Electroweak symmetry breaking beyond the Standard Model

Adam Falkowski
LPT Orsay

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in light of latest Higgs results:
Carmi,AA,Kuflik,Volansky [1202.3144]
AA,Rychkov,Urbano [1202.1532]

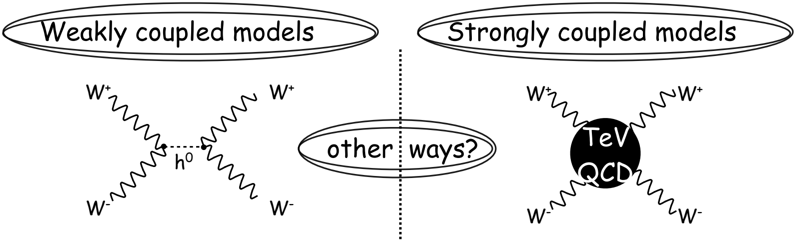
Who broke electroweak symmetry?

- Since LEP we know for a fact fundamental interactions of matter obey $SU(2) \times U(1)$ local symmetry that is however spontaneously broken (non-linearly realized), as W, Z and fermions have masses
- The Question for the LHC is the precise nature of electroweak symmetry breaking
- More rigorously, the question is what stops the growth of the scattering amplitudes of W and Z bosons:
    - In the SM (without Higgs) the tree-level amplitude for longitudinally polarized W's and Z's grows with energy, $\mathcal{M} \sim s/v^2$
    - Unitarity requires $\mathrm{Re}\,\mathcal{M}^J < 1/2$ for all partial waves. Perturbative unitarity is lost at TeV
    - Something else must enter before that scale!

Options for Electroweak Symmetry Breaking

3 basic possibilities. Unitarity saved by

- Non-Perturbative effects in the SM (no concrete framework so far)
- Strongly Coupled: composite vectors and/or scalars to WW and WZ
- Weakly Coupled: fundamental scalar coupled to WW and ZZ, otherwise known as the Higgs
- ...or a combination of the above...



picture stolen from C. Grojean

Only Higgs

- Current experimental data strongly suggest that the weakly coupled option is approximately true, at least for $E \lesssim 1$ TeV.
  - Electroweak precision tests
  - No new vector states observed at the Tevatron and LHC
  - Higgs-like excess near 125 GeV
- Furthermore, they point to the simplest realization with a single Higgs boson resposible for unitarizing WW scattering
  - Approximate global symmetries of SM, such as flavor and CP seem to be very well preserved

Why something else than Higgs out there

(almost) Unshakable Arguments

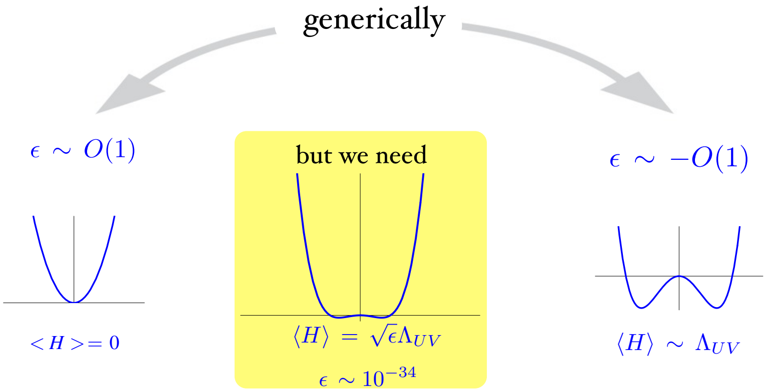
1. Observed `neutrino masses` imply new physics (at least, right-handed neutrinos) somewhere between 1 keV and 10^{15} GeV
2. Existence of `dark matter` requires new physics somewhere between sub-eV and 10^{19} GeV
3. Domination of `matter over anti-matter` requires new physics between 100 GeV and 10^{16} GeV

unfortunately, none of above guarantees new physics showing up in LHC

Some Esthetic Arguments

- `Fermion masses and mixings` suggests another sector generating the observed structures, at any scale above TeV and Planck
- Approximate `unification of gauge couplings` suggests new states at any scale between 100 and 10^{14} GeV
- `Instability of Higgs mass` against radiative corrections suggests new states at 100 GeV

only one, somewhat shaky argument clearly points to new physics in LHC



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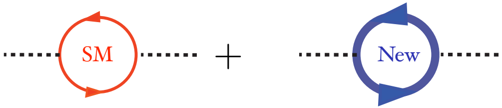
Fine-tuning puzzle

$\delta m_H^2 =$



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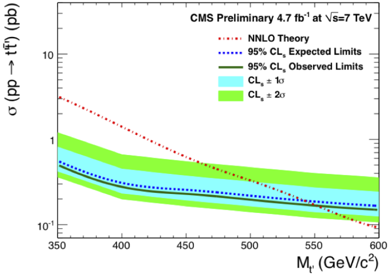
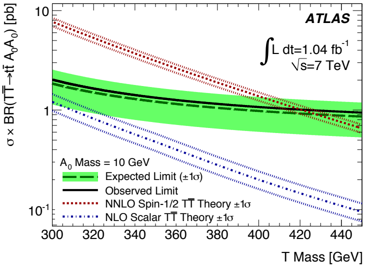
- Hierarchy problem dominated model building for last 30 years
- Two important classes of solutions
  - Supersymmetry: fermion-boson cancellation, may be weakly coupled up to Planck scale
  - Composite/Little Higgs: boson-boson or fermion-fermion cancellation, weakly coupled up to 3-10 TeV, then strongly coupled
- All existing models introduce a multitude of new particles at weak scale, and require serious conspiracy why they preserve approximate accidental symmetries of the SM, to avoid showing up indirectly in numerous precision measurements
- Typically, in specific realizations advertised as natural one has $1 - 0.1\%$ fine-tuning, after experimental constraints are taken into account

Fermionic top partners T

- Limits depending on dominant decay
- Constraints on $T \to bW$ channel (typically 50% branching ratio in models without T-parity) and on $T \to t$+MET (expected in models with T-parity)
- Current limits on mass around 400 − 500 GeV
- Naturalness under stress, but not completely dead yet...

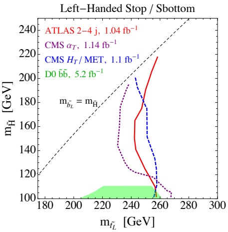


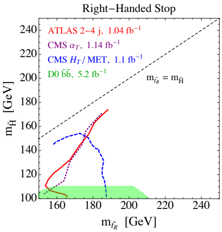


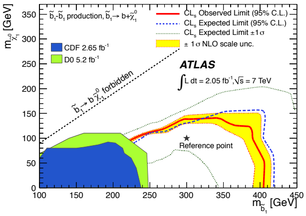
Naturalness with scalar partners

Scalar top partners $\tilde{t}$

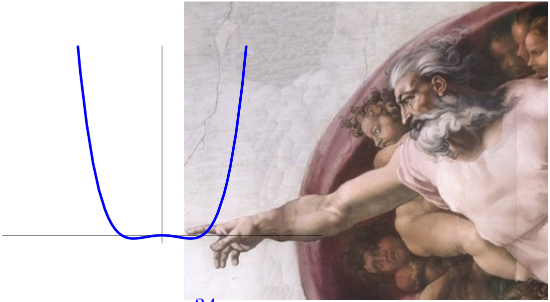
- In generic SUSY $m_{\tilde{t}} \gtrsim 1$ TeV $\rightarrow$ serious fine-tuning problem
- But, for $m_{\tilde{t}} \ll m_{\tilde{q}}$ and $m_{\tilde{t}} \ll m_{\tilde{g}}$ limits become much weaker
- Currently only theorist-level robust limit on stops, $m_{\tilde{t}} \gtrsim 150 - 250$ GeV, depending on decay mode and LSP mass Papucci et al [1110.6926]
- Related limits on direct sbottom production from ATLAS [1112.3832]
- Reasonanble fine-tuning still possible if stops and sbottom are only colored superpartner below TeV







- Naturalness window still half open
- But no experimental hint of a larger framework just around the corner
- Alternative solution:



$\epsilon \sim 10^{-34}$

stolen from V. Rychkov

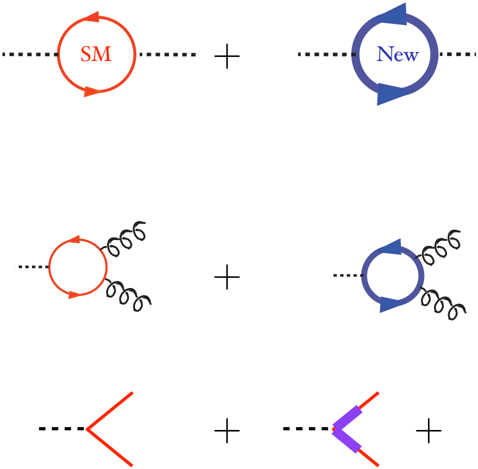
Dominant attitude in theory:

- Hierarchy problem may or may not be relevant
- Model building now dominated by LHC data, not theory prejudice


IT'S THE
data
STUPID!


IT'S THE
Higgs
STUPID!

Hierarchy problem and Higgs physics



stolen from R. Rattazzi

- The SM Higgs with mass $m_h \sim 125$ GeV has many decay channels that are potentially observable at the LHC
  - Now: $H \to ZZ^*$ and $H \to \gamma\gamma$
  - Shortly: $H \to WW^*$
  - Longer perspective: $H \to \tau^+\tau^-$, $H \to b\bar{b}$
- Also different production channels can be isolated
  - Now: gluon fusion
  - Shortly: vector boson fusion
  - Longer Perspective: W/Z and $t\bar{t}$ associated production and
- Rich Higgs physics available in near future
- If new physics exists, Higgs interactions likely to be modified
- If new physics restores naturalness, Higgs interactions are necessarily modified
- Measuring Higgs rates at the LHC may be the shortest route to new physics!

Higgs effective theory

Define effective Higgs Lagrangian at $\mu \approx m_h \sim 125 GeV$. Couplings relevant for current LHC data

$$\begin{aligned}\mathcal{L}_{eff} \quad = \quad & c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b \\ & + c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu}\end{aligned} \tag{1}$$

- Only one theoretical prejudice: custodial isospin requires same Higgs coupling to W and Z
- Top already integrated out, contributing to c_g and c_γ
- SM predicts $c_V = c_b = c_g = 1$ and $c_\gamma = 2/9$
- Any of the couplings can be modified in specific scenarios beyond the SM
- All LHC Higgs rates can be easily expressed as functions of the c_i couplings

Higgs Widths

The decay widths of the Higgs relative to the SM predictions are modified approximately as,

$$\begin{aligned}
\frac{\Gamma(h\to b\bar{b})}{\Gamma_{SM}(h\to b\bar{b})} &\simeq |c_b|^2 \\
\frac{\Gamma(h\to WW^*)}{\Gamma_{SM}(h\to WW^*)} = \frac{\Gamma(h\to ZZ^*)}{\Gamma_{SM}(h\to ZZ^*)} &\simeq |c_V|^2 \\
\frac{\Gamma(h\to gg)}{\Gamma_{SM}(h\to gg)} &\simeq |c_g|^2 \\
\frac{\Gamma(h\to \gamma\gamma)}{\Gamma_{SM}(h\to \gamma\gamma)} &\simeq \left|\frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM}}\right|^2
\end{aligned} \tag{2}$$

where, taking into account W loop and assuming $m_h \approx 125$, $\hat{c}_\gamma \approx c_\gamma - c_V$, and $\hat{c}_{\gamma,SM} \approx -0.8$

Assuming $H \to bb$ dominates Higgs widths

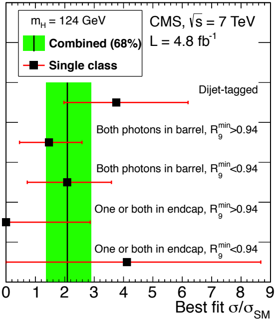
$$R_V \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_b}\right|^2, \tag{3}$$

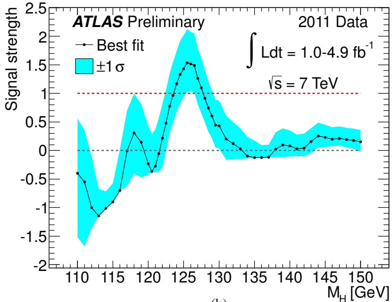
$$R_\gamma \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_g \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b}\right|^2, \tag{4}$$

$$R_{\gamma,VBF} \equiv \frac{\sigma(pp \to hjj)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to hjj)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_V \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b}\right|^2. \tag{5}$$

LHC Higgs data

- Several channels updated to 5 fb-1 in ATLAS and CMS
- Currently most information can be extracted from inclusive $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ channels

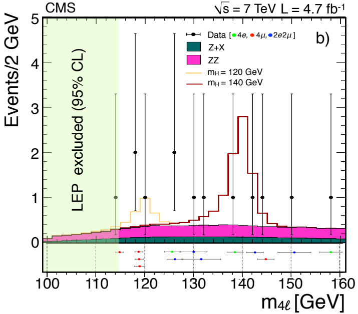


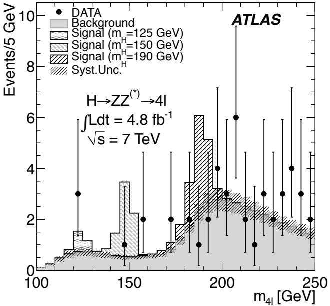


(b)

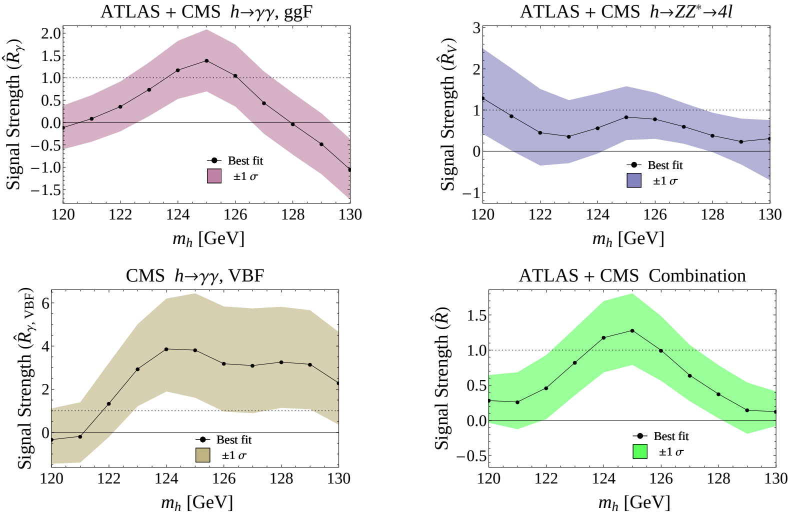
- Both ATLAS and CMS observe an excess near $m_h \sim 125$ GeV, ATLAS centered at 126 and CMS centered at 124
- In both case the best fit cross section at the peak exceeds the SM value, though the latter is well within uncertainties
- CMS also observes an excess in inclusive $\gamma\gamma jj$ channel dominated by VBF production mode, corresponding to cross section well exceeding the SM one (though, again, uncertainties are still large)

$H \rightarrow ZZ^* \rightarrow 4l$





- Very low background
- ATLAS has 3 events at $m_{4l} \approx 124$ GeV
- CMS has 2 events at $m_{4l} \approx 126$ GeV



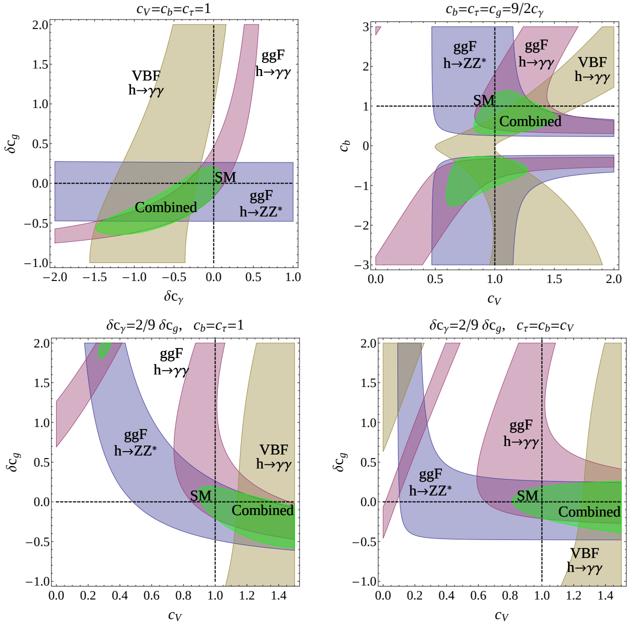
Bands are 1 sigma

Effective Theory Interpretation

$$
\begin{aligned}
\mathcal{L}_{eff} \quad = \quad & c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b \\
& + c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu}
\end{aligned}
$$

- We will find the region of effective theory parameter space favored by 2011 LHC 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 couplimgs (some of you don't even think Higgs has been discovered)
- Consider it a warm-up exercise, in preparation for serious signals

Fits assuming $m_h = 125$ GeV



Carmi [1202.3144] See also Azatov [1202.3415] and Espinosa [1202.3697]

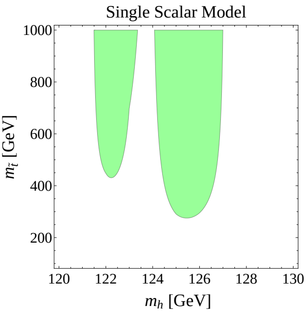
Scalar partner toy model

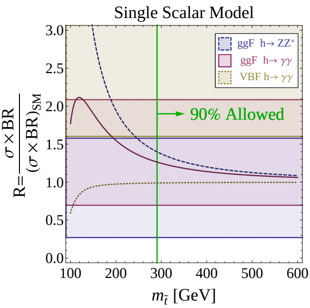
- Very toy "natural" model: just one scalar top partner (this is not SUSY, where at least two scalar partners are needed)
- Top partner interactions with Higgs to cancel top quadratic divergences

$$-\left(yHQt^c + \mathrm{h.c.}\right) - |\tilde{t}|^2\left(M^2 + 2y^2|H|^2\right).$$

- Only one free parameter: top partner mass $m_{\tilde{t}}^2 = M^2 + y^2 v^2$
- New contributions to effective dimension 5 Higgs interactions

$$\frac{c_g}{c_{g,\mathrm{SM}}} = \frac{c_\gamma}{c_{\gamma,\mathrm{SM}}} \simeq 1 + \frac{m_t^2}{2m_{\tilde{t}}^2}$$





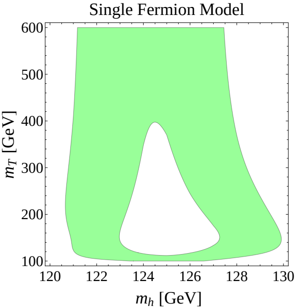
Fermion partner model

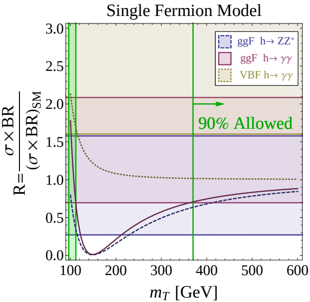
- For fermionic top partner, non-renormalizable interactions with Higgs needed to cancel top quadratic divergence
- Simple model inspired by T-parity conserving Little Higgs

$$-\left(y \sin(|H|/f) Q t^c + \mathrm{h.c.}\right) - y f \cos(|H|/f) T T^c$$

- Again only one free parameter: top partner mass $m_T = y f \cos(v/\sqrt{2} f)$
- New contributions to effective dimension 5 Higgs interactions

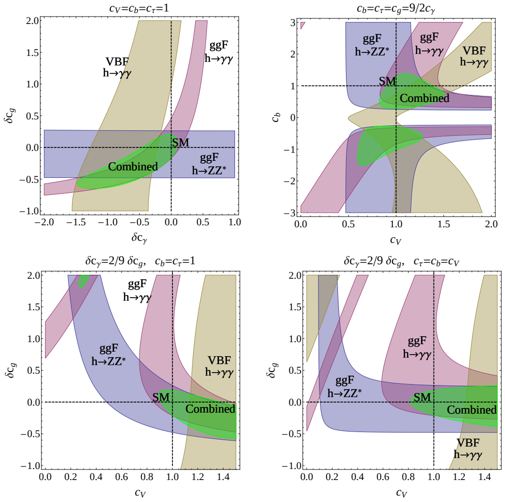
$$\frac{c_g}{c_{g,\mathrm{SM}}} = \frac{c_\gamma}{c_{\gamma,\mathrm{SM}}} \simeq 1 - \frac{m_t^2}{m_T^2} \, ,$$





- Beginning of a beautiful friendship
- More Higgs data from LHC may favor/disfavor particular BSM scenarios...
- ...or just confirm the SM again

One more thing...



- Current combined Higgs data allow, and VBF $\gamma\gamma$ channel in CMS favors increased Higgs coupling to *WW* and *ZZ*
- What if indeed $c_V > 1$?

What if $c_V > 1$?

- If SM Higgs doublet mixes with a singlet or another doublet, then always $c_V = \cos\alpha < 1$. Thus enhancement impossible in typical SUSY models.
- For Higgs being a pseudo-Goldstone boson of any compact coset (Little Higgs and composite Higgs), also $c_V = \cos(v/f) < 1$. Again, enhancement of c_V impossible
- Low et al [0907.5413] : sum rule proving $c_V > 1$ implies charge-2 Higgs
- AA et al [1202.1532] : stronger sum rule

$$1 - c_V^2 \approx \frac{v^2}{6\pi}\int_0^\infty \frac{ds}{s}\left(2\sigma_{I=0}^{\rm tot}(s) + 3\sigma_{I=1}^{\rm tot}(s) - 5\sigma_{I=2}^{\rm tot}(s)\right).$$

- For $c_V > 1$, enhancement of isospin 2 channel of WW scattering
- Simplest realization: a quintuplet of weakly coupled scalars $Q = \left(Q^{--}, Q^{-}, Q^{0}, Q^{+}, Q^{++}\right)$ coupled to electroweak gauge bosons as

$$\left\{\sqrt{\frac{2}{3}}Q^0\left(m_W^2 W_\mu^+ W_\mu^- - m_Z^2 Z_\mu^2\right) + \left(Q^{++} m_W^2 W_\mu^- W_\mu^- + \sqrt{2}Q^+ m_W m_Z W_\mu^- Z_\mu + \mathrm{h.c.}\right)\right\}$$

Summary

- The puzzle of electroweak symmetry breaking is about to be solved
- Hints from the LHC and other experiments consistently point to weakly coupled electroweak symmetry breaking with a light Higgs boson
- Measuring Higgs coupling may soon give us strong hints favoring or disfavoring particular models beyond the Standard Model
- At least *this year* is going to be exciting...