EFT-Naturalness: an effective field theory analysis of Higgs naturalness

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outline

- **Naturalness …**

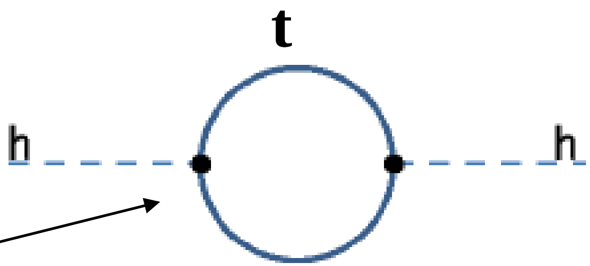
- **"EFT naturalness":**

  a complete parameterization of all higher dimensional effective operators (@ any dim.!) that can potentially "soften" the Λ^2 behavior of δm_h^2

  $\Rightarrow$ look for naturalness conditions in the heavy underlying theory

- **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

Naturalness

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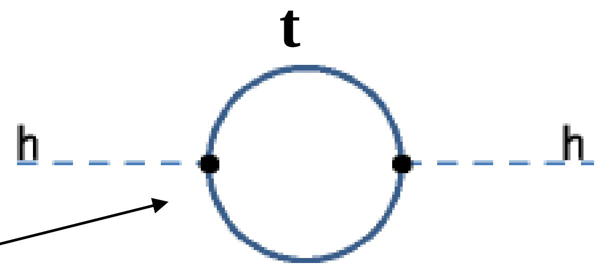

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driving force behind search for NP

The **hierarchy/naturalness problem:**

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

$$m_h(\mathrm{tree}) \simeq m_h \simeq 126\ \ \mathrm{GeV}$$

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

$$\delta m_h^2(\mathrm{SM}) = \frac{\Lambda^2}{16\pi^2}\left[24x_t^2 - 6\left(2x_W^2 + x_Z^2 + x_h^2\right)\right]$$

New Physics

NP particle masses are lighter than Λ

⇓

SM is not a complete description of the heavy physics below Λ; there being other particles yet to be discovered with masses below Λ

⇒ **The parameters of the theory are such that there are cancellations between the SM and NP contributions to δm_h (symmetries/accidental) …**

e.g., SUSY, little Higgs/composite models …

All NP particle masses are heavier than Λ

⇓

Λ = the scale of the effective action

use EFT techniques

Underlying setup:

new heavy physics

E

M ~ O(10 TeV)

Below M:

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

(SM fields and symmetries …)

Underlying setup:

E

new heavy physics

M ~ *O*(10 TeV)

$$M > \Lambda > v$$

Λ

Λ = the scale of the effective action (Wilsonian-like)

<u>EFT naturalness:</u>

conditions among f_i for theory to be natural at Λ < M

<u>Below M:</u>

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

(SM fields and symmetries …)

EFT Naturalness:

Ask: what are the "EFT naturalness" conditions?

⇒ ***the conditions for the physics above Λ that can soften naturalness in the Higgs sector***

The EFT-naturalness conditions are most likely due to a higher symmetry of the underlying physics …

The "roadmap" to EFT naturalness:
a taste of the problem …

$$\delta m_h^2 = \delta m_h^2(\mathrm{SM}) + \delta m_h^2(\mathrm{eff})$$

$$\delta m_h^2(\mathrm{SM}) = \frac{\Lambda^2}{16\pi^2}\left[24x_t^2 - 6(2x_W^2 + x_Z^2 + x_h^2)\right] \sim 8.2\frac{\Lambda^2}{16\pi^2}$$

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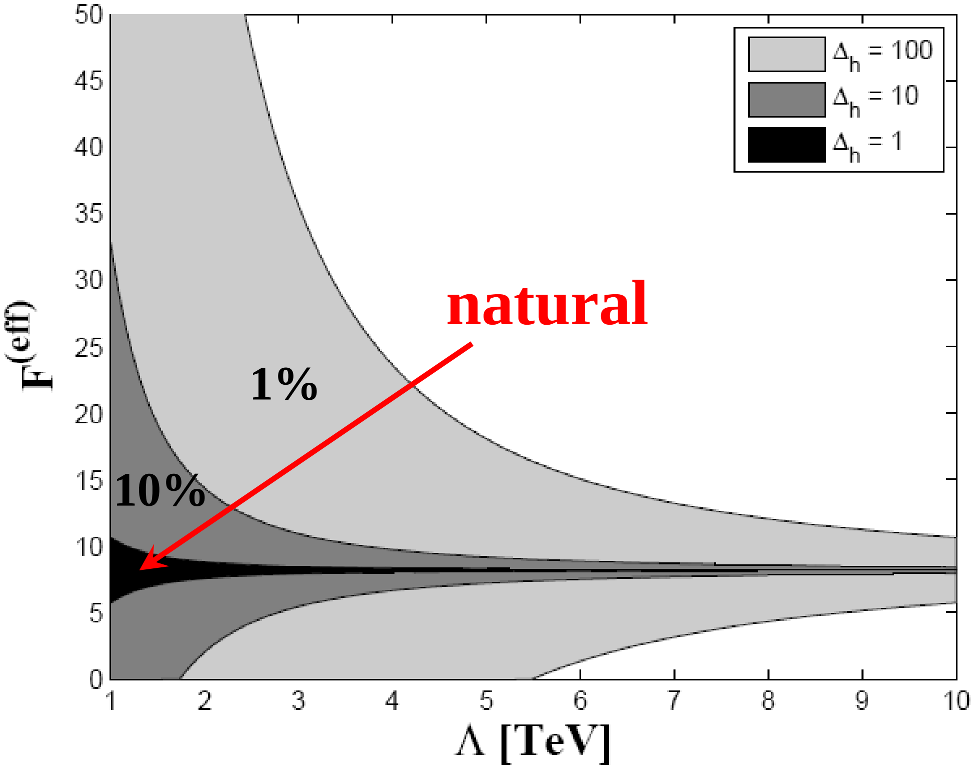
$$\delta m_h^2(\mathrm{eff}) = -\frac{\Lambda^2}{16\pi^2} F^{(\mathrm{eff})}$$

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

A theory, $F^{(\mathrm{eff})}$, for which $\Delta_h \sim 1$ is natural

while one with $\Delta_h \sim 10(100)$ suffers from fine-tuning of 10%(1%)

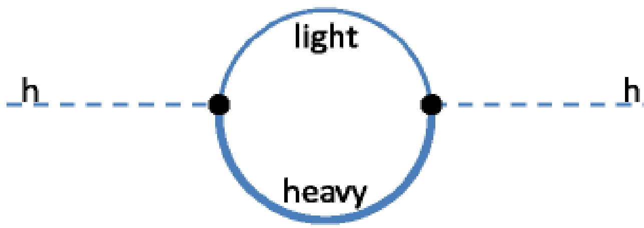


The EFT 1-loopv contribution to the Higgs mass:

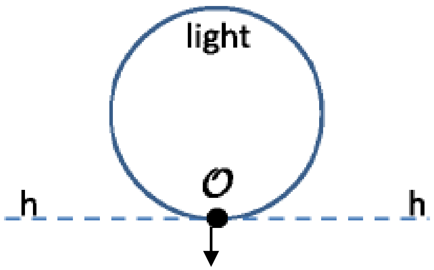
Integrating out the heavy fields (M);

generates an infinite series of vertices suppressed by inverse powers of Λ (< M)

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



$= \sum$



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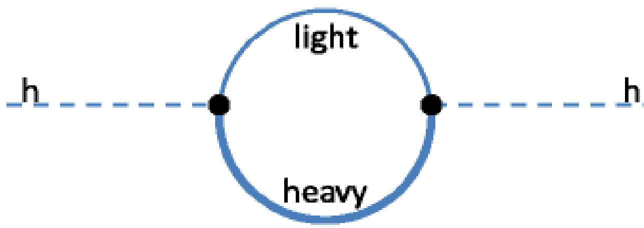

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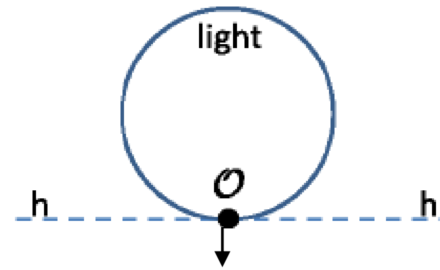

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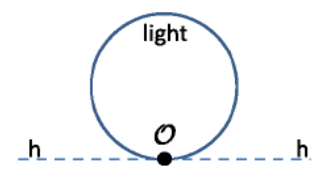
EFT naturalness: what eff. interactions can tame the little hierarchy problem?

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

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

We need the set of operators which give the <u>leading</u> contribution to $\sum$



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

EFT:

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

Its a mess in general – underlying physics not known, too many operators …

needs some guiding principles !

set the "rules of the game" …

EFT framework:

<u>Assume:</u> physics at E ≤ M is described by

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

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

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

(useful for classifying the higher dim operators)

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

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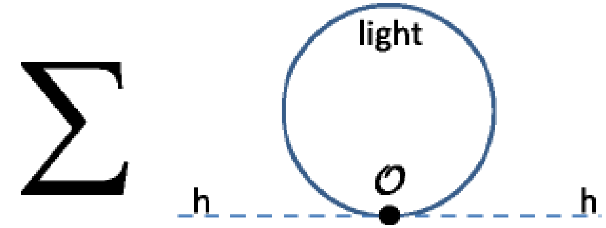
Many operators can be constructed under these conditions, O(50)

BUT: only very few can balance the SM's 1-loop quadratic terms !

EFT corrections to Higgs mass



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

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

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

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

EFT corrections to Higgs mass

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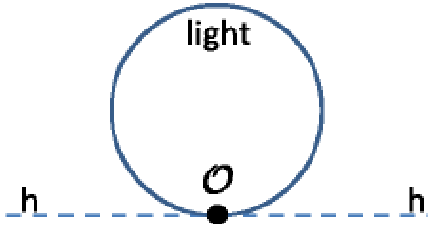

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From *heavy scalar* exchanges: singlets or triplets

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

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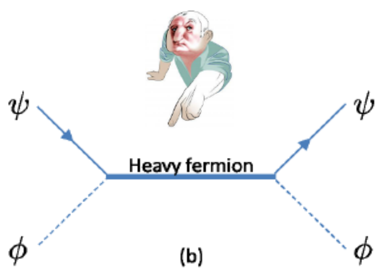

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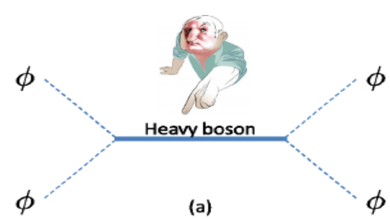

From *heavy fermion* exchanges: singlets, doublets or triplets

EFT corrections to Higgs mass

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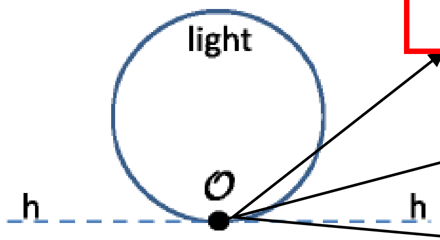

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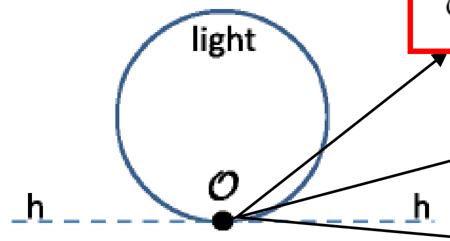

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$$F^{(\text{eff})} = \sum_{k=0}^{\infty}\frac{(\Lambda/M)^{2k}}{k+1}\sum_{\Phi}f_{\Phi}^{(2k+4)} - \sum_{k=0}^{\infty}\frac{(\Lambda/M)^{2k+2}}{k+2}\sum_{X}f_{X}^{(2k+6)} - \sum_{k=1}^{\infty}\frac{(-1)^k(\Lambda/M)^{2k}}{k+1}\sum_{\Psi,\psi}f_{\Psi-\psi}^{(2k+4)}$$

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

EFT naturalness upshot:

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

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

Provides the necessary conditions in the underlying theory (i.e., in terms of the coefficients of the higher dim. operators) for the theory to be natural (or to have a certain degree of fine-tuning)

$$\Lambda_{\Delta_h} = f(\Delta_h, f_i, M) \Rightarrow \Lambda_{natural} = f(1, f_i, M)$$

Less ignorance

More insight regarding the heavy new physics for naturalness

explicitly calculating the higher-dim coefficients …

Less ignorance:
examples of interactions of the new heavy particles that can address naturalness

heavy scalars Φ = singlets & triplets: $$\Delta\mathcal{L}_\Phi = u_\Phi \phi^\dagger \Phi \phi$$

heavy vectors X = singlets & triplets: $$\Delta\mathcal{L}_X = g_X X_\mu j_X^\mu$$

heavy fermions Ψ = singlets, doublets & triplets: $$\Delta\mathcal{L}_\Psi = y_{\Psi-\psi} \bar{\psi} \Psi \phi$$

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Integrate out heavy fields (Φ,X,Ψ) & allowing for the more general case of different scales $M_{\Phi,\Psi,X} \gtrsim \Lambda$

$$\begin{aligned}
f_\Phi^{(2k+4)}(u_\Phi, M_\Phi, M) &= \left|\frac{u_\Phi}{M_\Phi}\right|^2 \left(\frac{-M^2}{M_\Phi^2}\right)^k \\
f_{\Psi-\psi}^{(2k+4)}(y_{\Psi-\psi}, M_\Psi, M) &= \frac{1}{2} I_\Psi |y_{\Psi-\psi}|^2 \left(\frac{M^2}{M_\Psi^2}\right)^k \\
f_X^{(2k+6)}(g_X, M_X, M) &= I_X |g_X|^2 \left(\frac{-M^2}{M_X^2}\right)^{k+1}
\end{aligned}$$

Matching the effective theory @ Λ

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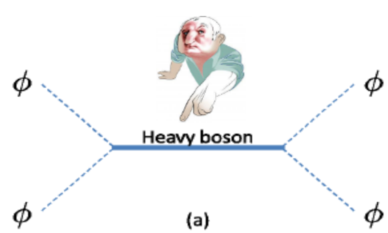

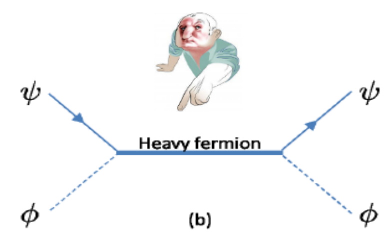

$$F^{(\text{eff})}(\Lambda) = \sum_{\Phi} \frac{|u_{\Phi}|^2}{M_{\Phi}^2} A\left(\frac{\Lambda^2}{M_{\Phi}^2}\right) + \frac{1}{2} \sum_{\Psi,\psi} I_{\Psi} |y_{\Psi-\psi}|^2 \left[1 - A\left(\frac{\Lambda^2}{M_{\Psi}^2}\right)\right] + \sum_{X} I_X |g_X|^2 \left[1 - A\left(\frac{\Lambda^2}{M_X^2}\right)\right]$$

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

EFT naturalness conditions – a simple example:

$$\delta m_h^2 = \delta m_h^2(\mathrm{SM}) + \delta m_h^2(\mathrm{eff})$$

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

Assume that the heavy masses are clustered around a value M:

$$F^{(\mathrm{eff})}(\Lambda) = (\xi - \eta) A\left(\frac{\Lambda^2}{M^2}\right) + \eta$$

$$\xi = \sum_{\Phi} \frac{|u_\Phi|^2}{M_\Phi^2} \qquad \eta = \frac{1}{2}\sum_{\Psi,\psi} I_\Psi |y_{\Psi-\psi}|^2 + \sum_X I_X |g_X|^2$$

expected values: $\xi, \eta \sim \mathcal{O}(1-10)$

e.g., $u_\Phi \sim 3M_\Phi$ and/or a triplet heavy vector-like (colored) quark with $y_{\Psi-\psi} \sim 1$

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find the values of (ξ,η) for which EFT corrections to m_h can "soften" naturalness in the Higgs sector at a certain Λ for some value of M of the NP threshold …

EFT naturalness conditions – a simple example:

$$F^{(\mathrm{eff})}(\Lambda) = (\xi - \eta) A\left(\frac{\Lambda^2}{M^2}\right) + \eta$$

$$\delta m_h^2 = \delta m_h^2(\mathrm{SM}) + \delta m_h^2(\mathrm{eff})$$

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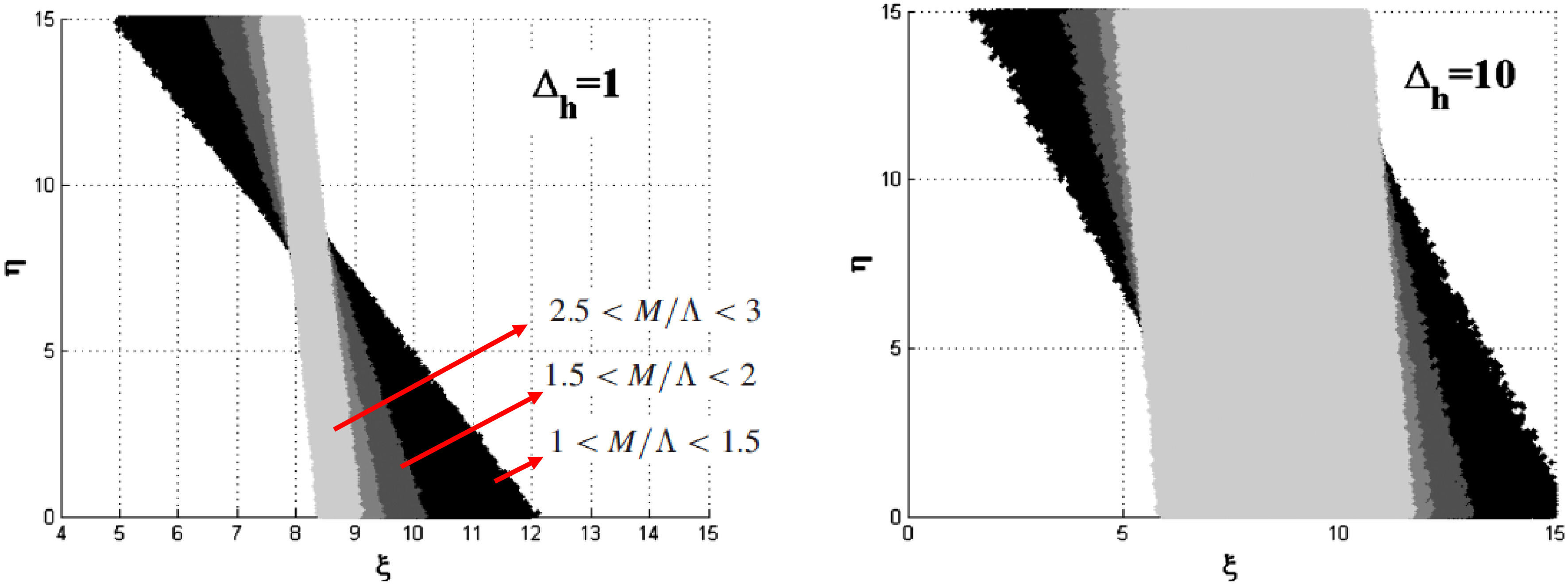
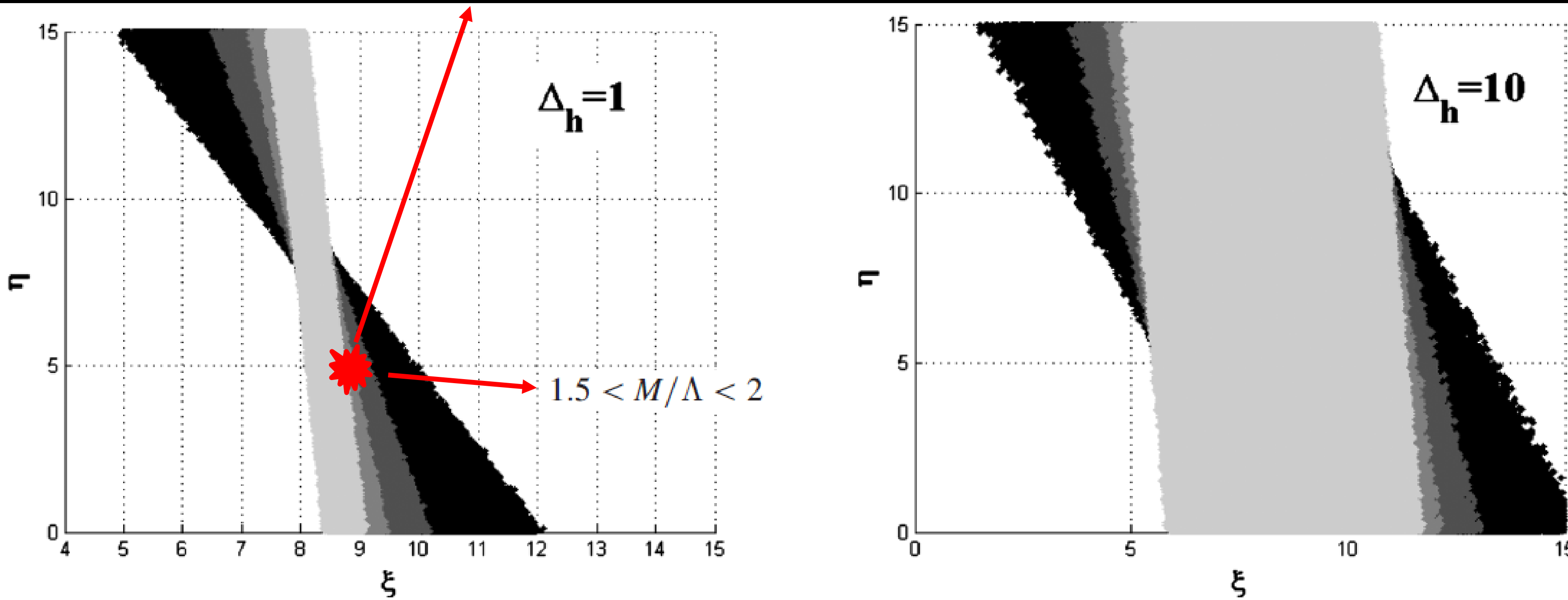
find the values of (ξ,η) for which EFT corrections to m_h can "soften" naturalness in the Higgs sector at a certain Λ for some value of M of the NP threshold …



Regions in the **ξ–η plane** which corresponds to **Δ_h=1** (natural) and **Δ_h=10** (10% fine-tuning) for an EFT-naturalness scale **3 < Λ < 10 TeV** & **Λ < M < 3Λ**

EFT naturalness conditions – a simple example:

Example: extensions of the SM with a typical mass scale of $M \sim 7$ TeV and with $\xi \sim 9$ & $\eta \sim 5$ will yield an effective action which is natural up to $\Lambda \sim 5$ TeV (an order of magnitude improvement over the pure SM …)



Regions in the **ξ–η plane** which corresponds to **Δ_h=1** (natural) and **Δ_h=10** (10% fine-tuning) for an EFT-naturalness scale **3 < Λ < 10 TeV** & **Λ < M < 3Λ**

Constraints from current data

EFT naturalness operators can cause 2 types of effects:

- A shift to the ρ-parameter

M(scalar triplet,vectors) > ~ 10 TeV

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

no useful limit …

Expected signals of EFT-Naturalness

Modified vertices involving Higgs, gauge-bosons and fermions from the EFT-naturalness higher-dim operators

Operator	h^3	h^4	hWW	h^2W^2	h^3W^2	h^4W^2	hZZ	h^2Z^2	h^3Z^2	h^4Z^2	$h\psi\psi$	$h^2\psi^2$
$\mathcal{O}_S^{(2k+4)}$	✓	✓										
$\mathcal{O}_\chi^{(2k+4)}$	✓	✓	✓	✓	✓	✓						
$\mathcal{O}_{\tilde{\chi}}^{(2k+4)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_v^{(2k+6)}$							✓	✓	✓	✓		
$\mathcal{O}_{\tilde{v}}^{(2k+6)}$			✓	✓	✓	✓						
$\mathcal{O}_{\mathbf{V}}^{(2k+6)}$			✓	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{\Psi-\psi}^{(2k+4)}$											✓	✓

Tail of new physics responsible for EFT-naturalness can be searched for in multi-boson associated production of the form:

$\psi\psi/VV \rightarrow n\cdot h + m\cdot V + X$ (n,m=0,1,2, …)

e.g., pp $\rightarrow$ Wh+X, Zh+X

Summary

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

- **What do we know about the underlying NP?**

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• **Our EFT-naturalness analysis:**

- **provides insight about this theory:**

  relations among parameters of the UV theory (for naturalness)

- **signals expected in multi-boson scattering processes, e.g., pp $\rightarrow$Wh+X, Zh+X**

Summary

- *There is a UV completion to the SM which is*

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- **What do we know about the underlying NP?**

- **Our EFT-naturalness analysis:**

  - **provides insight about this theory:**

    relations among parameters of the UV theory (for naturalness)

  - **signals expected in multi-boson scattering processes, e.g., pp → Wh+X, Zh+X**

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

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

THANK YOU!

backups

Loop calculations

vectors loop

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

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

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

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

$$\Downarrow$$

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

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

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

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

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

scalars loop

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

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

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

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

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

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

$$O_\psi = \frac{1}{2} h^2 \bar\psi_{L,R} (i\not\partial)^{2k-1} \psi_{L,R} \qquad \not\partial \psi \to -i \not p \psi$$

$$\delta m_h^2(\psi) = \underset{O_\psi}{\cdots} = \frac{i}{2} \times (-1) \int \frac{d^4p}{(2\pi)^4} \, tr\, i \frac{\{L_R [i(-i\not p)]^{2k-1}\}}{\not p}$$

$$= \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} tr\left[L_R \not p^{2k-2}\right] = \int \frac{d^4p}{(2\pi)^4} (p^2)^{k-1}$$

wick rot.

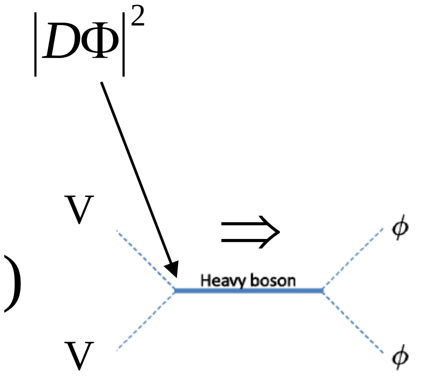
$$= \frac{i}{(4\pi)^2} \int_0^\Lambda dp_E^2\, p_E^2 (-p_E^2)^{k-1} = \frac{i}{16\pi^2} \frac{(-1)^{k-1}}{k+1} \Lambda^{2k+2}$$

$$\Downarrow$$

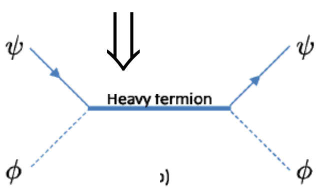
$$\delta m_h^2(\psi) = \frac{(-1)^k}{16\pi^2} \Lambda^2 \sum_{k=1}^{\infty} \frac{f_\psi^{(2k+4)}}{k+1}$$

Signals of potential heavy *natural* NP

- ***deviations in Higgs pair production***



  - $VV \to hh$ (s-channel exchange of heavy bosons)



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

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