A 125 GeV Higgs: From naturalness to fourth generation and beyond

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Dean Carmi, Adam Falkowski, EK, Tomer Volansky [1202.3144]
EK, Tomer Volansky, Yossi Nir [1204.1975]
Outline

- Naturalness vs. Discovery
- Higgs at the LHC
- Constraints on BSM physics (SUSY, 4th generation, ...)
Learning from the Higgs

The Higgs is an excellent tool to study new physics and hierarchy problem.

- Discovering the Higgs is a loop-effect

- No loop suppression relative to Standard Model to see new physics

- Very sensitive to new physics
Chronic Hierarchy Problem Slide

- Hierarchy problem dominated model building for last 30 years.

Why is the weak force so much stronger than gravity?

\[
\delta m_h^2 = \frac{3 m_t^2}{2 \pi^2 v^2} \Lambda^2
\]
Solutions to the Hierarchy Problem

- Standard Model → New effective theory at the TeV scale
  - Supersymmetry
    - Weakish scale soft-SUSY breaking masses
  - Extra Dimensions
    - ADD, RS, ...
  - Strong Dynamics
    - Technicolor, Little Higgs, ...
Where is the new physics that was promised to me?

All these theories predict new physics at the TeV scale, then where is it?

All existing models introduce a multitude of new particles, which typically require a few percent tuning to avoid constraints.

Wasn’t low-energy supersymmetry coming from M-Theory compactified on a G2-manifold supposed to be discovered before I graduated?
Higgs Discovery vs. Hierarchy Problem

- In fact, the cancellation of the Higgs’ mass divergence and the production and decay are profoundly related.

- Precision Higgs is telling us how natural our world is.

Dermisek, Low, 0701235
Low, Rattazzi, Vichi, 0907.5413
Arvanitaki, Villadoro, 1112.4835
Top partners—particles that make the Higgs mass natural—are colored/charged.

Top partners cancel $\Lambda^2$ divergence.

Changes Higgs rates. With the same couplings.
Higgs at the LHC

- The SM Higgs with mass around 125 GeV has many decay channels that are potentially observable at the LHC
  - Now: $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$
  - Soon: $H \rightarrow WW^*$
  - Later: $H \rightarrow \tau\tau$ and $H \rightarrow b\overline{b}$

- Also different production channels can be isolated
  - Now: gluon fusion
  - Soon: vector boson fusion
  - Later: associated production with W/Z and $t\overline{t}$

- Rich Higgs physics available in the near future.
Most relevant LHC search channels updated to 5 fb-1 in ATLAS and CMS

Currently most information can be extracted from $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$

Strong hints for 125 GeV Higgs, while other mass ranges are roughly excluded.

$[\text{Giardino et al., 2012}]$
• Significant background, but great mass resolution
• Both ATLAS and CMS observe an excess, ATLAS: 126 GeV and CMS: 124 GeV.
• In both cases the best fit cross section at the peak exceeds the SM value, though well within uncertainties.
• CMS observes an excess in the dijet class, which is expected to be dominated by VBF production mode.
Fermiophobic Higgs bosons motivated searches

- Can only be produced through vector boson fusion (VBF) and associated production with vector bosons (VH, V = W; Z).
- Both observe an excess in inclusive dijet channel dominated by VBF production mode, corresponding to cross section well exceeding the SM one (though, again, uncertainties are still large)

$$3.3 \pm 1.1 \times \text{SM rate}$$
Very low background, great mass resolution

ATLAS has 3 events at 124 GeV

CMS has 2 events at 126 GeV
\[ h \rightarrow WW \]

- Significant background, poor mass resolution, better for exclusion than discovery
- No excess?
  - Custodial symmetry: if excess in ZZ (or VBF) then there should be an excess in WW.
- Points to a somewhat enhanced rate in $VH$ production channel
- Doesn't strongly favor any mass between 120 and 135 GeV– the likelihood is flat.
The Higgs boson has been discovered, seen, and has mass near 125 GeV.
A Standard Model Higgs?

$m_h = 125$ GeV

[Giardino et al., 2012]
New physics should cancel the quadratic divergence, so the new particles must be light.

We observe SM-like rates, so the new particles must be heavy.

More little hierarchy problems will become stronger with more data.
Technical Details

\[ \Gamma(h \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_h^3}{128 \sqrt{2\pi}^3} \left| g_{hVV} A_1(\tau_V) + N_c Q_f^2 g_{hf\bar{f}} A_1^{\frac{1}{2}}(\tau_f) + N_c Q_f^2 \frac{g_{h\bar{f}f}}{m_{\bar{f}}^2} A_0(\tau_{\bar{f}}) \right|^2 \]

\[ \tau_i = m_h^2/4m_i^2 \]

For \( \tau_i \rightarrow 0 \)

\[ A_1(\tau_V) \rightarrow -7 \quad A_1^{\frac{1}{2}}(\tau_f) \rightarrow \frac{4}{3} \quad A_0(\tau_{\bar{f}}) \rightarrow \frac{1}{3} \]

- In the SM, the W-boson dominates, but the top deconstructively interferes
- Fermions contribute 4 times greater (same as the beta function)
- \( g_{hf\bar{f}} = 1 \) for fermions getting their mass from the Higgs vev, but
  \( g_{hf\bar{f}} = \lambda_{hf\bar{f}} v/\sqrt{2}m_f \) for vector-like fermion

\[ \Gamma(h \rightarrow gg) = \frac{3G_F \alpha_s^2 M_h^3}{192 \sqrt{2\pi}^3} \left| g_{hf\bar{f}} A_1^{\frac{1}{2}}(\tau_f) + \frac{g_{h\bar{f}f}}{m_{\bar{f}}^2} A_0(\tau_{\bar{f}}) \right|^2 \]

- In the SM, the top dominates.
New physics will increase one, while decreasing the other.

\[
\Gamma(h \rightarrow \gamma\gamma) = |W - top \pm T|^2
\]

\[
\Gamma(h \rightarrow gg) = |top \pm T|^2
\]

Largest contribution

Interference-20% of the W-boson contribution
Changing the Rates

- In the limit $\frac{m_h^2}{4m_T^2} \to 0$ (integrating out heavy top partners), we can relate the loop to the coefficient of the $h F_{\mu \nu} F^{\mu \nu}$ operator from the QCD beta-function

- Turn on a background Higgs and calculate the threshold effects from the Top partner

$$- \frac{1}{4g^2(\mu)} F_{\mu \nu} F^{\mu \nu} = - \frac{1}{4} \left( \frac{1}{g_A^2} - \frac{b_0}{16\pi^2} \log \frac{\Lambda^2}{\mu^2} - \frac{b_T}{16\pi^2} \log \frac{M_T^2(h)}{\mu^2} - \ldots \right) F_{\mu \nu} F^{\mu \nu}$$

- The coefficient of the $h F_{\mu \nu} F^{\mu \nu}$ operator is proportional to

$$b_T \left. \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h} \right|_{h=v/\sqrt{2}}$$
Cancelling the Divergence

• Cancellation of the quadratic divergence is given in terms of Coleman–Weinberg effective potential. Coleman, Weinberg 1973

\[ V_{\text{eff}} = \frac{1}{32\pi^2} \Lambda^2 STr M^2(h) + \ldots \]

\[ b_T \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h} \bigg|_{h=v/\sqrt{2}} \quad \leftrightarrow \quad STr M^2(h) \]
EFT Approach

\[ \mathcal{L}_{\text{eff}} = c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h Z_\mu Z_\mu - c_b \frac{m_b}{v} h \bar{b}b - c_b \frac{m_\tau}{v} h \bar{\tau}\tau 
+ c_g \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h A_{\mu\nu} A_{\mu\nu} \]

- We will find the region of effective theory parameter space favored by Higgs data.
- Interesting to check whether the current LHC data are consistent with the SM Higgs.
- Also interesting, whether they favor or disfavor any particular BSM scenario.
- Of course at this stage one cannot make very strong statements about Higgs couplings (some of you don't even think Higgs has been discovered).
- Consider it a warm-up exercise, in preparation for serious signals.
- Recently Carmi [1202.3144], Azatov [1202.3415], Espinosa [1202.3697], and Giardino [1203.4254].
For $m_h \sim 125$ GeV total Higgs width scales as

$$\frac{\Gamma(h)}{\Gamma_{SM}(h)} \simeq 0.65c_b^2 + 0.25c_V^2 + 0.1c_g^2$$

Assuming $H \rightarrow bb$ dominates Higgs widths

$$R_V \equiv \frac{\sigma(pp \rightarrow h)Br(h \rightarrow ZZ^*)}{\sigma_{SM}(pp \rightarrow h)Br_{SM}(h \rightarrow ZZ^*)} \simeq \left( \frac{c_g c_V}{c_b} \right)^2,$$

$$R_\gamma \equiv \frac{\sigma(pp \rightarrow h)Br(h \rightarrow \gamma\gamma)}{\sigma_{SM}(pp \rightarrow h)Br_{SM}(h \rightarrow \gamma\gamma)} \simeq \left( \frac{c_g \hat{c}_\gamma}{\hat{c}_\gamma,SM c_b} \right)^2,$$

$$R_{\gamma, VBF} \equiv \frac{\sigma(pp \rightarrow hjj)Br(h \rightarrow \gamma\gamma)}{\sigma_{SM}(pp \rightarrow hjj)Br_{SM}(h \rightarrow \gamma\gamma)} \simeq \left( \frac{c_V \hat{c}_\gamma}{\hat{c}_\gamma,SM c_b} \right)^2.$$

$$R_{\text{Tev}} \equiv \frac{\sigma(p\bar{p} \rightarrow Vh)Br(h \rightarrow b\bar{b})}{\sigma_{SM}(p\bar{p} \rightarrow Vh)Br_{SM}(h \rightarrow b\bar{b})} \simeq c_V^2,$$
- Only dimension-5 Higgs couplings allowed to vary
- On this plane Tevatron never within 1 sigma band

- Composite Higgs inspired parametrization
- Couplings to fermions and gauge boson allowed to vary independently

**New particles in the loops**

**Strongly Interacting Light Higgs**
Top partner models relation $c_\gamma = 2c_g/9$
A single scalar partner will cancel quadratic divergence but contribute the same as the top to the rates.

\[ \mathcal{L}_{\text{stop}} = -(yHQt^c + \text{h.c.}) - |\tilde{t}|^2 (M^2 + \lambda|H|^2) \]

\[ \lambda = 2y^2 \]

\[ \Lambda^2 \downarrow \quad h \rightarrow gg \uparrow \quad h \rightarrow \gamma\gamma \downarrow \]

\[ \chi^2_{\text{min}} = 14 \]
Two Scalar Top Partners - SUSY

- But with mixing, the signs can change

\[-\mathcal{L}_{\text{stop}} = |\tilde{t}|^2 (\tilde{m}^2 + y^2|H|^2) + |\tilde{c}|^2 (\tilde{m}_c^2 + y^2|H|^2) + y|H|X_t (\tilde{t} \tilde{t}^c + \text{h.c.})\]

- Intersecting 99% CL region. No constraint from the Higgs mass.

- Cancellation of quadratic divergence comes from both stops, so bounds will be weaker.

- Can tune the mixing, to get light stops.
Fermion Partner

- Exactly cancel quadratic divergence:

\[ -\mathcal{L} = M_T T \bar{T} - \frac{1}{\Lambda_T} hh^* \bar{T} \bar{T} \]

\[ \frac{1}{\Lambda_T} = \frac{\lambda_t^2}{2M_T} \]

\[ \Lambda^2 \downarrow \quad h \to gg \downarrow \quad h \to \gamma \gamma \uparrow \]
Implications of Higgs Searches on the Four Generation Standard Model

with Yossi Nir and Tomer Volansky

[1204.1975]
Fourth Generation

\[ \Gamma_{h \to gg} \sim |\text{Top} + \text{Top}' + \text{Bottom'}|^2 \sim 9 \times \text{SM} \]

\[ \Gamma_{h \to \gamma\gamma} \sim |W - \text{Top} - \text{Top}' - \text{Bottom'} - \text{Tau'}|^2 \sim \frac{1}{5} \times \text{SM} \]

\[ R_{\gamma\gamma} \sim 1.8 \quad \text{but} \quad R_{ZZ} \sim 5 \]

Fourth generation is ruled out!
Fourth Generation – Leading Order

Not the entire story: There is a heavy neutrino, and the Higgs can decay mostly invisibly.

Fourth Generation Saved!
More to the entire story:

- At next-to-leading-order (NLO), the large Yukawa-couplings for heavy fermions can contribute significantly to all widths.
- Complete NLO widths have been calculated by Denner et. Al. [1111.6395] and implemented in HDECAY and Prochecy4f
- For very heavy fermion masses, up to the perturbative limit, the corrections to the decay rates to fermions and heavy gauge bosons can be as large as a factor of 2
  - Tend to increase the width to fermions, while decreasing the widths to WW and ZZ.
- The NLO corrections to $h \rightarrow gg$ are found to be less significant.
Not the entire story:

- The LO value of the $h \rightarrow \gamma\gamma$ width is already accidentally small due to the destructive interference between the W-boson and fermion loops.
- NLO corrections are very large!

$$\Gamma_{h\rightarrow\gamma\gamma} \sim |W - Top - Top' - Bottom' - Tau' - 2\ Loop|^2$$

Two loop diagrams lead to an even larger cancellation between the W-loop and fermion-loops.

- For fermion masses at the pertubative limit (600 GeV fermions), the cancelation between the LO and NLO correction is 90%.
- The cancellation can be as large as 99% for some masses.

$$R_{\gamma\gamma} \sim 1/100$$
Denner, Dittmaier, Muck, Passarino, Spira, Sturm, Uccirato, Webber, 1111.6395
Will it work?

- \( R_{VV} \sim \frac{\sigma_{gg} Br_{VV}}{\sigma_{gg} Br_{VV}|_{sm}} \sim 10 \frac{\Gamma_{bb}}{\Gamma_{NN}} \)

- \( R_{\gamma\gamma} \sim R_{\gamma\gamma, VBF} \sim \frac{\sigma_{gg} Br_{\gamma\gamma}}{\sigma_{gg} Br_{\gamma\gamma}|_{sm}} \sim .1 \frac{\Gamma_{bb}}{\Gamma_{NN}} \)

- \( R_{bb} \sim \frac{\sigma_{VH} Br_{bb}}{\sigma_{VH} Br_{bb}|_{sm}} \sim \frac{\Gamma_{bb}}{\Gamma_{NN}} \)

Improving the constraints from WW and ZZ searches will make constraints from other searches stronger.
EW Constraints

Includes $\gamma\gamma$, $VBF, \gamma\gamma$ (FB), $ZZ$, $b\bar{b}$, $WW$

SM Excluded at 97%

Scan within 99% EW constraints

Includes
\( \gamma \gamma \), \( VBF, \gamma \gamma \) (MVA), \( ZZ \), \( b \bar{b} \), \( WW \), SM Excluded at 86%
Robust?

\[ \Gamma_{h \rightarrow \gamma\gamma} \sim |W - \text{Top} - \text{Top}^\prime - \text{Bottom}^\prime - \text{Tau}^\prime - 2 \text{ Loop}|^2 \]

- Care should be taken with the numerical codes as they only approximate the correction to \( h \rightarrow \gamma\gamma \) at NLO to about 1% accuracy
  - Can result in an large inaccuracy in the actual width
- NNLO corrections may be large for the heavier masses.
- Weakest constraints are obtained when the fourth generation masses are lightest.
  - Smaller Yukawa couplings imply smaller corrections, and a small cancellation for \( h \rightarrow \gamma\gamma \).
  - Also the range we expect the uncertainties to be lowest
    - NLO cancellation is less significant
    - NNLO corrections are smallest
More Constraints – Precision EW

- Combining with precision electroweak can lead to much stronger constraints
- Instead of scanning over allowed parameter space from oblique parameters, including EWPO in the $\chi^2$ would lead to much stronger constraints

Eberhardt, Herbert, Lacke, Lenz, Menzel, Nierste, Wiebusch
[1204.3872]
Even more constraints –
Direct Searches

- Very strong, somewhat model dependent bounds on heavy quarks. They tend to push SM4 outside the perturbative regime.

4th generation quarks: Summary

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Channel</th>
<th>$\int L dt [fb^{-1}]$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$Qq \rightarrow Wqq'$</td>
<td>1.0</td>
<td>$m_Q &gt; 900,\text{GeV}$</td>
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<td>ATLAS</td>
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<td>ATLAS</td>
<td>$QQ \rightarrow (Wq)(Wq)$</td>
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<td>$m_Q &gt; 350,\text{GeV}$</td>
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<td>CMS</td>
<td>chiral $Q \rightarrow WbX$</td>
<td>1.1</td>
<td>$m_Q &gt; 490,\text{GeV}$</td>
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<td>ATLAS</td>
<td>$TT \rightarrow (Wb)(Wb)$</td>
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<td>$m_T &gt; 404,\text{GeV}$</td>
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<tr>
<td>ATLAS</td>
<td>$TT \rightarrow (tA_0)(tA_0) \rightarrow lX$</td>
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<tr>
<td>CMS</td>
<td>$TT \rightarrow (Wb)(Wb) \rightarrow llX$</td>
<td>4.7</td>
<td>$m_T &gt; 552,\text{GeV}$</td>
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<td>$BB \rightarrow (Wt)(Wt) \rightarrow ljjjjjjX$</td>
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<td>ATLAS</td>
<td>$BB \rightarrow (Wt)(Wt) \rightarrow llX (SS,l)$</td>
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<tr>
<td>CMS</td>
<td>$BB \rightarrow (Wt)(Wt)\rightarrow$</td>
<td>4.6</td>
<td>$m_B &gt; 600,\text{GeV}$</td>
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</table>
Direct Searches + EWP

- An LHC search at 7 TeV with 1 fb$^{-1}$ of data can exclude fourth generation charged leptons with masses up to 250 GeV. Carpenter, Rajarman, Whiteson [1010.1011]
- S&T parameters constrain $m_{l'} - m_{N'} < 250$ GeV.
- Kill the 4th generation when combined with EWPO and Higgs rates.
Summary

• Finally, a new particle might have maybe possibly been seen.
• Higgs measurements are close to SM-like
  – Little Hierarchy Problem
• New physics can be seen in Higgs production and decay
  – Related to Naturalness
  – Has begun to rule out models
The End.
2HDM

\[ \tan \beta \]

\[ \sin \alpha \]

Ferreira, Santos, Sher, Silva, 1112.3277
Ferreira, Santos, Sher, Silva, 1201.0019
Cerver, Gerard, 1202.1973
Blum, D'Agnolo, 1202.2364