246\mathrm{GeV})$$

**driving force behind search for NP**

**Natural (when kids not at home)**

**Natural (when kids are at home)**

**Unnatural (regardless …)**

# Naturalness

The **hierarchy/naturalness problem:**

$$m_h^2(physical\ \ mass) = m_h^2(tree) + \delta m_h^2(SM) \approx 126\,GeV$$

$$m_h(\text{tree}) \simeq m_h \simeq 126\ \text{GeV}.$$

$$\delta m_h^2(\text{SM}) > m_h^2(\text{tree}) \text{ when } \Lambda \gtrsim 500 \text{ GeV}$$

# EFT Naturalness:
# an EFT analysis of Higgs-naturalness

**A modest goal:**

***acquire insight*** **regarding the underlying new physics which can potentially alleviate the (little) hierarchy problem in the SM Higgs sector up to some scale** $\Lambda$


**Exploit: EFT techniques**

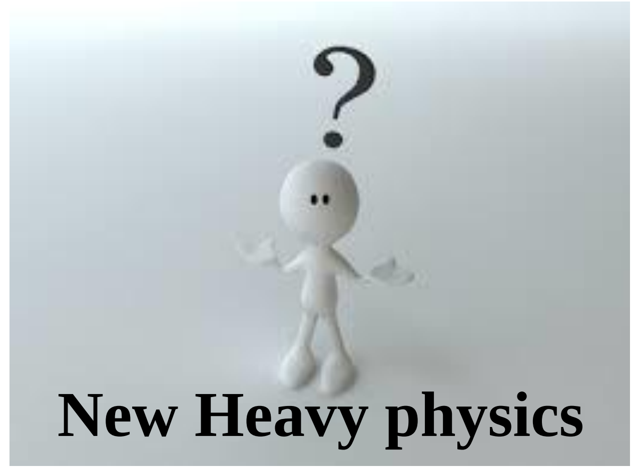
**Assume: underlying physics lies *above*** $\Lambda$**!**

**Ask: what are the "EFT naturalness" conditions?**

$\Rightarrow$ ***the conditions for the physics above Lambda that can soften naturalness in the Higgs sector***

# Underlying setup:

E


**Λ**

**Λ = the scale below which the Higgs sector is natural**

**[no little hierarchy up to Λ < M(heavy)]**

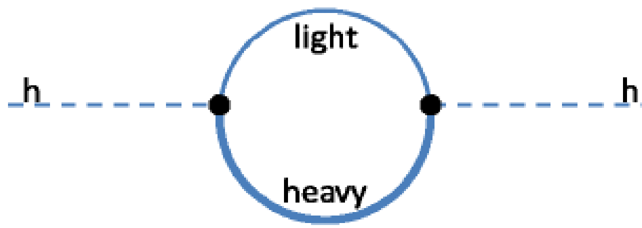
***<u>EFT naturalness:</u>* *conditions among $f_i$ for theory to be natural at Λ***

$$\text{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

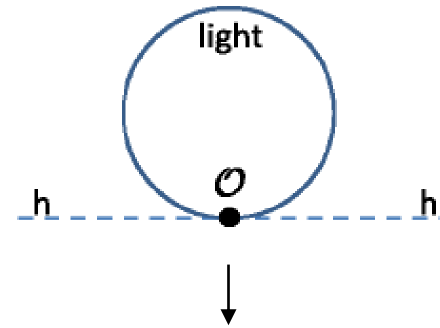
(SM fields and symmetries …)

## *Integrating out the heavy fields (M); generates an infinite series of vertices suppressed by inverse powers of Λ (< M)*

$\delta m_h^2(\text{eff})$:




$= \sum$




$$\sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

**EFT naturalness: what eff. interactions can tame the little hierarchy problem?**

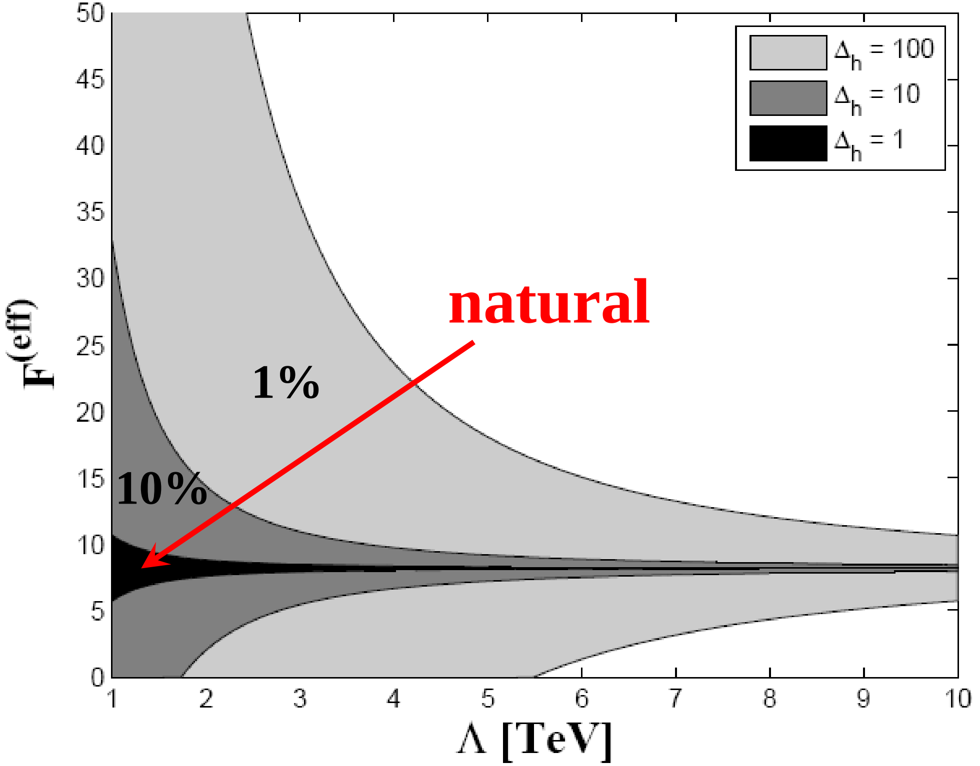
$$\delta m_h^2(\text{SM}) + \delta m_h^2(\text{eff}) \lesssim m_h^2 \text{ when } \Lambda \gg m_h$$

# EFT naturalness "map"

$$\delta m_h^2(\mathrm{eff}) = -\frac{\Lambda^2}{16\pi^2}F^{(\mathrm{eff})}$$

$$\Delta_h \equiv \frac{\left|\delta m_h^2\right|}{m_h^2} = \frac{\Lambda^2}{16\pi^2 m_h^2}\left|F^{(eff)} - 8.2\right|$$

SM term



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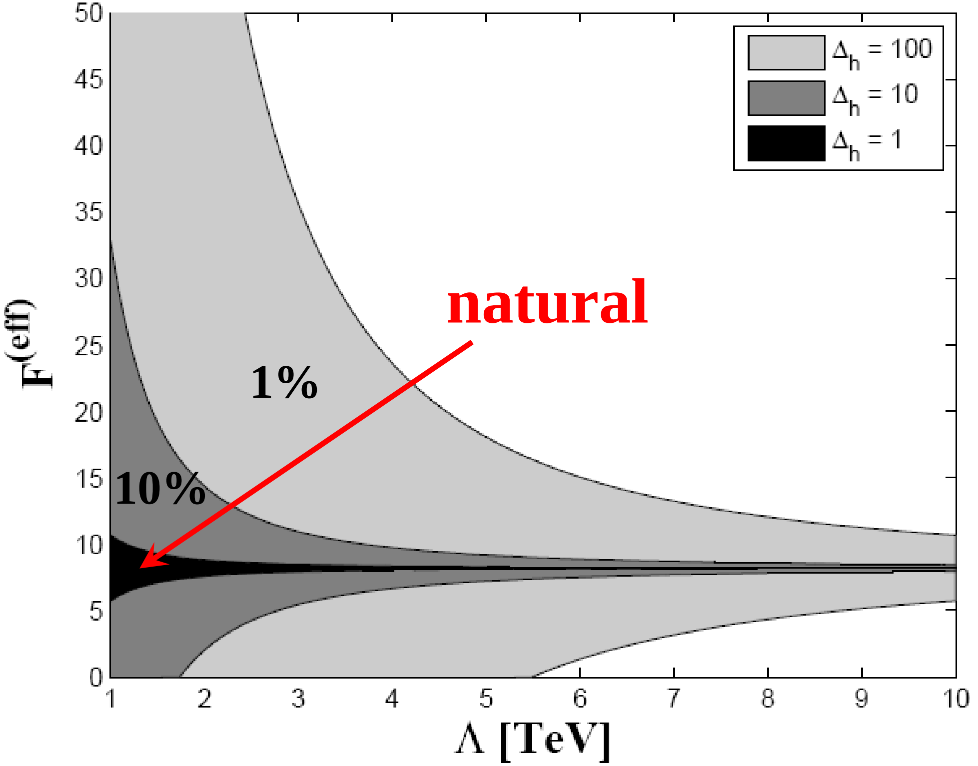
**SM term**




**A theory, $F^{(eff)}$, for which $\Delta_h$~1 is natural, while one with $\Delta_h$~10(100) suffers from fine-tuning of 10%(1%)**

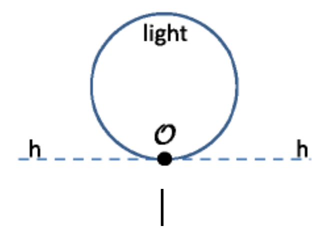
**e.g., theories which are natural up to Λ ~ 10 TeV:**

require: $8.17 \lesssim F^{(\text{eff})} \lesssim 8.23$ ⇒ **accidental, symmetry ???**


***To Calculate*** $\delta m_h^2(\mathrm{eff}) = -\frac{\Lambda^2}{16\pi^2}F^{(\mathrm{eff})}$

***We need the set of operators which give***

***the <u>leading</u> contribution to*** $\sum$




$$\sum_{n=5}^{\infty}\frac{1}{\Lambda^{(n-4)}}\sum_i f_i^{(n)}\mathcal{O}_i^{(n)}$$

# EFT:

**Assume:** **physics at E ≤ Λ is described by**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

✓ **"light fields" [@ E ≤ Λ]** = SM fields

✓ **Gauge-symmetry [@ E ≤ Λ]** = SM: SU(3)xSU(2)xU(1)

**(useful for classifying the higher dim operators)**

✓ **Underlying NP ($\phi_{heavy}$) is weakly coupled, renormalizable, obeys gauge-invariance & preserves symmetries of the known dynamics (SM)**

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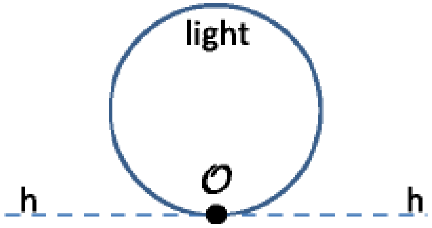
✓ **Underlying NP ($\phi_{\rm heavy}$) is weakly coupled, renormalizable, obeys gauge-invariance & preserves symmetries of the known dynamics (SM)**

**(useful for classifying the higher dim operators)**

**Many operators can be constructed under these conditions, O(50)**
***BUT: only very few can balance the SM's 1-loop quadratic terms !***

# EFT corrections to Higgs mass

$\sum$ 

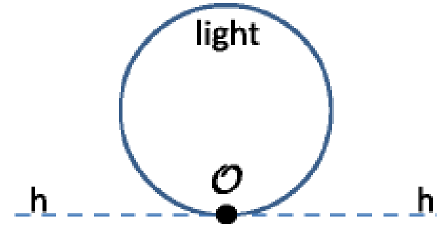

$$\mathcal{O}_S^{(2k+4)} = \frac{1}{2}|\phi|^2 \Box^k |\phi|^2 \ , \quad \mathcal{O}_{\boldsymbol{\chi}}^{(2k+4)} = \frac{1}{2}(\phi^\dagger \tau_I \phi) D^{2k} (\phi^\dagger \tau_I \phi) \ , \quad \mathcal{O}_{\tilde{\boldsymbol{\chi}}}^{(2k+4)} = \frac{1}{4}(\phi^\dagger \tau_I \tilde{\phi}) D^{2k} (\tilde{\phi}^\dagger \tau_I \phi)$$

$$j^\mu = i\phi^\dagger D^\mu \phi + \text{H.c.} \ , \quad \tilde{j}^\mu = i\tilde{\phi}^\dagger D^\mu \phi \ , \quad J_I^\mu = i\phi^\dagger \tau^I D^\mu \phi + \text{H.c.} \ ,$$

$$\mathcal{O}_v^{(2k+6)} = \frac{1}{2} j_\mu \Box^k j^\mu \ , \quad \mathcal{O}_{\tilde{v}}^{(2k+6)} = \tilde{j}_\mu^\dagger \Box^k \tilde{j}^\mu \ , \quad \mathcal{O}_{\mathbf{V}}^{(2k+6)} = \frac{1}{6} J_{I\mu} D^{2k} J_I^\mu$$

$$\mathcal{O}_{\Psi-\psi}^{(2k+4)} = |\phi|^2 \, \bar{\psi} \, (i \not{D})^{2k-1} \, \psi$$

# EFT corrections to Higgs mass

$\sum$ 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**From *heavy scalar* exchanges: singlets or triplets**

$$j^\mu = i\phi^\dagger D^\mu\phi + \mathrm{H.c.} \;, \quad \tilde{j}^\mu = i\tilde{\phi}^\dagger D^\mu\phi \;, \quad J_I^\mu = i\phi^\dagger\tau^I D^\mu\phi + \mathrm{H.c.} \;,$$

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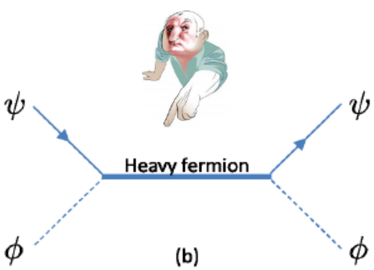
**From *heavy vector* exchanges: singlets or triplets**

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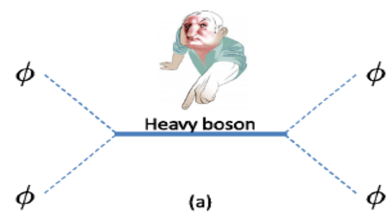
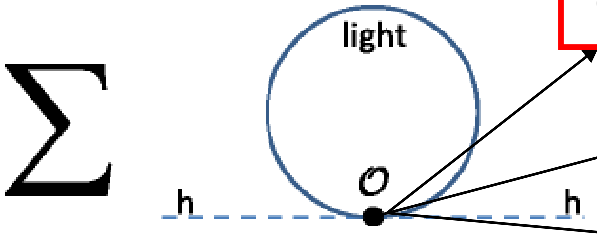



**From *heavy fermion* exchanges: singlets, doublet or triplets**

# EFT corrections to Higgs mass

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$$\mathcal{O}_{\Psi-\psi}^{(2k+4)} = |\phi|^2\,\bar{\psi}\,(i\,\not{D})^{2k-1}\,\psi$$

$$\left(L_{eff} \sim \sum f_i O_i \;\ldots\right)$$

$$\delta m_h^2(\text{eff}) = -\frac{\Lambda^2}{16\pi^2}F^{(\text{eff})}$$

$$F^{(\text{eff})} = \sum_{k=0}^{\infty}\frac{1}{k+1}\sum_{\Phi}f_\Phi^{(2k+4)} - \sum_{k=0}^{\infty}\frac{1}{k+2}\sum_{X}f_X^{(2k+6)} - \sum_{k=1}^{\infty}\frac{(-1)^k}{k+1}\sum_{\Psi,\psi}f_{\Psi-\psi}^{(2k+4)}$$

$$\Phi = S,\ \chi,\ \tilde{\chi}\ \text{and}\ X = v,\ \tilde{v},\ \mathbf{V}$$

# *Less ignorance*


**insight regarding the heavy new physics for naturalness …**

# Less ignorance:

*examples of potentially natural interactions of the heavy new physics*

**heavy scalars:** $$\Delta\mathcal{L}_\Phi = u_S S|\phi|^2 + u_{\boldsymbol{\chi}}\phi^\dagger\boldsymbol{\chi}\phi + \frac{1}{2}\left(u_{\tilde{\boldsymbol{\chi}}}\tilde{\phi}^\dagger\tilde{\boldsymbol{\chi}}\phi + \mathrm{H.c}\right)$$

**heavy vectors:** $$\Delta\mathcal{L}_X = g_v v_\mu j^\mu + g_{\mathbf{V}}\mathbf{V}_\mu J_I^\mu + \left(g_{\tilde{v}}\tilde{v}_\mu\tilde{j}^\mu + \mathrm{H.c.}\right)$$

$$j^\mu = i\phi^\dagger D^\mu\phi + \mathrm{H.c.}\,, \quad \tilde{j}^\mu = i\tilde{\phi}^\dagger D^\mu\phi\,, \quad J_I^\mu = i\phi^\dagger\tau^I D^\mu\phi + \mathrm{H.c.}\,,$$

**heavy fermions:** $$\Delta\mathcal{L}_\Psi = \sum_{\Psi,\,\psi}\left(y_{\Psi-\psi}\bar{\psi}\Psi\phi + \mathrm{H.c}\right)$$

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**heavy scalars:** $$\Delta\mathcal{L}_\Phi = u_S S|\phi|^2 + u_\chi \phi^\dagger \chi \phi + \frac{1}{2}\left(u_{\tilde{\chi}} \tilde{\phi}^\dagger \tilde{\chi} \phi + \mathrm{H.c}\right)$$

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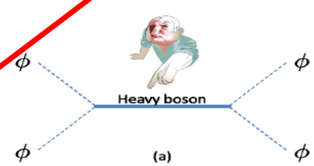
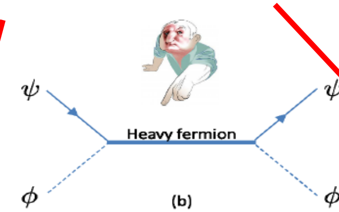
**heavy fermions:** $$\Delta\mathcal{L}_\Psi = \sum_{\Psi,\,\psi} \left(y_{\Psi-\psi} \bar{\psi} \Psi \phi + \mathrm{H.c}\right)$$

**explicitly calculate the coefficients;**

**$f_\Phi(\Lambda)$, $f_X(\Lambda)$, $f_{\Psi\text{-}\psi}(\Lambda)$**

$$\delta m_h^2(\mathrm{eff}) = -\frac{\Lambda^2}{16\pi^2} F^{(\mathrm{eff})}$$




$$F^{(\mathrm{eff})} = \sum_{k=0}^{\infty} \frac{1}{k+1} \sum_{\Phi} f_\Phi^{(2k+4)} - \sum_{k=0}^{\infty} \frac{1}{k+2} \sum_{X} f_X^{(2k+6)} - \sum_{k=1}^{\infty} \frac{(-1)^k}{k+1} \sum_{\Psi,\psi} f_{\Psi-\psi}^{(2k+4)}$$

# Matching the effective theory @ Λ

$$f_{\Phi}^{(2k+4)} = \left|\frac{u_\Phi}{M_\Phi}\right|^2 \left(\frac{-\Lambda^2}{M_\Phi^2}\right)^k \qquad f_X^{(2k+6)} = I_X |g_X|^2 \left(\frac{-\Lambda^2}{M_X^2}\right)^{k+1} \qquad f_{\Psi-\psi}^{(2k+4)} = \frac{1}{2} I_\Psi |y_{\Psi-\psi}|^2 \left(\frac{\Lambda^2}{M_\Psi^2}\right)^k$$

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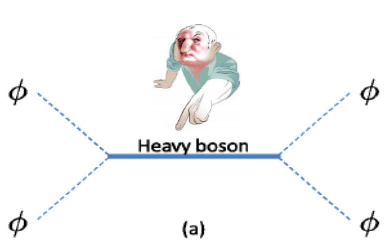
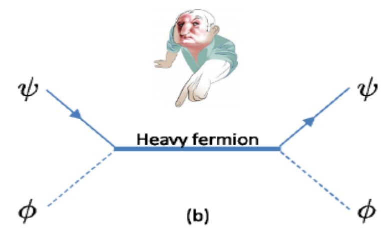



$$F^{(\text{eff})} = \sum_{\Phi} \frac{|u_\Phi|^2}{M_\Phi^2} A\left(\frac{\Lambda^2}{M_\Phi^2}\right) + \frac{1}{2} \sum_{\Psi,\psi} I_\Psi |y_{\Psi-\psi}|^2 \left[1 - A\left(\frac{\Lambda^2}{M_\Psi^2}\right)\right] + \sum_X I_X |g_X|^2 \left[1 - A\left(\frac{\Lambda^2}{M_X^2}\right)\right]$$

$A(x) = \ln(1+x)/x$. $\Rightarrow$ $1 > A(x) \geq 0$ **$F^{(\text{eff})} > 0$ !**

# Upshot of EFT naturalness study:

$$F^{(\mathrm{eff})} = \sum_{\Phi} \frac{|u_\Phi|^2}{M_\Phi^2} A\left(\frac{\Lambda^2}{M_\Phi^2}\right) + \frac{1}{2}\sum_{\Psi,\psi} I_\Psi |y_{\Psi-\psi}|^2 \left[1 - A\left(\frac{\Lambda^2}{M_\Psi^2}\right)\right] + \sum_X I_X |g_X|^2 \left[1 - A\left(\frac{\Lambda^2}{M_X^2}\right)\right]$$

***Given** the masses & couplings of the new heavy states (**heavy fermions, scalars and/or vectors**) we can derive the scale $\Lambda$ - below which the theory is natural (or has a certain degree of fine-tuning)*

$$\Lambda_{\Delta_h} = f(\Delta_h, g_{heavy}, M_{heavy}) \Rightarrow \Lambda_{natural} = f(1, g_{heavy}, M_{heavy})$$

**simplest example:**

**the case of a heavy scalar singlet …**

# Less ignorance: the case of a heavy scalar singlet (S)

**consider SM +** $\Delta\mathcal{L}_\Phi = u_S S|\phi|^2$

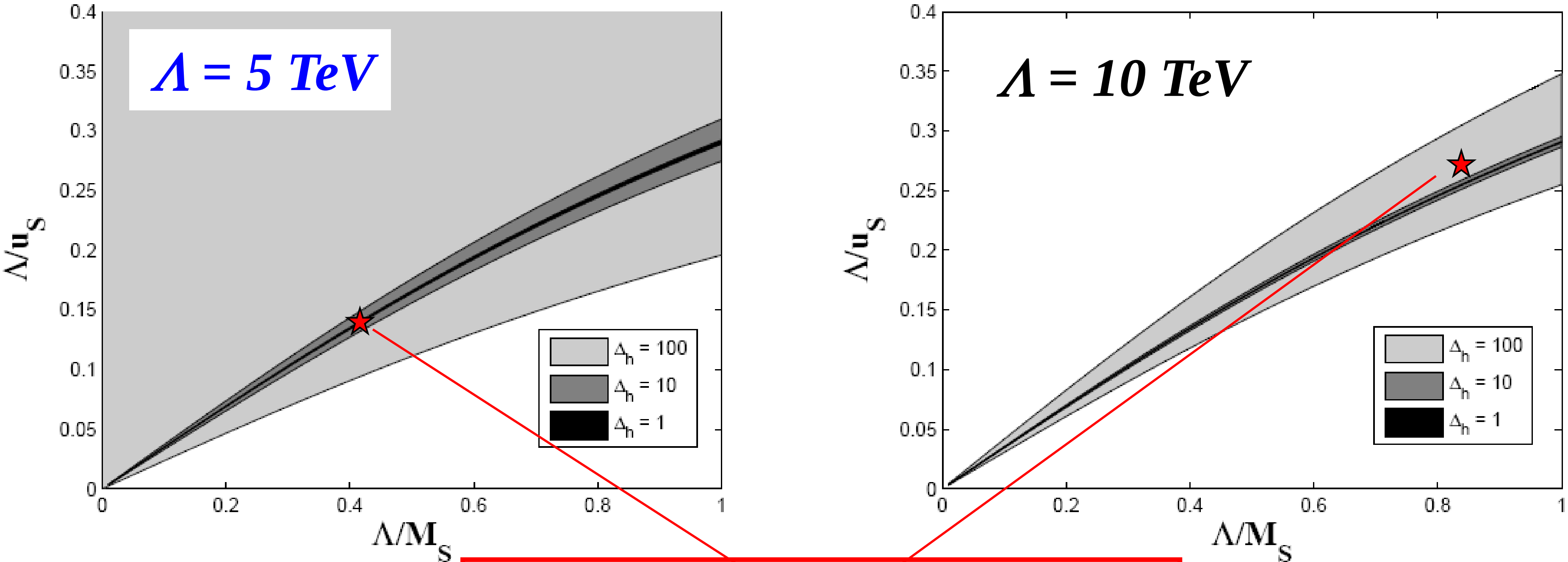
***What is the scale below which this "theory" is natural?***

***Depends on the mass & coupling of the singlet to $\phi^2$ …***

$$\delta m_h^2(eff;S) = -\frac{\Lambda^2}{16\pi^2} F_S^{(eff)} = -\frac{|u_S|^2}{16\pi^2}\ln\left(1+\frac{\Lambda^2}{M_S^2}\right)$$

$$\delta m_h^2 = \delta m_h^2(SM) + \delta m_h^2(eff;S) \approx \frac{\Lambda^2}{16\pi^2}\left(24\frac{m_t^2}{v^2} - \frac{u_S^2}{\Lambda^2}\ln\left(1+\frac{\Lambda^2}{M_S^2}\right)\right)$$

# EFT naturalness: the case of a heavy scalar singlet




***e.g., $M_S \sim 12$ TeV, $u_S \sim 36$ TeV***

***⇒ Higgs sector is natural up to $\Lambda \sim 5$ TeV***

***Higgs sector requires fine-tuning of ~4% for $\Lambda \sim 10$ TeV***

# Constraints from current data

**EFT naturalness operators can cause 2 types of effects:**

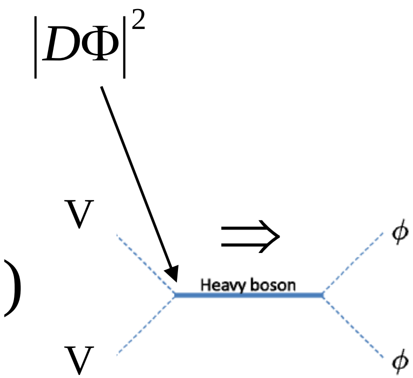
- A shift to the ρ-parameter

**Λ(scalar triplet,vectors) > ~ 10 TeV**

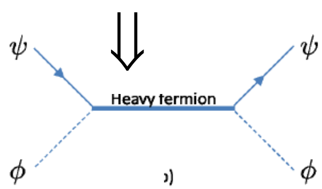
- A shift of the Higgs couplings
  to SM fermions & gauge-bosons

**no useful limit …**

# Signals of potential heavy ***natural*** NP

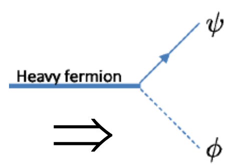



- ***deviations in Higgs pair production***
  - VV $\rightarrow$ hh  (s-channel exchange of heavy bosons)




  - qq,ee $\rightarrow$ hh (t-channel exchange of heavy fermions)

- ***Higgs+jet/lepton production via off-shell heavy fermion ``decay"***
  - $\Psi^* \rightarrow h\psi$ ($\psi$ = quark or lepton)



# summary


- ***There exists!***

  ***a UV completion to the SM which is natural up to some scale Λ!***

- **Does nature "know" of this theory?**

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- **Our EFT-analysis of naturalness:**

  - **insight about this theory**

  - **provides relations among parameters of the UV theory (for naturalness)**

  - **signals expected in Higgs pair-production or Higgs+lepton/jet production**

# summary


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  ***a UV completion to the SM which is natural up to some scale $\Lambda$!***

- **Does nature “know” of this theory?**

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  - **signals expected in Higgs pair-production or Higgs+lepton/jet production**

- ***Naturalness in the UV is not that complicated*:**

***need* new singlet(s) or triplet(s) bosons *or else* singlet, doublet or triplet fermion(s)**

# backups

# Loop calculations

## vectors loop

$$O_v = \frac{1}{2} j \Box^k j = -\frac{1}{2} h^2 \left(\chi^0 \Box^{k+1} \chi^0\right) + \dots$$

$$O_{\tilde v} = -\frac{1}{2} h^2 \left(\chi^+ \Box^{k+1} \chi^-\right) + \dots$$

$$O_V = \frac{1}{6} \vec{J}_r \Box^k \vec{J}^r = -\frac{1}{6} h^2 \left(2\chi^+ \Box^{k+1} \chi^- + \chi^0 \Box^{k+1} \chi^0\right) + \dots$$

$$u = -i\left(-\frac{p^2}{\Lambda^2}\right)^{k+1} \qquad p = p(x)$$

| | $O_v$ | $O_{\tilde v}$ | $O_V$ |
|---|---|---|---|
| $h^2 \chi^{0\,2}$ | $2u f_v$ | — | $\frac{2}{3} u f_V$ |
| $h^2 \chi^+ \chi^-$ | — | $u f_{\tilde v}$ | " |

$$I = \int_0^\Lambda \frac{d^4p}{(2\pi)^4} \frac{i}{p^2} u = -i \frac{\Lambda^2}{16\pi^2} \frac{1}{k+2} \equiv -i\tilde{O}$$

$$\delta m_h^2(O_v) = \underbrace{\frac{1}{2}}_{\text{sym}} \times 2 f_v \tilde{O} = f_v \tilde{O}$$

$$\delta m_h^2(O_{\tilde v}) = f_{\tilde v} \tilde{O}$$

$$\delta m_h^2(O_V) = \frac{1}{2} \times \frac{2}{3} f_V \tilde{O} + \frac{2}{3} f_V \tilde{O} = f_V \tilde{O}$$

## scalars loop

$$O_{S\chi,\tilde\chi} \to \frac{1}{8} h^2 \Box^k h^2$$

$$\Box h^2 = 2(\partial h)^2 + 2h\Box h \qquad \partial^2 h \to -p^2 h^2$$

$$O_\Phi \to \frac{1}{4}\left[h^2(\partial h)^2 + h^3 \partial^2 h\right]$$

$$(\partial h)^2 \to (-ip)^2 h^2 = -p^2 h^2$$

$\delta m_\phi^2 =$  $= -\frac{1}{\Lambda^{2k}} \frac{c}{4} \int \frac{d^4p}{(2\pi)^4} \frac{(-p^2)^k \times i}{p^2}$

combinatoric factor $= -\frac{c}{4}(-1)^k \int (p^2)^{k-1}$

$$= \frac{c}{4} \frac{\Lambda^2}{16\pi^2} \sum_{k=0}^{\infty} \frac{f_\phi^{(2k+4)}}{k+1}$$

($c = 4$; $c = 1$ for $h^2(\partial h)^2$, $c = 3$ for $h^3(\partial^2 h)$)

## fermions loop

$$O_\psi = \frac{1}{2} h^2 \bar\psi_{L/R} (i\partial\!\!\!/)^{2k-1} \psi_{L/R} \qquad \partial\!\!\!/\psi \to -ip\!\!\!/\psi$$

$\delta m_h^2(\psi) =$  $= \frac{i}{2} \times (-1) \int \frac{d^4p}{(2\pi)^4} \mathrm{tr}\, i \frac{\{P_{L/R}[i(-ip\!\!\!/)]^{2k-1}\}}{p\!\!\!/}$

$$= \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} \mathrm{tr}\left[P_{L/R}\, p\!\!\!/^{\,2k-2}\right] = \int \frac{d^4p}{(2\pi)^4} (p^2)^{k-1}$$

wick rot.

$$= \frac{i}{(4\pi)^2} \int_0^\Lambda dp_E^2\, p_E^2 \left(-p_E^2\right)^{k-1} = \frac{i}{16\pi^2} \frac{(-1)^{k-1}}{k+1} \Lambda^{2k+2}$$

$$\Downarrow$$

$$\delta m_h^2(\psi) = \frac{(-1)^k}{16\pi^2} \Lambda^2 \sum_{k=1}^{\infty} \frac{f_\psi^{(2k+4)}}{k+1}$$

# EFT: the art of …

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

***Its a mess in general – underlying physics not known,***

***too many operators …***

***needs some guiding principles !***


***set the "rules of the game" …***