EFFECTIVE FIELD THEORY AND THE HIGGS

Jamison Galloway

Aspen Center for Physics
January 2014

CCPP
CENTER FOR COSMOLOGY AND PARTICLE PHYSICS

NEW YORK UNIVERSITY

Loosely based on ongoing work with

M. Luty, A. Martin

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[past, present, future]

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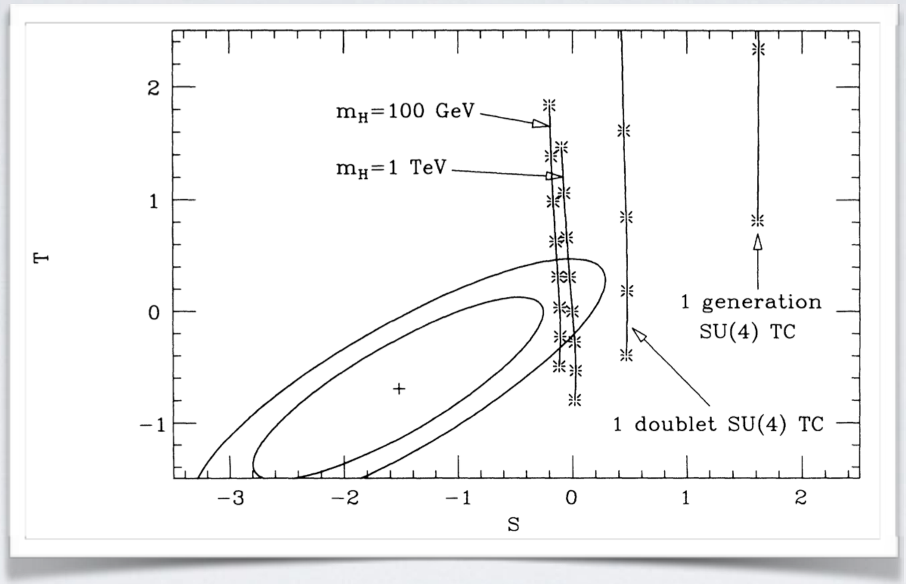
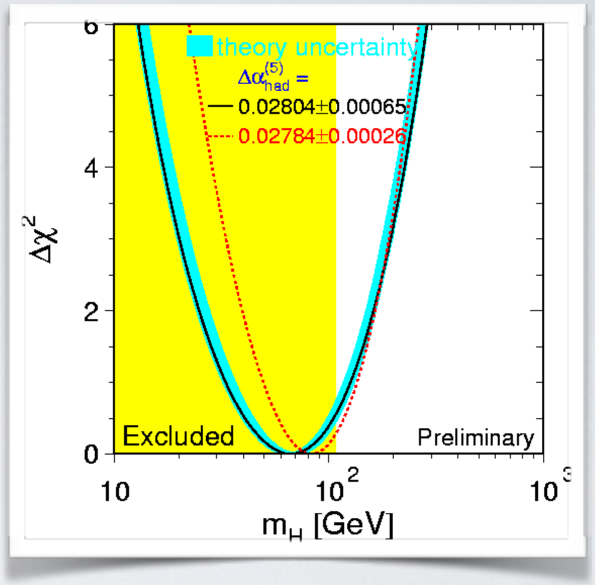
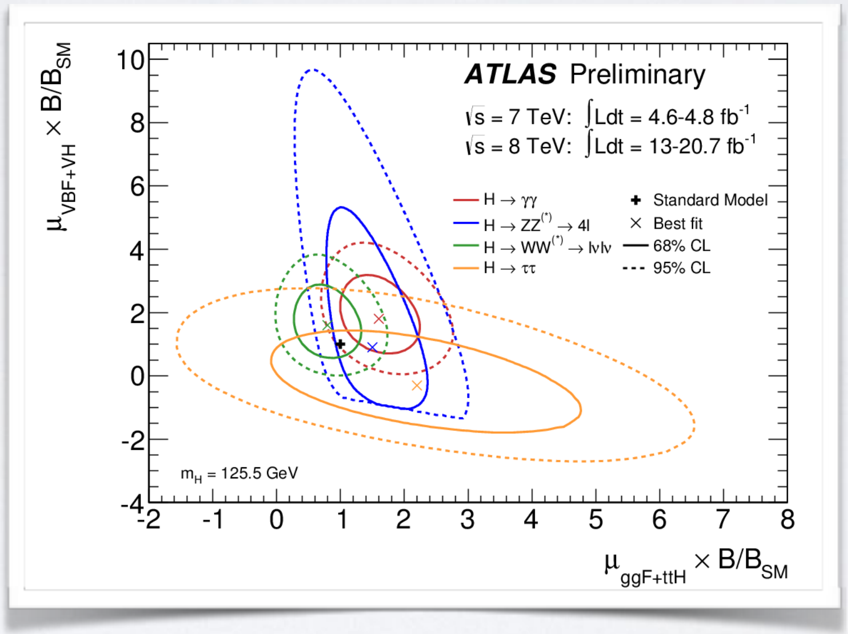
OUTLINE

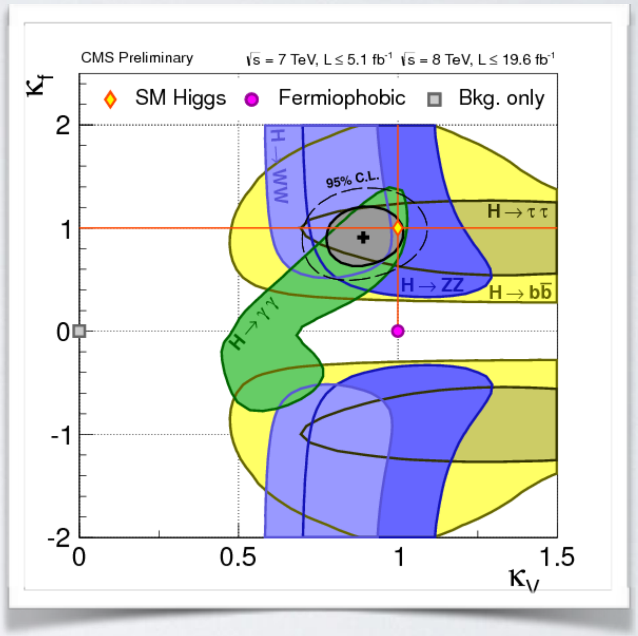
1. PAST





2. PRESENT





3. FUTURE

? ? ?
(preliminary)

[Some simple moral lessons arise in each era]

THEME

Ask not what you can do for your EFT,
ask what your EFT can do for you!

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Ask not what you can do for your EFT,
ask what your EFT can do for you!

AFTER ALL…

- o Daunting param' space
- o There's some art to this science;
- o Assumptions in *L* dictate interpretation;
- o A seemingly general Lagrangian might not be;

(illustrations to come)

THE HIGGS PROGRAM

Question for the next years, decades:

Is this newly observed particle part of a doublet with the three Goldstones, all sitting on top of a 246 GeV VEV?

Where might EFT enter?

- Measurements at the LHC can be framed in an effective language; nonstandard behavior can point the way to new scales of interest

- Given the input to an effective theory, EFT allows to probe and constrain new physics indirectly…
… and can help to see where deviations might be sought <u>in the first place</u>

THE HIGGS PROGRAM

Question for the next years, decades:

Is this newly observed particle part of a doublet with the three Goldstones, all sitting on top of a 246 GeV VEV?

To highlight (with sparse detail) in the realm of Higgs physics:

> EFT has a tremendous legacy to live up to (part 1)

> Its scope has broadened immensely since 2011/2012 (part 2)

> Caveats to the 'conventional' schemes that can afford interesting pheno insights and model-building opportunities (part 3)

1. PAST

[pre*Higgs*tory]

PAST

[prior to accessing 125 GeV]

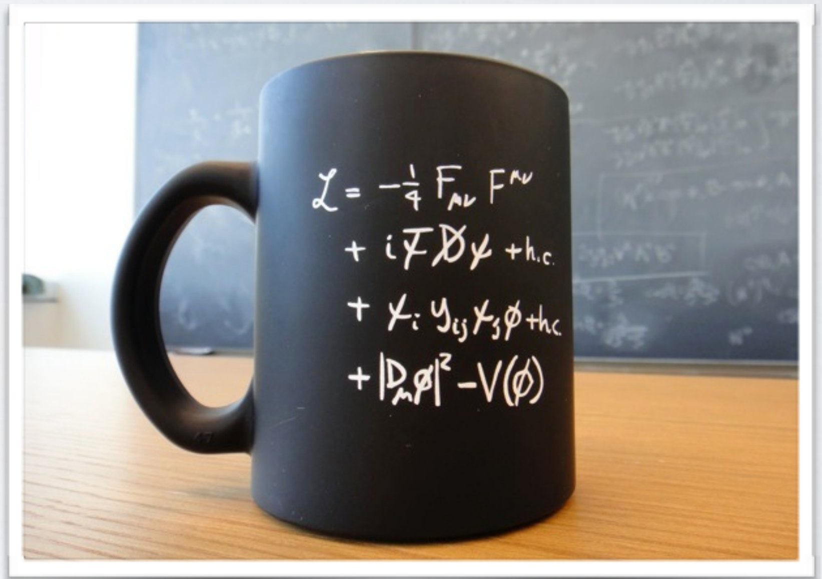
General hypotheses to test:

a. “Parsimony rules.”
- William of Ockham

b. “So does linearly realized local symmetry.”
- Glashow, Weinberg, Salam, …

---

a+b
$$\begin{cases} \mathcal{L} = c_i O_i(W_\alpha^{\mu\nu}, \psi_\beta; H \supset \{h, G\}) \\ H = \square_{1/2} \\ [O_i] \leq 4 \end{cases}$$



(so far so good)

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[prior to accessing 125 GeV]

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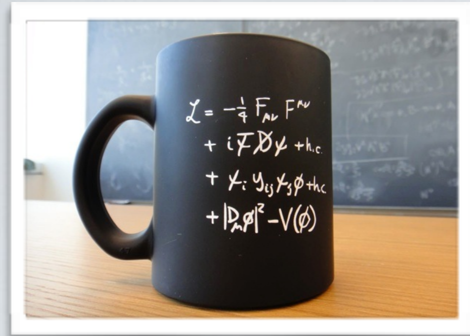
a. "Parsimony rules."
- William of Ockham

b. "So does linearly realized local symmetry."
- Glashow, Weinberg, Salam, …

~~a~~ + **b**

$$\begin{cases} \mathcal{L} = c_i O_i(W_\alpha^{\mu\nu}, \psi_\beta; H \supset \{h, G\}) \\ H = \square_{1/2} \\ [O_i] \not\leq 4 \quad [O_i] \leq 6 \end{cases}$$



$$+ \quad \begin{aligned}\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\ & + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\ & + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\ & + \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu} \\ & + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,\end{aligned}$$

$$+ \quad \begin{aligned}\Delta\mathcal{L}_{F_1} = {} & \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\ & + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\ & + \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\ & + \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\ & + \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right),\end{aligned}$$

$$+ \quad \begin{aligned}\Delta\mathcal{L}_{F_2} = {} & \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c \sigma^{\mu\nu} u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c \sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\ & + \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H \sigma^{\mu\nu} d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H \sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\ & + \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H \sigma^{\mu\nu} l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\,W^i_{\mu\nu} + h.c.\end{aligned}$$

+ (22+5+6 others)

- (2 redundancies)

→ **59 new parameters**

(reviewed/updated/constrained in 1303.3876)

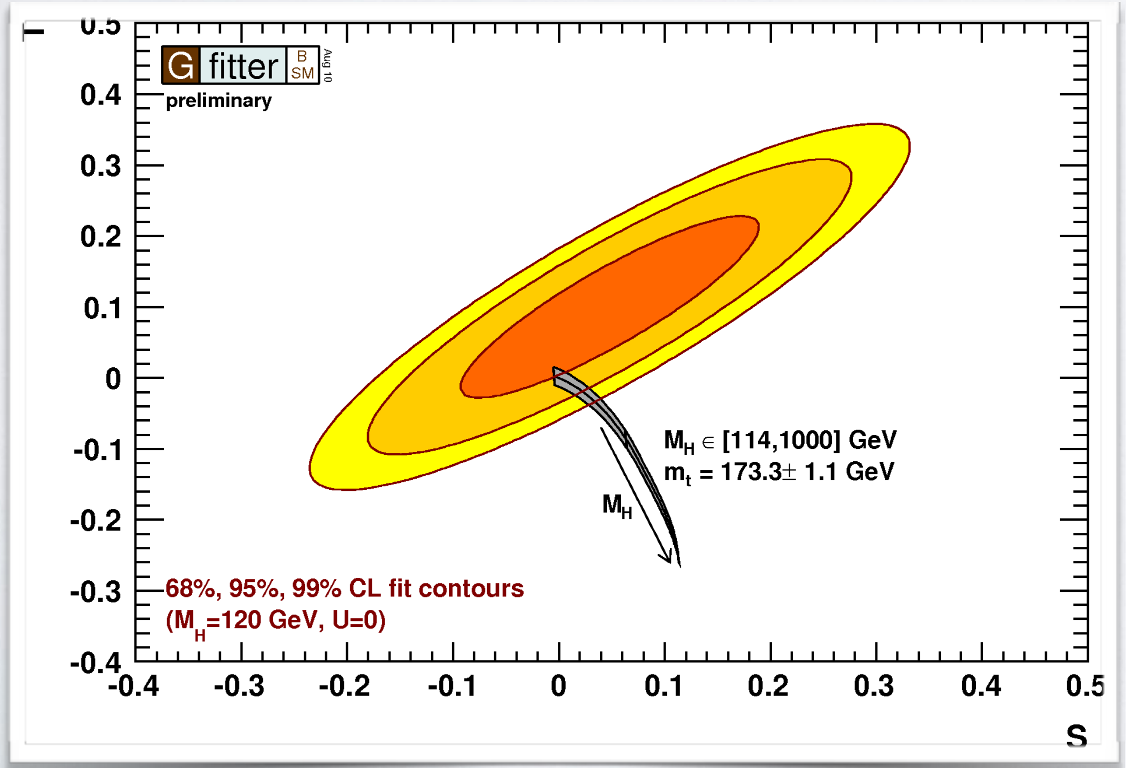
What can (did) this effective field theory do for us?

PAST

Physics at LEP: loads of Z bosons, a conspicuous absence of Higgses

- learn about H only through its VEV, as it (observably) affects gauge fields in dim 6 operators
- reduction of 59 general parameters to just TWO

$$(H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu} \qquad \left| H^\dagger D_\mu H \right|^2$$



$$m_h \ll \text{TeV}$$

in fact lighter than the top, assuming small threshold contributions

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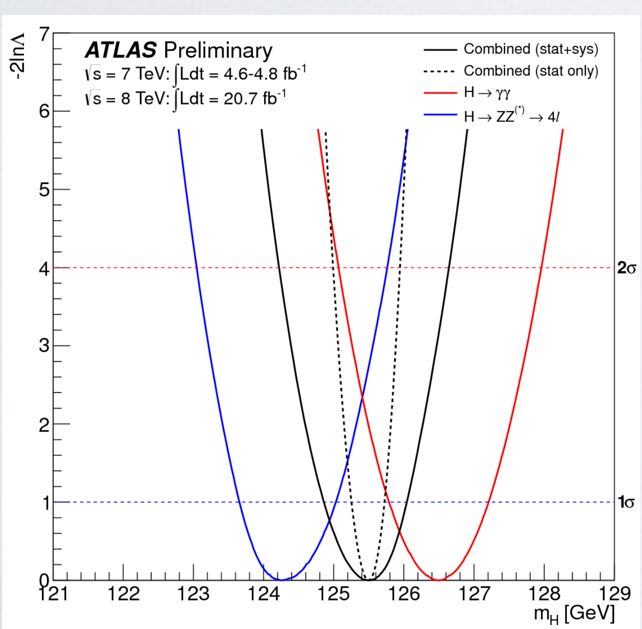

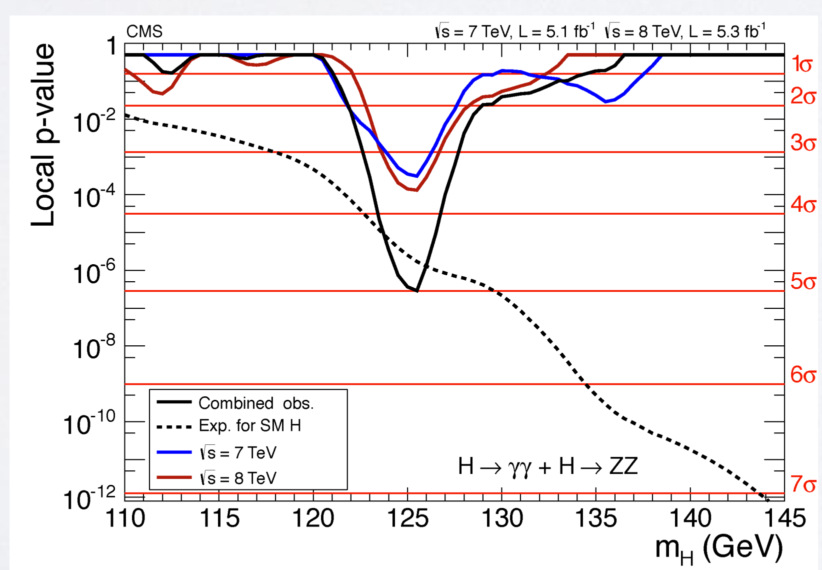

$$m_h \simeq 125.5\,\mathrm{GeV}$$

(so far so good)

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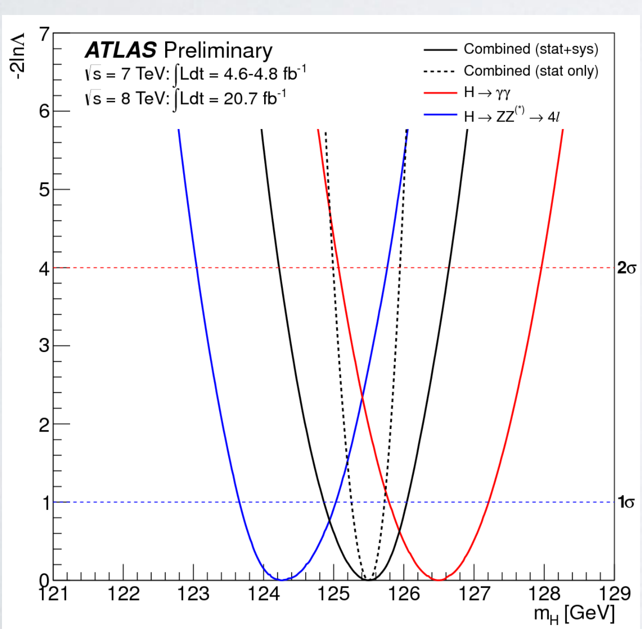
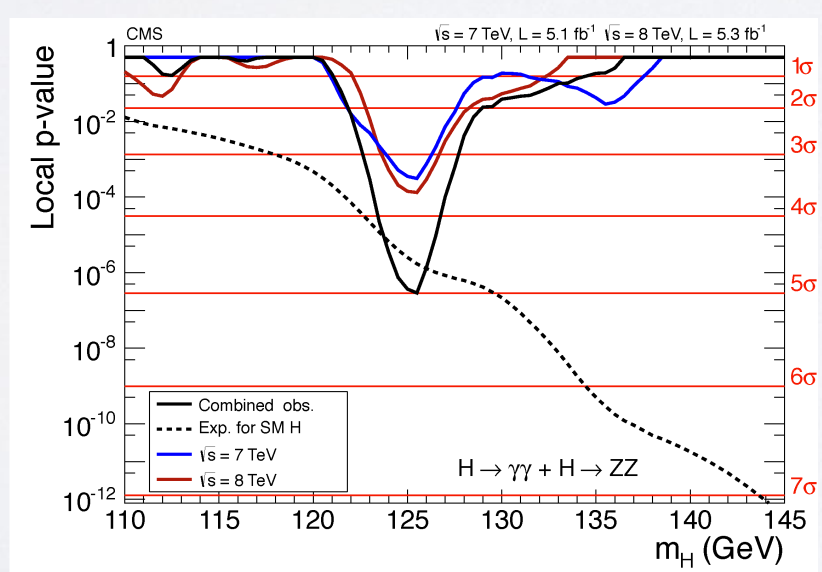




$$m_h \simeq 125.5\,\mathrm{GeV}$$

Even a general EFT can succeed in prediction, provided some forethought

2. PRESENT

[Probing excitations of H = the return of several dim 6 operators;
any plausible highly non-SM couplings governing our Higgs today?]

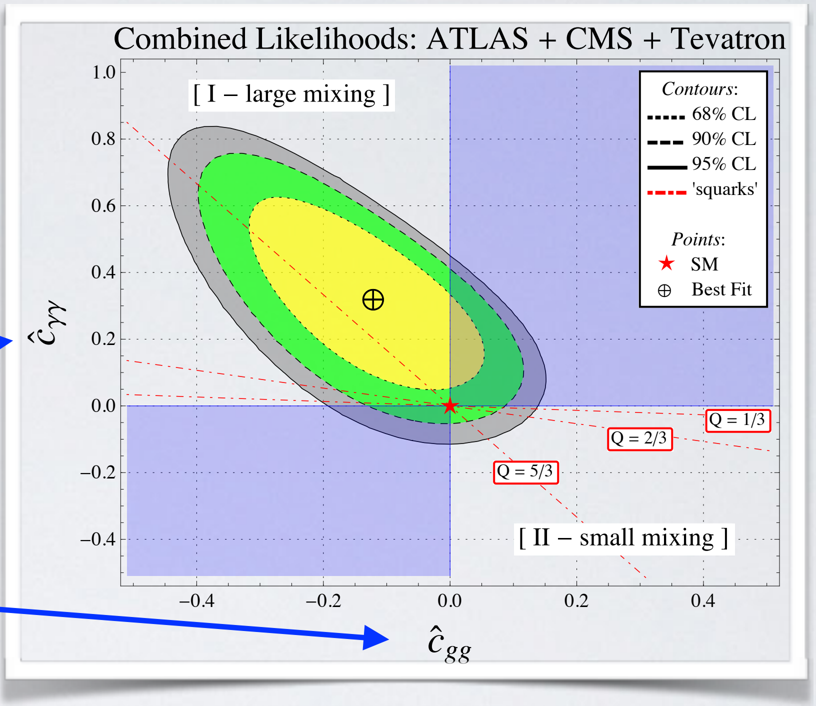
PRESENT

[case study: loop-mediated composite Higgs processes]

Early LHC hints of deviations via new operators…

$$H^\dagger H (B_{\mu\nu})^2$$

$$H^\dagger H (G^a_{\mu\nu})^2$$



(2012)

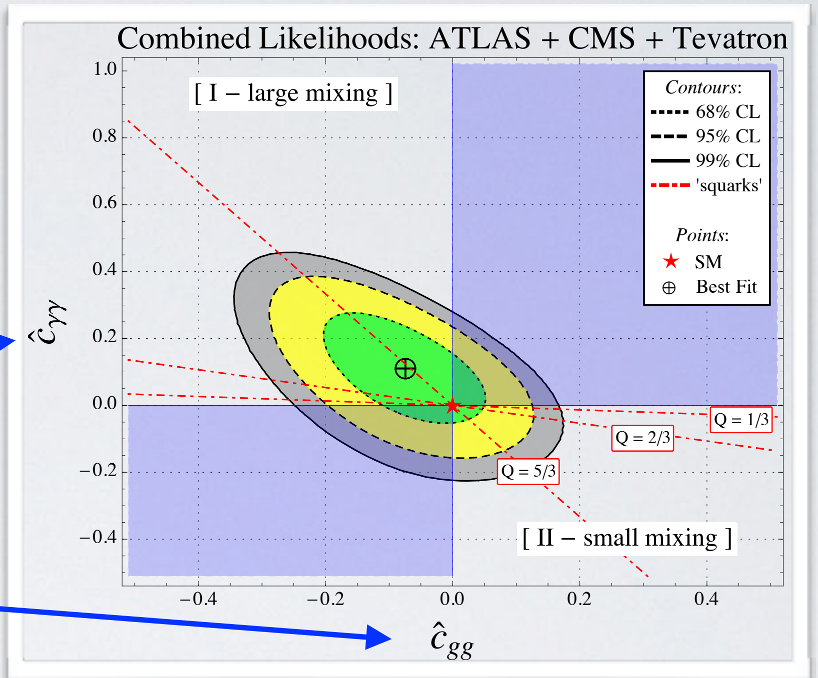
PRESENT

[case study: loop-mediated composite Higgs processes]

… may have been red herrings (??)

$$H^\dagger H (B_{\mu\nu})^2$$

$$H^\dagger H (G^a_{\mu\nu})^2$$



(2013)

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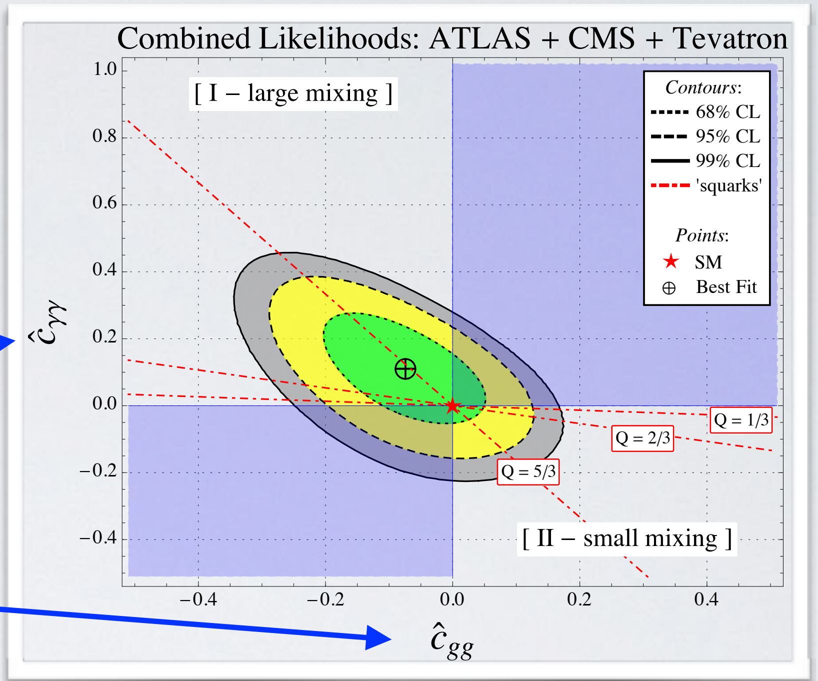


(2013)

Again we should apply some forethought:

o A light composite Higgs (SILH) needs sufficient protection via a shift symmetry

o Both operators up there are in clear violation of that

o Contribution from heavy partners <u>vanishes</u> in minimal setups

o Instead: are there cases that respect this symmetry?

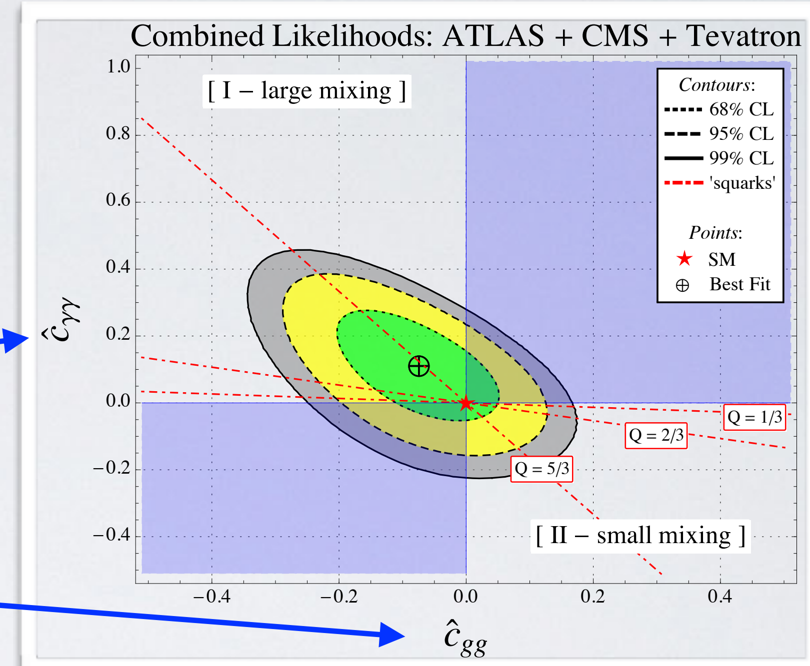
PRESENT

[case study: loop-mediated composite Higgs processes]

… may have been red herrings (??)

$H^\dagger H (B_{\mu\nu})^2$

$H^\dagger H (G^a_{\mu\nu})^2$



(2013)

Which are the cases that respect the symmetry?

[i.e. w/ excitation of H derivatively coupled]

Two such operators, combining to contribute to Higgs decay to Z + photon:

$$\mathcal{A}_{h\to Z\gamma} \propto \bar{c}_{HW} - \bar{c}_{HB}$$

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = &\frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
&+ \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
&+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
&+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger\sigma^i\left(D^\nu H\right)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right)B_{\mu\nu} \\
&+ \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}$$

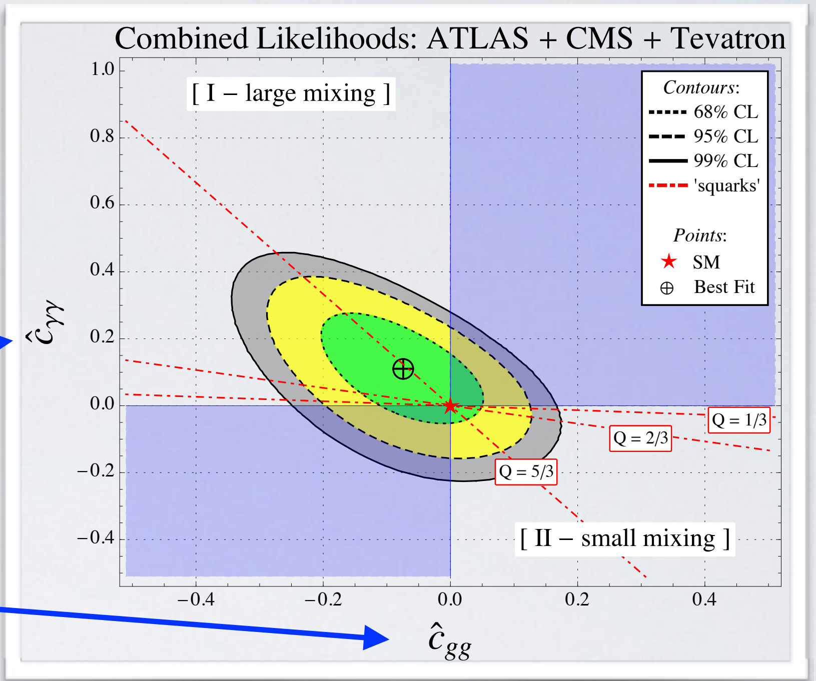
PRESENT

[case study: loop-mediated composite Higgs processes]

… may have been red herrings (??)

$$H^\dagger H (B_{\mu\nu})^2$$

$$H^\dagger H (G^a_{\mu\nu})^2$$



(2013)

Goldstone preserving

vs.

Goldstone violating operators:

$$\frac{\delta\Gamma}{\Gamma} \overset{G}{\sim} \frac{m_W^2}{M^2}\frac{g_*^2}{g^2} \sim \frac{v^2}{f^2} \longleftarrow Z\text{+photon}$$

$$\frac{\delta\Gamma}{\Gamma} \overset{\not G}{\sim} \frac{m_W^2}{M^2}\frac{g_*^2}{g^2} \times \boxed{\frac{g_{\not G}^2}{g_*^2}} \sim \boxed{\frac{1}{16\pi^2}}\frac{v^2}{f^2} \longleftarrow \text{2 gluons, 2 photons}$$

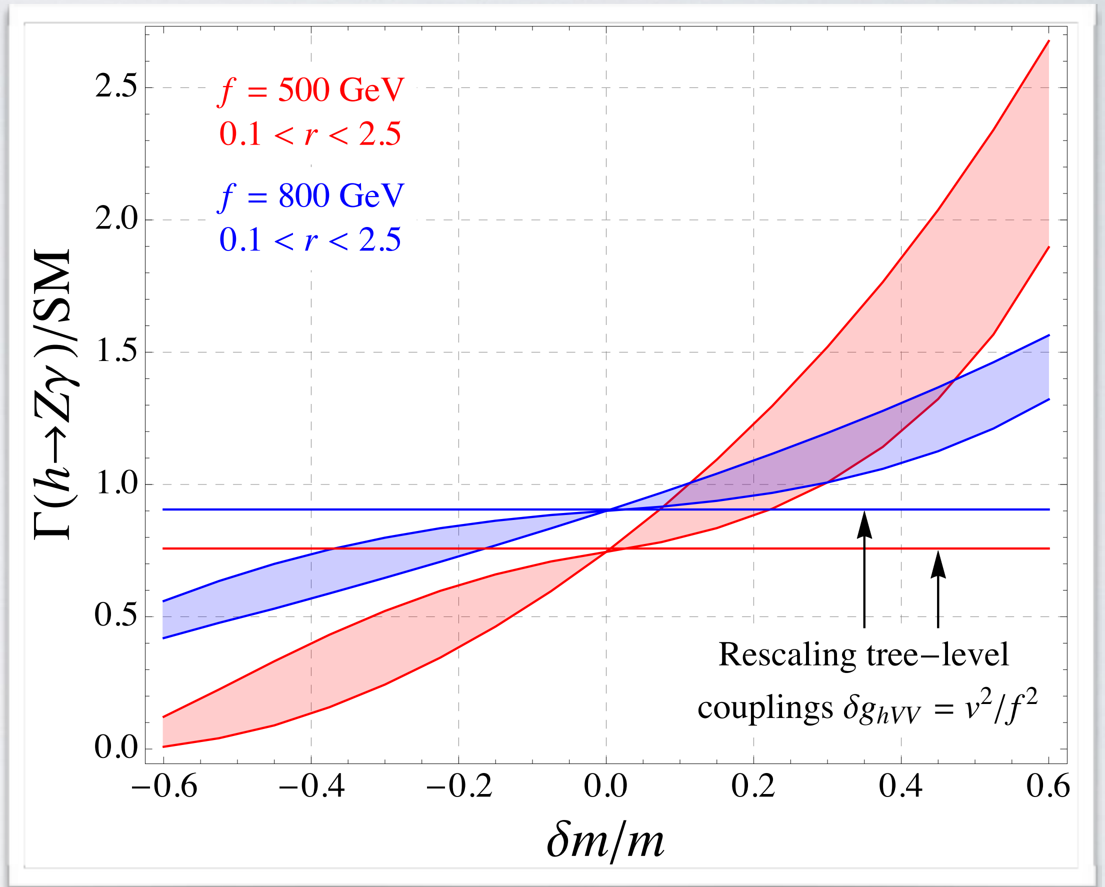
PRESENT

[case study: loop-mediated composite Higgs processes]

Projections from a realistic model

[PNGB Higgs from SO(5)/SO(4);
fermionic partner states in the 10;
10's masses split to softly break LR]

Order one deviations in this decay;
SMALL deviations in other loops



partner fermions in the > 2 TeV range; effect can persist even when direct detection is out of reach @ LHC.
EFT (+ forethought) points out promising directions

3. FUTURE

[What if everything in the near term is SMish –
Does this general theory allow for a still non-SM Higgs somehow?]

FUTURE

[case study: Higgs self-interaction with multi-Higgses]

A basic assumption of the SILH-like approach:
H carries all light scalars of the theory*.
Self-interactions modified by $(H^\dagger H)^3,\ (\partial_\mu (H^\dagger H))^2$:

*No good for multi-Higgs models!
Mass basis and Higgs basis differ by $\delta = \frac{\pi}{2} - (\beta - \alpha)$.

{ Goldstones live in more than one doublet. So?

FUTURE

[case study: Higgs self-interaction with multi-Higgses]

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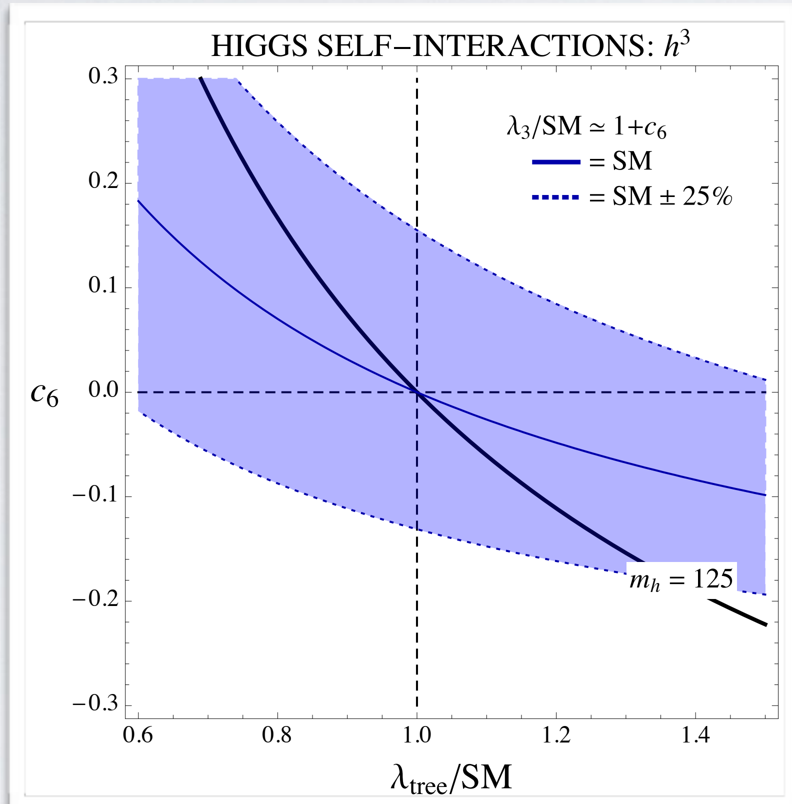

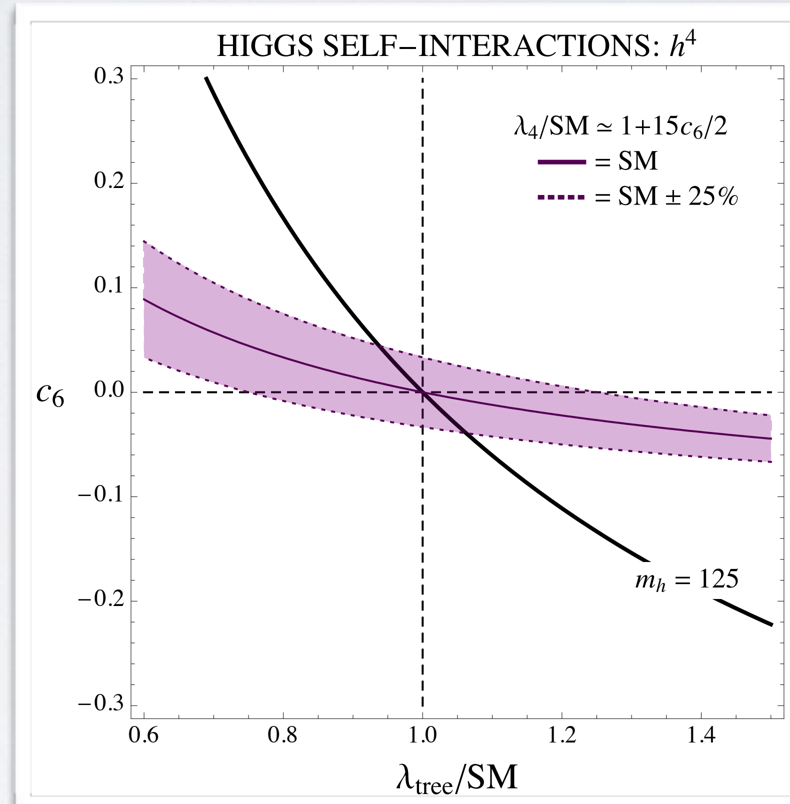

Observably small cubic in SILH is highly nongeneric;
hVV and hff ~ SM *does* paint us into a corner

---

*No good for multi-Higgs models!
Mass basis and Higgs basis differ by $\delta = \frac{\pi}{2} - (\beta - \alpha)$.

Goldstones live in more than one doublet

FUTURE

[case study: Higgs self-interaction with multi-Higgses]

What we 'know':

h*VV* coupling > 0.9 x SM ~> VEV > 220 GeV

This could leave > 100 GeV to account for…

FUTURE

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---

to consider { Two Higgs doublets, H & Σ, with a hierarchy of couplings:

$$V = \mu_H^2 H^\dagger H - \mu_\Sigma^2 \Sigma^\dagger \Sigma + \kappa\mu(H^\dagger\Sigma + \text{h.c.}) + \lambda(\Sigma^\dagger\Sigma)^2$$

Supposing $\langle\Sigma\rangle = f$ and $\lambda f^2 \gg m_h$, the heavy field can be integrated out

$\Rightarrow$ $\Delta V(h) \sim \kappa\mu f \times h(x)$

(no SILH counterpart;
additional EWSB spurion required)

FUTURE

[case study: Higgs self-interaction with multi-Higgses]

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Supposing $\langle \Sigma \rangle = f$ and $\lambda f^2 \gg m_h$, the heavy field can be integrated out

→ $\Delta V(h) \sim \kappa\mu f \times h(x)$ (no SILH counterpart; additional EWSB spurion required)

→ VEV for h generated w/o Mexican hat;
effective linear term displaces minimum

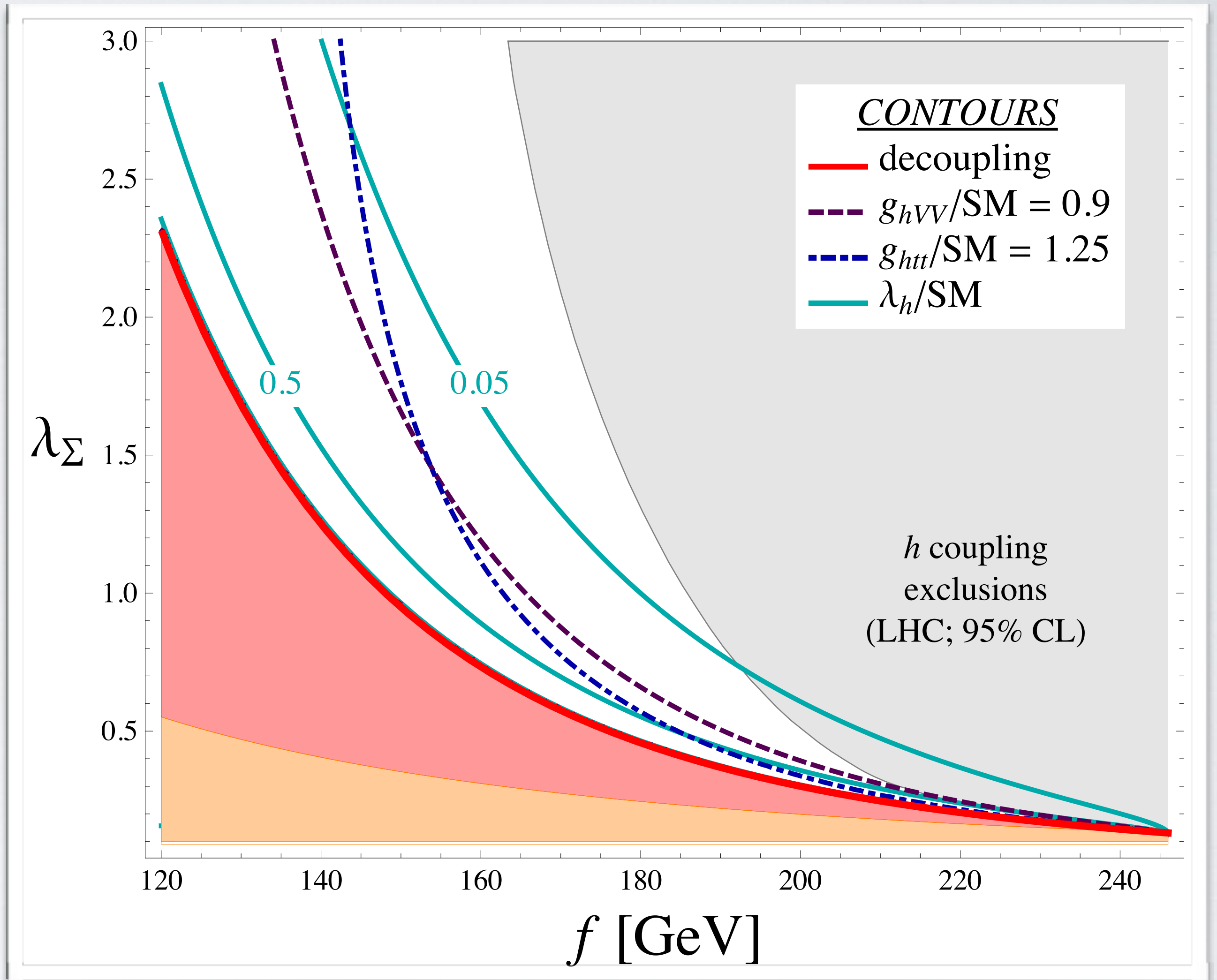
FUTURE

[case study: Higgs self-interaction with multi-Higgses]

$$V = \mu_H^2 H^\dagger H - \mu_\Sigma^2 \Sigma^\dagger \Sigma + \kappa\mu(H^\dagger\Sigma + \text{h.c.}) + \lambda(\Sigma^\dagger\Sigma)^2$$

Fixing Higgs and W mass leaves simple 2D space…

… allowing highly suppressed quartic (and cubic), even for highly SM-like couplings to other SM fields



SILH-type thinking *can* parametrize many effects in 2HDM, NOT ALL
Relaxing SILH's assumptions buys wiggle room in pheno and modeling

RECAP

o EFT in pre-Higgs days provided framework for testing SM; bolstered anticipation of a light Higgs with low energy data **(e.g. S&T parameters)**

o General effective description of today's Higgs requires many new terms; gross characteristics of model classes limit scope and EFT proves useful still **(e.g. PNGB Higgs, $h \to Z + \gamma$)**

o Perturbations from SM-ness can be implemented more generally than is accomplished with only higher dimension operators of H; anticipating/interpreting novel phenomenology and model building opportunities may require exploring consequences of subtle caveats **(e.g. elementary Higgs quartic in presence of other EWSB spurion)**