Beyond the Standard Model Effective Field Theory: The Singlet Extended Standard Model

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S. Adhikari, **I.M. Lewis**, M. Sullivan, Physical Review D (2021) 075027

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Approaches for Beyond the Standard Model Physics

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- Effective Field Theory:
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  - Write a power expansion in inverse powers of a heavy new physics scale Λ:

    $$\mathcal{L} = \mathcal{L}_{SM} + \sum_k \frac{c_{1,k}}{\Lambda} \mathcal{O}_{1,k} + \sum_k \frac{c_{2,k}}{\Lambda^2} \mathcal{O}_{2,k} + \cdots$$

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  - Any new high scale physics will induce these operators: the Standard Model Effective Field Theory is inevitable.

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    The operators consist of Standard Model fields and are invariant under Standard Model symmetries.
  - Any new high scale physics will induce these operators: the Standard Model Effective Field Theory is inevitable.
- Note: you can also classify according to topology. N. Craig, P. Draper, KC Kong, Y. Ng, D. Whiteson, arXiv:1610.09392; J.H. Kim, KC. Kong, B. Nachman, D. Whiteson JHEP 04 (2020) 030

Simplified Models

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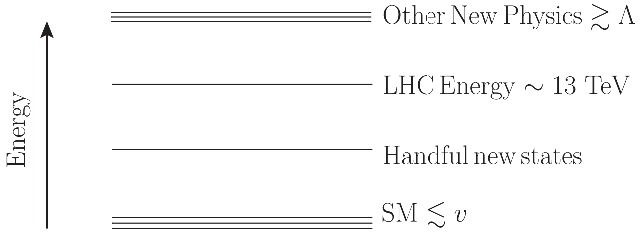


- As with Standard Model Effective Field Theory, the new physics beyond the LHC reach will inevitably manifest itself as an EFT:

$$\mathcal{L} = \mathcal{L}_{ren} + \sum_k \frac{c_{1,k}}{\Lambda} \mathcal{O}_{1,k} + \sum_k \frac{c_{2,k}}{\Lambda^2} \mathcal{O}_{2,k} + \cdots$$

  - Now $\mathcal{L}_{ren}$ is the renormalizable theory, and the operators $\mathcal{O}_{n,k}$ consist of the fields of and are invariant under the symmetries of the simplified model.
- The goal: use EFT methods to test the assumptions of the simplified models:
  - Can the effects of heavy new physics be ignored?

Case Study: Scalar Singlet EFT

- First, review the renormalizable model.
- Add a real gauge singlet, scalar singlet S to SM:

$$V(\Phi, S) = V_\Phi(\Phi) + V_{\Phi S}(\Phi, S) + V_S(S)$$

- Higgs potential:

$$V_\Phi(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- Scalar singlet potential:

$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

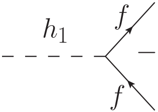
- Mixing terms:

$$V_{\Phi S}(\Phi, S) = \frac{a_1}{2} \Phi^\dagger \Phi S + \frac{a_2}{2} \Phi^\dagger \Phi S^2$$

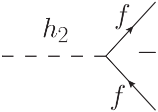
- After electroweak symmetry breaking, have two mass eigenstates:
  - h_1 with mass $m_1 = 125$ GeV.
  - h_2 with mass $m_2 > m_1$.
  - SM Higgs and singlet scalar mix with a mixing angle θ.

Relevant Feynman Diagrams

- Couplings to fermions:



$$-i\cos\theta\frac{m_f}{v}$$



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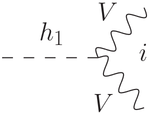
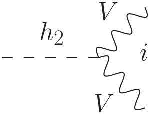
- Couplings to gauge bosons:



$$i\cos\theta\frac{2m_V^2}{v}g_{\mu\nu}$$



$$i\sin\theta\frac{2m_V^2}{v}g_{\mu\nu}$$

- All SM-like Higgs rates suppressed $\cos^2\theta$ relative to SM predictions.
- Since h_2 couplings to fermions and gauge bosons proportional to SM coupling, it is produced through same mechanisms as SM Higgs boson. Again, search predictions are relatively straight forward.

Interpretation of Fits

- Bound parameters by a χ^2 fit to Higgs signal strengths:

$$\mu_i^f = \frac{\sigma_i(pp \to h_1)}{\sigma_{i,\mathrm{SM}}(pp \to h_1)} \frac{\mathrm{BR}(h_1 \to f)}{\mathrm{BR}_{\mathrm{SM}}(h_1 \to f)}$$

- Without effective operators:

$$\sigma(pp \to h_1 + X) = \cos^2\theta\, \sigma_{\mathrm{SM}}(pp \to h_1 + X) \quad BR(h_1 \to XX) = \mathrm{BR}_{\mathrm{SM}}(h_1 \to XX)$$

- θ is the mixing angle between Scalar singlet and SM Higgs.
- Then signal strengths to all initial and final states are the same:

$$\mu_i^f = \cos^2\theta$$

- Hence, we have a simple interpretation at 95% CL:

$$|\sin\theta| < 0.24$$

- No longer true with effective operators. Different production and decay channels have different dependencies on the EFT, changing the interpretation of fits considerably Dawson, **Lewis** PRD95 (2017) 015004

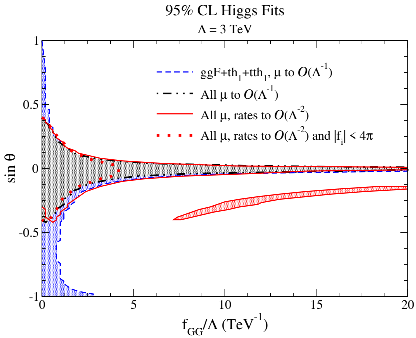
Adding EFT operators

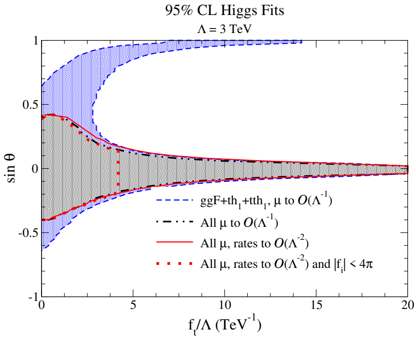
- What if we add non-renormalizable interactions to dimension-5?
  - Perturb the model and see how stable our conclusions are.

$$
\begin{aligned}
\mathcal{L} \quad = \quad & g_s^2 \frac{f_{GG}}{16\pi^2\Lambda} S G^{\mu\nu,a} G^a_{\mu\nu} + \frac{g'^2 c_{BB}}{16\pi^2\Lambda} S B^{\mu\nu} B_{\mu\nu} + \frac{g^2 c_{WW}}{16\pi^2\Lambda} S W^{\mu\nu,a} W^a_{\mu\nu}\,. \\
& - \left(\frac{\sqrt{2} m_t}{v} \frac{f_t}{\Lambda} S \overline{Q}_{3L} \widetilde{\Phi} t_R + \sum_{f=\tau,\mu,b} \frac{\sqrt{2} m_f}{v} \frac{f_f}{\Lambda} S \overline{F}_L \Phi f_R + \text{h.c} \right) \\
& - \left(\frac{a_3}{2\Lambda} \Phi^\dagger \Phi S^3 + \frac{a_4}{2\Lambda} (\Phi^\dagger \Phi)^2 S + \frac{b_5}{5\Lambda} S^5 \right)
\end{aligned}
$$

- After scalar mixing, these operators introduce new interactions between the gauge bosons and the Higgs.
- See also Baur, Butter, Gonzalez-Fraile, Plehn, Rauch PRD95 (2017) 055011 with dimension-6 terms, or Dawson, Lewis PRD95 (2017) 015004 for my previous work.

95% CL Fits to Higgs Data

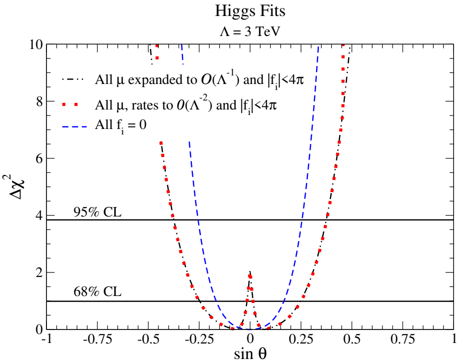




2-D Fits to f_{GG}, other parameters profiled over. 2-D Fits to f_t, other parameters profiled over.

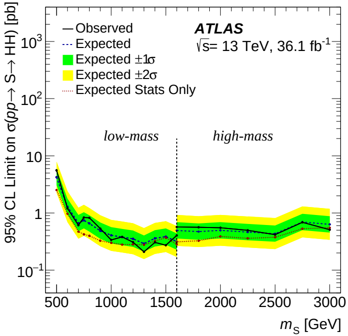
- Combination of all Higgs measurements from ATLAS and CMS.
- Renormalizable model corresponds to Wilson coefficients set to zero.
- Non-zero Wilson coefficients change bounds on scalar mixing angle.

1-D Fits: Comparing EFT to Renormalizable Model



- Combination of all Higgs measurements from ATLAS and CMS.
- Black and red: EFT
- Blue: Renormalizable model
- Clearly the EFT changes in interpretation of measurements and searches.
  - High scale new physics can have large impact on the simplified model.
- There are also direct searches for heavy scalar resonances that must be accounted for.

Detour: Combining Higgs Fits with Direct Search Limits



- What is usually done:

$$\text{Accept point if } \sigma \leq \sigma_{obs}, \quad \text{Reject point if } \sigma > \sigma_{obs}$$

  where σ_{obs} is the observed 95% CL upper limit.
- However, statistically, when combining many measurements you can have 2-sigma fluctuations, and this prescription does not allow for it.

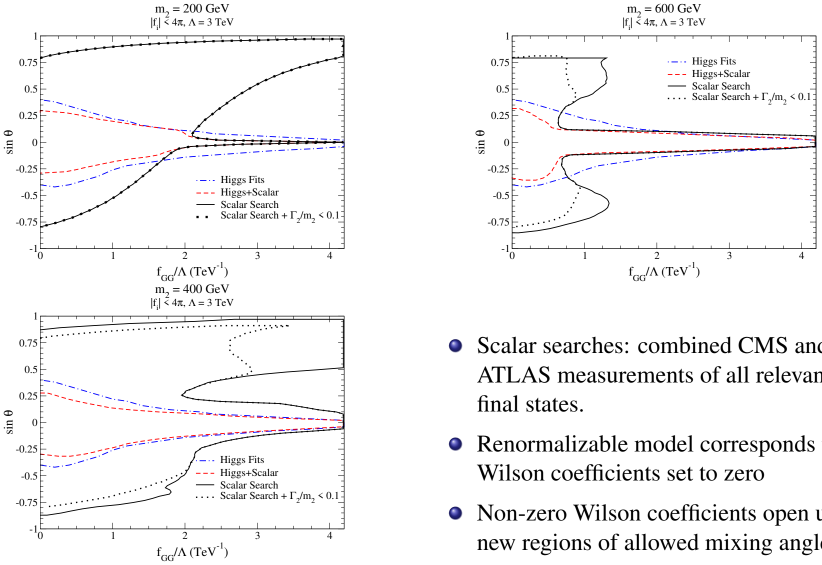
Detour: Combining Higgs Fits with Direct Search Limits

- We proposed a new way of incorporating bounds from Brazilian bands:
  - First, work in Gaussian limit and assume no large upper fluctuations.
  - Assuming all data is SM-like, then every search is a SM measurement.
  - Each measurement has a 95% uncertainty band.
  - The upper limit of these error bands is the 95% limit on how large an additional signal can be on top of the signal.
- Make a series of assumptions:
  - Assume data in good agreement with the Standard Model.
  - Assume Gaussianity.
  - We ignored interference between signal and background.
- Hence, the χ^2 for direct searches:

$$\chi^2 = \begin{cases} \frac{(\sigma_{sig}-\sigma_{obs}+\sigma_{exp})^2}{(\sigma_{exp}/1.96)^2} & \text{if } \sigma_{obs} \geq \sigma_{exp} \\ \frac{(\sigma_{sig})^2}{(\sigma_{obs}/1.96)^2} & \text{if } \sigma_{obs} < \sigma_{exp} \end{cases}$$

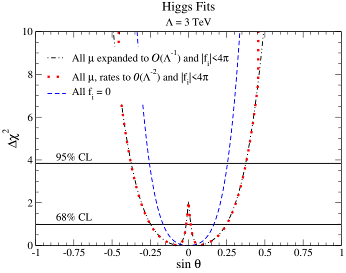
- σ_{sig}: signal cross section, σ_{obs}: observed upper limit, σ_{exp}: expected uper limit.
- Can check for one measurement and one degree of freedom the 95% CL gives $\sigma_{sig} < \sigma_{obs}$, consistent with usual approach.

Combined Higgs Fits and Direct Searches

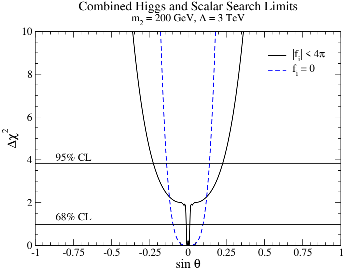


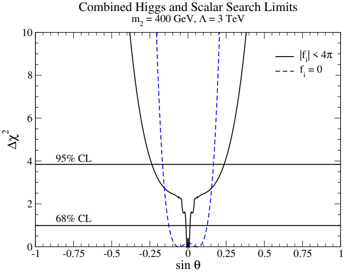
- Scalar searches: combined CMS and ATLAS measurements of all relevant final states.
- Renormalizable model corresponds to Wilson coefficients set to zero
- Non-zero Wilson coefficients open up new regions of allowed mixing angle

1-D Fits: Comparing EFT to Renormalizable Model



Higgs fits only.





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Conclusions

- The LHC has completed two very successful runs and the data analysis is under way.
- Still may expect to see new physics. Two interesting ways forward:
  - Simplified models: only a few new particles at LHC energies.
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  - Interpretation of Higgs physics is considerably changed, even with multi-TeV new physics.
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  - Could have complementary information.

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  - Could have complementary information.
- Another example of BSM EFT: top partner can couple to top and gluons/photons via a chromomagnetic and magnetic dipole operator:
  - Introduces new decay channels can open: $T \to t\gamma$ and $T \to tg$ Kim, **Lewis**, JHEP 05 (2018) 095; Alhazmi, Kim, Kong, **Lewis** JHEP 01 (2019) 139
  - New production modes: $gg \to Tt$ Kim, **Lewis**, JHEP 05 (2018) 095; also see Xing Wang's talk yesterday

Thank You

Comment on Counting

- First, review regular EFT counting with amplitude to dimension-6:
  - Amplitude has terms up to Λ^{-2}.
  - Amplitude squared includes terms that go as Λ^{-4}.:

$$|\mathcal{A}|^2 \sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2}|^2 \sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4}$$

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    - g_{SM} is a generic Standard Model coupling.
  - Same order as dimension-8 contributions:

$$\begin{aligned} |\mathcal{A}|^2 &\sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-8}}{\Lambda^4}|^2 \\ &\sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4} + g_{SM} \times \frac{c_{dim-8}}{\Lambda^4} + O(\Lambda^{-6}) \end{aligned}$$

  - Validity of keeping dimension-6 squared without dimension-8:
    - Strongly interacting theory: $c \gg g_{SM}$ so that $c_{dim-6}^2 \gg c_{dim-8} \times g_{SM}$.
    - Or the UV completion suppresses the dimension-8 terms.

Beyond the SM EFT Counting

- Consider production or decay of an h_1. Then to dimension-6 there are three contributions:
  - Renormalizable amplitude proportional to SM amplitude: $A_{ren} \sim \cos\theta A_{SM}$.
  - Dimension-5 amplitude from the new scalar: $A_{5,S}$
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- Contributions from new scalar suppressed by $\sin\theta$.
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- Full amplitude:

$$A_{h_1} \sim \cos\theta A_{SM} + \cos\theta \frac{A_{6,SM}}{\Lambda^2} + \sin\theta \left(\frac{A_{5,S}}{\Lambda} + \frac{A_{6,S}}{\Lambda^2} \right) + O(\Lambda^{-3})$$

- Amplitude squared:

$$\begin{aligned} |A_{h_1}|^2 \quad \sim \quad & \cos^2\theta |A_{SM}|^2 + \sin\theta\cos\theta \frac{A_{SM}A_{5,S}}{\Lambda} \\ & + \frac{1}{\Lambda^2}\left(\sin^2\theta |A_{5,S}|^2 + \sin\theta\cos\theta A_{SM}A_{6,S} + \cos^2\theta A_{SM}A_{6,SM} \right) + O(\Lambda^{-3}) \end{aligned}$$

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- Large mixing angle limit: $\sin\theta \to \pm 1$ and $\cos\theta \to 0$
  - The amplitude becomes:

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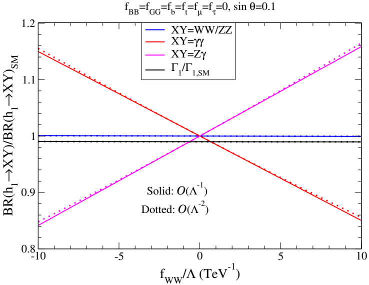
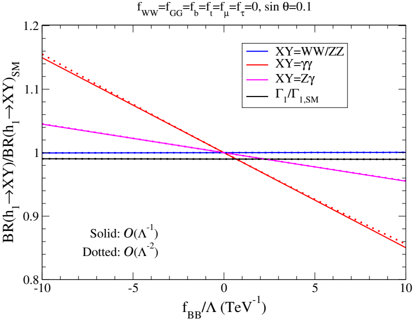
- Counting depends on the angle.
- For h_2 production $\sin\theta \leftrightarrow \cos\theta$ up to signs. The $|A_{5,S}|^2$ dominates at small angles.

Direct Contributions to Important Branching Ratios



Nonzero effective *W* coupling.



Nonzero effective hypercharge coupling.

Adhikari, **Lewis**, Sullivan, arXiv:2003.10449

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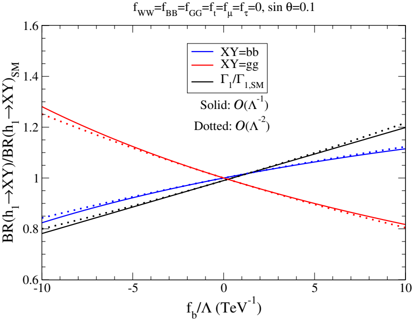
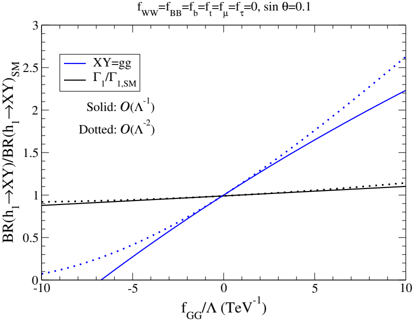


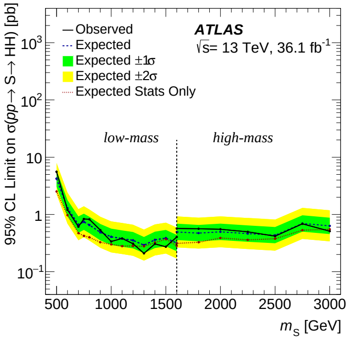
Nonzero effective b-quark coupling.



Nonzero effective gluon coupling.

Adhikari, **Lewis**, Sullivan, arXiv:2003.10449

Detour: Combining Higgs Fits with Direct Search Limits



- With this logic, we can construct a χ^2:

$$\chi^2 = \frac{\left(\sigma_{SM+sig} - \hat{\sigma}_{SM+sig}\right)^2}{(\sigma_{exp}/1.96)^2}$$

  - σ_{SM+sig} is the predicted SM+signal cross section
  - $\hat{\sigma}_{SM+sig}$ is the measured rate in a signal search
  - σ_{exp} is the expected 95% CL upper limit.

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- Ignoring interference, we can approximate the SM+signal cross section as the addition of the SM and signal cross sections

$$\sigma_{\text{SM}+sig} = \sigma_{\text{SM}} + \sigma_{sig}$$

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$$\sigma_{\rm SM+\mathit{sig}} = \sigma_{\rm SM} + \sigma_{sig}$$

- For the measurement, we assume that it is mostly SM like and that any deviation is reflected in the deviation between the expected and observed 95% CL:

$$\hat{\sigma}_{\rm SM+\mathit{sig}} = \sigma_{\rm SM} + \sigma_{obs} - \sigma_{exp},$$

where σ_{obs} is the observed 95% CL.

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- For the measurement, we assume that it is mostly SM like and that any deviation is reflected in the deviation between the expected and observed 95% CL:

$$\hat{\sigma}_{\mathrm{SM}+sig} = \sigma_{\mathrm{SM}} + \sigma_{obs} - \sigma_{exp},$$

  where σ_{obs} is the observed 95% CL.

- The χ^2 then becomes:

$$\chi^2 = \frac{\left(\sigma_{\mathrm{SM}+sig} - \hat{\sigma}_{\mathrm{SM}+sig}\right)^2}{(\sigma_{exp}/1.96)^2} = \frac{\left(\sigma_{sig} - \sigma_{obs} + \sigma_{exp}\right)^2}{(\sigma_{exp}/1.96)^2}$$

Detour: Combining Higgs Fits with Direct Search Limits

- Problem: If observed limit is smaller than expected limit, best fit value for signal cross section is negative:

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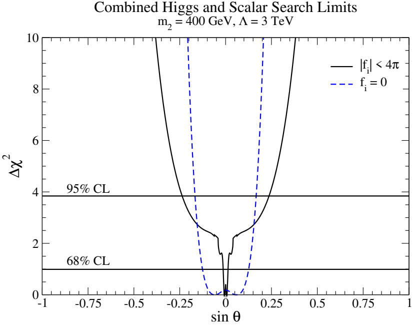
- Hence, the χ^2 for direct searches:

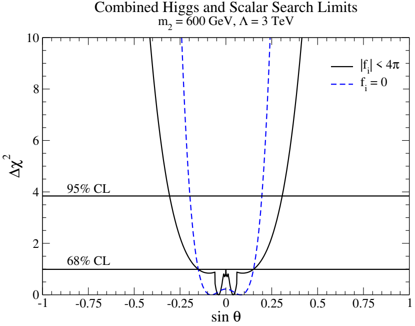
$$\chi^2 = \begin{cases} \frac{\left(\sigma_{sig} - \sigma_{obs} + \sigma_{exp}\right)^2}{(\sigma_{exp}/1.96)^2} & \text{if } \sigma_{obs} \geq \sigma_{exp} \\ \frac{\left(\sigma_{sig}\right)^2}{(\sigma_{obs}/1.96)^2} & \text{if } \sigma_{obs} < \sigma_{exp} \end{cases}$$

- Can check for one measurement and one degree of freedom the 95% CL gives $\sigma_{sig} < \sigma_{obs}$, consistent with usual approach.
- Now can combine measurements and limits in a statistically consistent way.

1-D Fits: Comparing EFT to Renormalizable Model



$m_2 = 400$ GeV



$m_2 = 600$ GeV

- Black: EFT
- Blue: Renormalizable model
- Clearly the EFT changes in interpretation of measurements and searches.