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

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• Naturalness …

• “EFT naturalness”:
  a complete parameterization of all higher dimensional effective operators (@ any dim.!) that can potentially “soften” the $\Lambda^2$ behavior of $\delta m_h^2$

  ⇒ look for naturalness conditions in the heavy underlying theory

• Constraints, signals of EFT naturalness & concluding remarks
Naturalness

The “master equation”:

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

driving force behind search for NP
Naturalness

The “master equation”:

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

driving force behind search for NP

The hierarchy/naturalness problem:

\[ m_h^2(\text{physical mass}) = m_h^2(\text{tree}) + \delta m^2_h(SM) \approx 126 \text{ GeV} \]

\[ m_h(\text{tree}) \approx m_h \approx 126 \text{ GeV}. \]

\[ \delta m^2_h(SM) > m^2_h(\text{tree}) \] when \( \Lambda \gtrsim 500 \text{ GeV} \)
New Physics

NP particle masses are lighter than $\Lambda$

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

$\Rightarrow$ The parameters of the theory are such that there are cancellations between the SM and NP contributions to $\delta m_h$ (symmetries/accidental) ...

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

All NP particle masses are heavier than $\Lambda$

$\downarrow$

$\Lambda =$ the scale of the effective action

use EFT techniques
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 the scale of the effective action $\Lambda$.

**Exploit:** EFT techniques

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

**Ask:** what are the “EFT naturalness” conditions?

⇒ *the conditions for the physics above $\Lambda$ that can soften naturalness in the Higgs sector*
Ask: what are the “EFT naturalness” conditions?

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

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

- **EFT naturalness:** conditions among $f_i$ for theory to be natural at $\Lambda < M$
- $M > \Lambda > v$
- $\Lambda = \text{the scale of the effective action (Wilsonian-like)}$
- $M \sim O(10 \text{ TeV})$

**New heavy physics:**
Underlying setup:

EFT naturalness: conditions among $f_i$ for theory to be natural at $\Lambda < M$

$\Lambda = \text{the scale of the effective action (Wilsonian-like)}$

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 …)

new heavy physics

$M \sim O(10 \text{ TeV})$

$M > \Lambda > \nu$

$\Lambda$
The “roadmap” to EFT naturalness:

a taste of the problem …

\[
\delta m_h^2 = \delta m_h^2(\text{SM}) + \delta m_h^2(\text{eff})
\]

\[
\delta m_h^2(\text{SM}) = \frac{\Lambda^2}{16\pi^2} [24x_t^2 - 6(2x_W^2 + x_Z^2 + x_h^2)] \sim 8.2 \frac{\Lambda^2}{16\pi^2}
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\delta m_h^2(\text{eff}) = -\frac{\Lambda^2}{16\pi^2} F^{(\text{eff})}
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The “roadmap” to EFT naturalness: a taste of the problem …

\[ \delta m_h^2 = \delta m_h^2(\text{SM}) + \delta m_h^2(\text{eff}) \]

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

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

\[ \Delta_h \equiv \frac{|\delta m_h^2|}{m_h^2} = \frac{\Lambda^2}{16\pi^2 m_h^2} |F^{(\text{eff})} - 8.2| \]

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

while one with \( \Delta_h \sim 10(100) \) suffers from fine-tuning of \( 10\% (1\%) \)
Integrating out the heavy fields \((M)\);
generates an infinite series of vertices suppressed by inverse powers of \(\Lambda \ (< M)\)

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

\[
\sum_{n=5}^{\infty} \frac{1}{M^{(n-4)}} \sum_i f_i^{(n)} O_i^{(n)}
\]
The EFT contribution to the Higgs mass:

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

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

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

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

\[ \sum_{n=5}^{\infty} \frac{1}{M^{(n-4)}} \sum_i f_i^{(n)} O_i^{(n)} \]
EFT:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{M^{(n-4)}} \sum_{i} f_{i}^{(n)} O_{i}^{(n)} \]

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

*needs some guiding principles !*

*set the “rules of the game” …*
EFT framework:

Assume: physics at \( E \leq M \) is described by

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

✓ “light fields” \([@ E \leq M]\) = SM fields

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

(useful for classifying the higher dim operators)

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

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EFT framework:

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✓ Underlying NP ($\phi_{\text{heavy}}$) 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, $\mathcal{O}(50)$

**BUT:** only very few can balance the SM’s 1-loop quadratic terms!
EFT corrections to Higgs mass

\[ O_{S}^{(2k+4)} = \frac{1}{2} |\phi|^2 \Box^k |\phi|^2 , \quad O_{\chi}^{(2k+4)} = \frac{1}{2} (\phi^\dagger T_I \phi) D^{2k} (\phi^\dagger T_I \phi) , \quad O_{\tilde{\chi}}^{(2k+4)} = \frac{1}{4} (\phi^\dagger T_I \tilde{\phi}) D^{2k} (\phi^\dagger T_I \phi) \]

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

\[ O^{(2k+6)} = \frac{1}{2} j_{\mu} \Box^{k} j^\mu , \quad O_{\tilde{\chi}}^{(2k+6)} = \tilde{j}_{\mu} \Box^{k} \tilde{j}^\mu , \quad O_{\Psi}^{(2k+6)} = \frac{1}{6} J_{I\mu} D^{2k} J_I^\mu \]

\[ O^{(2k+4)}_{\Psi - \Psi} = |\phi|^2 \bar{\psi} (i D)^{2k-1} \psi \]
EFT corrections to Higgs mass

\[ O_{S}^{(2k+4)} = \frac{1}{2}|\phi|^2 \Box^k |\phi|^2, \quad O_{\chi}^{(2k+4)} = \frac{1}{2}(\phi^\dagger \tau_I \phi) D^{2k} (\phi^\dagger \tau_I \phi), \quad O_{\tilde{\chi}}^{(2k+4)} = \frac{1}{4}(\phi^\dagger \tau_I \tilde{\phi}) D^{2k} (\phi^\dagger \tau_I \phi) \]

From heavy scalar exchanges: singlets or triplets

\[ j^\mu = i\phi^\dagger D^\mu \phi + \text{H.c.}, \quad \tilde{j}^\mu = i\tilde{\phi}^\dagger D^\mu \tilde{\phi}, \quad J^\mu_I = i\phi^\dagger \tau^I D^\mu \phi + \text{H.c.} \]

\[ O_v^{(2k+6)} = \frac{1}{2}j_\mu \Box^k j^\mu, \quad O_{\tilde{v}}^{(2k+6)} = \tilde{j}_\mu \Box^k \tilde{j}^\mu, \quad O_V^{(2k+6)} = \frac{1}{6}J_I \mu D^{2k} J_I^\mu \]

From heavy vector exchanges: singlets or triplets

From heavy fermion exchanges: singlets, doublets or triplets

\[ O_{\Psi-\psi}^{(2k+4)} = |\phi|^2 \overline{\psi} (i D)^{2k-1} \psi \]
EFT corrections to Higgs mass

\[ O_{S}^{(2k+4)} = \frac{1}{2} |\phi|^2 \Box^k |\phi|^2, \quad O_{\chi}^{(2k+4)} = \frac{1}{2} (\phi^3 \tau I \phi) D^{2k} (\phi^T \tau I \phi), \quad O_{\tilde{\chi}}^{(2k+4)} = \frac{1}{4} (\phi^3 \tau I \phi) D^{2k} (\tilde{\phi}^T \tau I \tilde{\phi}) \]

\[ O_{v}^{(2k+6)} = \frac{1}{2} j^{\mu} D^{k} j^{\mu}, \quad O_{\tilde{v}}^{(2k+6)} = \tilde{j}^{\mu} \Box^{k} \tilde{j}^{\mu}, \quad O_{\psi}^{(2k+6)} = \frac{1}{6} J_{I \mu} D^{2k} J_{I}^{\mu} \]

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

\[ O_{\psi - \bar{\psi}}^{(2k+4)} = |\phi|^2 \bar{\psi} (i D)^{2k-1} \psi \]
EFT corrections to Higgs mass

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

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

\[ \Phi = S, \chi, \tilde{\chi} \text{ and } X = v, \tilde{v}, V \]
EFT naturalness upshot:

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

\[ \Delta_n \equiv \frac{\delta m_h^2}{m_h^2} = \frac{\Lambda^2}{16\pi^2 m_h^2} |F^{(\text{eff})} - 8.2| \]

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)

\[ \Lambda_{\Delta h} = f(\Delta_h, f_i, M) \quad \Rightarrow \quad \Lambda_{\text{natural}} = f(1, f_i, M) \]
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** $\Phi = \text{singlets & triplets:}$

$$\Delta \mathcal{L}_\Phi = u_\Phi \phi^\dagger \Phi \phi$$

**heavy vectors** $X = \text{singlets & triplets:}$

$$\Delta \mathcal{L}_X = g_X X_{\mu} j_{X}^{\mu}$$

**heavy fermions** $\Psi = \text{singlets, doublets & triplets:}$

$$\Delta \mathcal{L}_\Psi = y_\Psi - \bar{\psi} \Psi \phi$$
Less ignorance:
examples of interactions of the new heavy particles that can address naturalness

\textbf{heavy scalars } \Phi = \text{ singlets & triplets:} \quad \Delta \mathcal{L}_\Phi = u_\Phi \phi^\dagger \Phi \phi

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\textbf{heavy fermions } \Psi = \text{ singlets, doublets & triplets:} \quad \Delta \mathcal{L}_\Psi = y_{\Psi - \bar{\Psi}} \bar{\Psi} \Psi \phi

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

\[
\begin{align*}
 f_{\Phi}^{(2k+4)}(u_\Phi, M_\Phi, M) &= \left| \frac{u_\Phi}{M_\Phi} \right|^2 \left( \frac{-M^2}{M_\Phi^2} \right)^k \\
 f_{\Psi - \bar{\Psi}}^{(2k+4)}(y_{\Psi - \bar{\Psi}}, M_\Psi, M) &= \frac{1}{2} I_{\Psi} |y_{\Psi - \bar{\Psi}}|^2 \left( \frac{M^2}{M_\Psi^2} \right)^k \\
 f_{X}^{(2k+6)}(g_X, M_X, M) &= I_X |g_X|^2 \left( \frac{-M^2}{M_X^2} \right)^{k+1}
\end{align*}
\]
Matching the effective theory @ $\Lambda$

\[
\begin{align*}
    f^{(2k+4)}_{\Phi}(u_\Phi, M_\Phi, M) &= \left| \frac{u_\Phi}{M_\Phi} \right|^2 \left( \frac{-M^2}{M_{\Phi}^2} \right)^k \\
    f^{(2k+6)}_X(g_X, M_X, M) &= I_X |g_X|^2 \left( \frac{-M^2}{M_X^2} \right)^{k+1} \\
    f^{(2k+4)}_{\Psi-\psi}(y_{\Psi-\psi}, M_\Psi, M) &= \frac{1}{2} I_{\Psi} |y_{\Psi-\psi}|^2 \left( \frac{M^2}{M_{\Psi}^2} \right)^k
\end{align*}
\]

\[
F^{(\text{eff})} = \sum_{k=0}^{\infty} \frac{(\Lambda/M)^{2k}}{k' + 1} \sum_{\Phi} f^{(2k+4)}_{\Phi} - \sum_{k=0}^{\infty} \frac{(\Lambda/M)^{2k+2}}{k' + 2} \sum_{X} f^{(2k+6)}_X - \sum_{k=1}^{\infty} \frac{(-1)^k (\Lambda/M)^{2k}}{k' + 1} \sum_{\Psi, \psi} f^{(2k+4)}_{\Psi-\psi}
\]

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Higgs Physics
Matching the effective theory @ $\Lambda$

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

\[
A(x) = \ln(1 + x)/x, \quad \Rightarrow \quad 1 > A(x) \geq 0 \quad F^{(\text{eff})} > 0 !
\]

\[
f^{(2k+4)}(u_{\Phi}, M_{\Phi}, M) = \left| \frac{u_{\Phi}}{M_{\Phi}} \right|^2 \left( -\frac{M_{\Phi}^2}{M_{\Phi}^2} \right)^k \quad f^{(2k+6)}(g_{\chi}, M_{\chi}, M) = I_{\chi} |g_{\chi}|^2 \left( -\frac{M_{\chi}^2}{M_{\chi}^2} \right)^{k+1}
\]

\[
F^{(\text{eff})} = \sum_{k=0}^\infty \frac{(\Lambda / M)^{2k}}{k+1} \sum_{\Phi} f^{(2k+4)}_{\Phi} - \sum_{k=0}^\infty \frac{(\Lambda / M)^{2k+2}}{k+2} \sum_{\Phi} f^{(2k+4)}_{\Phi}
\]

\[
\delta m^2_{\Phi}(\text{eff}) = -\frac{\Lambda^2}{16\pi^2} F^{(\text{eff})}
\]

\[
\begin{align*}
\text{(a)} & & \text{Heavy boson} \\
\text{(b)} & & \text{Heavy fermion}
\end{align*}
\]
Assume that the heavy masses are clustered around a value $M$:

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

$$\xi = \sum_{\phi} \frac{|u_{\phi}|^2}{M_{\phi}^2}$$

$$\eta = \frac{1}{2} \sum_{\psi, \overline{\psi}} I_{\psi} |y_{\psi - \overline{\psi}}|^2 + \sum_{X} I_{X} |g_{X}|^2$$

**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 $y_{\psi - \overline{\psi}} \sim 1$_
EFT naturalness conditions – a simple example:

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

\[ \delta m_h^2 = \delta m_h^2(\text{SM}) + \delta m_h^2(\text{eff}) \]

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

find the values of \((\xi, \eta)\) for which EFT corrections to \(\Delta m_h\) can “soften” naturalness in the Higgs sector at a certain \(\Lambda\) for some value of \(M\) of the NP threshold …
EFT naturalness conditions – a simple example:

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Find the values of \((\xi, \eta)\) for which EFT corrections to \(\Delta m_h\) can “soften” naturalness in the Higgs sector at a certain \(\Lambda\) for some value of \(M\) of the NP threshold …

Regions in the \(\xi - \eta\) plane which corresponds to \(\Delta_h = 1\) (natural) and \(\Delta_h = 10\) (10% fine-tuning) for an EFT-naturalness scale \(3 < \Lambda < 10\) TeV & \(\Lambda < M < 3\Lambda\)
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 $\xi$–$\eta$ plane which corresponds to $\Delta_h=1$ (natural) and $\Delta_h=10$ (10% fine-tuning) for an EFT-naturalness scale $3 < \Lambda < 10$ TeV & $\Lambda < M < 3\Lambda$
EFT naturalness operators can cause 2 types of effects:

• A shift to the $\rho$-parameter

$$M(\text{scalar triplet, vectors}) > \sim 10 \text{ TeV}$$

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

no useful limit …
Expected signals of EFT-Naturalness

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

<table>
<thead>
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<th>Operator</th>
<th>$h^3$</th>
<th>$h^4$</th>
<th>$hWW$</th>
<th>$h^2W^2$</th>
<th>$h^3W^2$</th>
<th>$h^4W^2$</th>
<th>$hZZ$</th>
<th>$h^2Z^2$</th>
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</table>

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

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

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

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

- What do we know about the underlying NP?
Summary

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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., $pp \rightarrow Wh+X, Zh+X$
Summary

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

• What do we know about the underlying NP?

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  • provides insight about this theory: relations among parameters of the UV theory (for naturalness)
  • signals expected in multi-boson scattering processes, e.g., $pp \rightarrow Wh+X, Zh+X$

• 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
vectors loop

\[ \mathcal{O}_v = \frac{i}{2} \sum_{j} j^j = -\frac{1}{2} \hbar^2 \left( \sum_{k=1}^{n} a^{k-n} x^k \right) + \ldots \]
\[ \mathcal{O}_s = \frac{i}{2} \hbar^2 \left( \sum_{k=1}^{n} x^k \right) + \ldots \]
\[ \mathcal{O}_f = \frac{1}{6} \sum_{k=1}^{n} f^k = \frac{1}{6} \hbar^2 \left( 2 \sum_{k=1}^{n} x^k \right) \]

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</p>

fermions loop

\[ \mathcal{O}_\psi = \frac{i}{2} \hbar^2 \left( \sum_{k=1}^{n} a^{k-n} \right) \psi_{\chi} \]
\[ \mathcal{O}_\chi \rightarrow \frac{i}{2} \hbar^2 \left( \sum_{k=1}^{n} a^{k-n} \right) \psi_{\chi} \]
\[ \mathcal{O}_f \rightarrow \frac{1}{4} \left[ \hbar^2 (2 \hbar^2 + h^3 x^2) \right] \]
\[ \mathcal{O}_\psi \rightarrow \frac{1}{4} \left[ \hbar^2 (2 \hbar^2 + h^3 x^2) \right] \]

\[ \delta m^2_{\chi} = \frac{1}{4} \sum_{k=1}^{n} \frac{h^3 x^2}{\hbar^2} \]
\[ \delta m^2_{\psi} = \frac{1}{4} \sum_{k=1}^{n} \frac{h^3 x^2}{\hbar^2} \]

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Signals of potential heavy natural NP

- **deviations in Higgs pair production**
  - VV → hh (s-channel exchange of heavy bosons)
  - qq,ee → hh (t-channel exchange of heavy fermions)

- **Higgs+jet/lepton production via off-shell heavy fermion ``decay''**
  - Ψ* → hψ (ψ = quark or lepton)