

Theory Intro

Les Houches

Physics in TeV colliders

Session 2 BSM Higgs

A collection of topics related to BSM Higgs

Presentation of Higgs results

- ◆ An effort in Les Houches 2013, summarized in arXiv:1307.5865
- ◆ Not implemented but not completely ignored
- ◆ Overall, presentation of Higgs results improved since, though still far from perfect
- ◆ How badly we need further progress? How strongly we should insist?

Fiducial cross sections

- ◆ Experiments quote directly observable cross sections in a given phase space, unfolding detector effects
- ◆ In principle completely theory independent
- ◆ A challenge is to identify a set of fiducial cross section that are experimentally accessible and theoretically interesting

Lots of work in session 1, see Wiki
to be continued in session 2

Pseudo-observables

- ◆ One more step towards theory.
- ◆ Identify theoretical quantities that are experimentally accessible, well-defined from QFT point of view, and sensitive to BSM
- ◆ Soft QED and QCD effects deconvoluted
- ◆ Example: partial Z widths at LEP-1
- ◆ Advantage: need to be analyzed just once, independent of theory progress (higher loops) or BSM models
- ◆ Challenge: define PO for Higgs at LHC

EFT for Higgs

- ◆ These days it is a very well motivated hypothesis that new physics is heavy, $\Lambda \gg v$, and EW breaking is realized linearly and spontaneously broken by Higgs vev
- ◆ Then EFT to describe BSM in a model independent way, with leading correction from $D=6$ BSM operators
- ◆ Studies hindered by a large number of parameters: 2499 in general case; 78 for flavor blind parameters
- ◆ Higgs Basis in LHCHSWG to project to a (much smaller) subset of parameters relevant for Higgs and not constrained by EWPT

Higgs Basis: Higgs couplings to matter

In Higgs basis, Higgs couplings to gauge bosons are described by 6 CP even and 4 CP odd parameters that are unconstrained by EWPT tests

Linearly realized SU(3)×SU(2)×U(1) with D=6 operators enforces relations between Higgs couplings to gauge bosons (otherwise, 5 more parameters)

Corrections to Higgs Yukawa couplings to fermions are also unconstrained by EWPT

$$\begin{aligned} \text{CP even : } & \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \\ \text{CP odd : } & \tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg} \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{\text{hvv}} = & \frac{h}{v} [2(1 + \delta c_w) m_W^2 W_\mu^+ W_\mu^- + (1 + \delta c_z) m_Z^2 Z_\mu Z_\mu \\ & + c_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 (W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}) \\ & + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{eg_L}{2c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g_L^2}{4c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\ & + c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\ & + \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{eg_L}{2c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g_L^2}{4c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}] \end{aligned}$$

$$\begin{aligned} \delta c_w &= \delta c_z + 4\delta m, \\ c_{ww} &= c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\ \tilde{c}_{ww} &= \tilde{c}_{zz} + 2s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma}, \\ c_{w\Box} &= \frac{1}{g_L^2 - g_Y^2} [g_L^2 c_{z\Box} + g_Y^2 c_{zz} - e^2 s_\theta^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) s_\theta^2 c_{z\gamma}], \\ c_{\gamma\Box} &= \frac{1}{g_L^2 - g_Y^2} [2g_L^2 c_{z\Box} + (g_L^2 + g_Y^2) c_{zz} - e^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) c_{z\gamma}] \end{aligned}$$

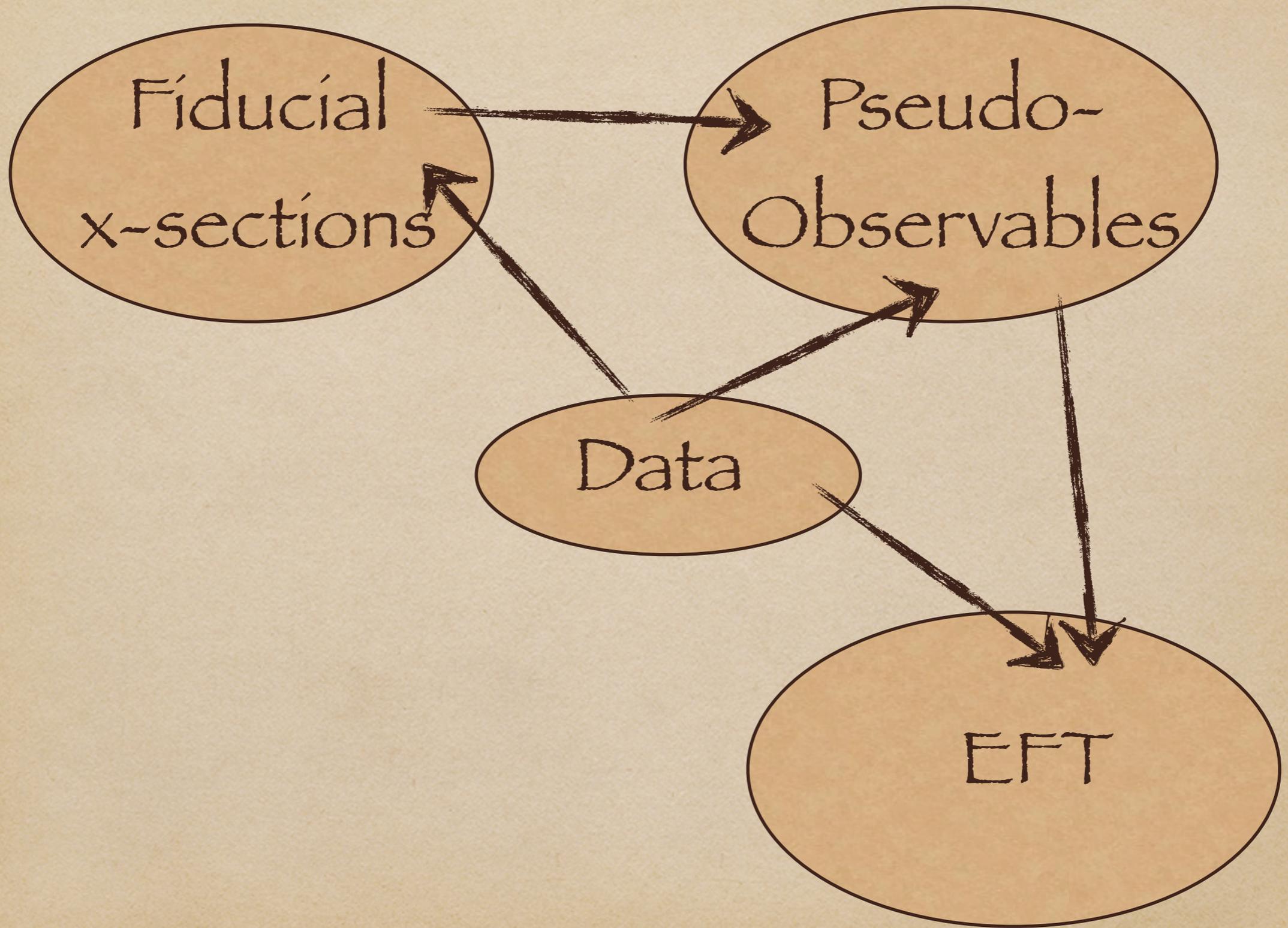
$$\begin{aligned} \text{CP even : } & \delta y_u \quad \delta y_d \quad \delta y_e \\ \text{CP odd : } & \phi_u \quad \phi_d \quad \phi_e \end{aligned}$$

$$\mathcal{L}_{\text{hff}} = - \sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}$$

Higgs basis

- ◆ Assuming MFV Yukawa couplings, Higgs signal strength + LEP-2 WW data constrain all 9 parameters to be in EFT regime
- ◆ How to better probe these couplings via $h \rightarrow 4f$, VBF, and VH distributions?

$$\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.02 \pm 0.17 \\ 0.69 \pm 0.42 \\ -0.32 \pm 0.19 \\ 0.009 \pm 0.015 \\ 0.002 \pm 0.098 \\ -0.0052 \pm 0.0027 \\ 0.57 \pm 0.30 \\ -0.24 \pm 0.35 \\ -0.12 \pm 0.20 \\ -0.162 \pm 0.073 \end{pmatrix},$$



Monte Carlo for Higgs

- ◆ What else do we need to realize fiducial, pseudo-observables, and EFT programs?
- ◆ Existing realizations of EFT: SILH basis in eHDECAY, SILH basis in MG, cross-basis Rosetta program

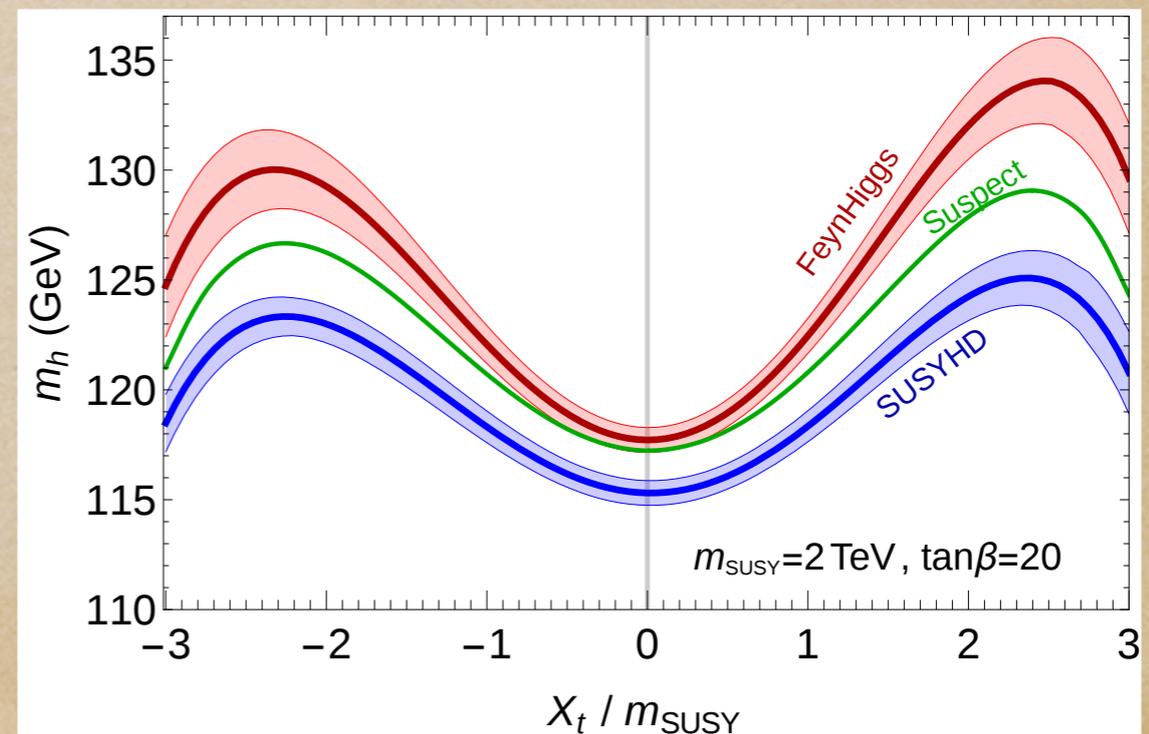
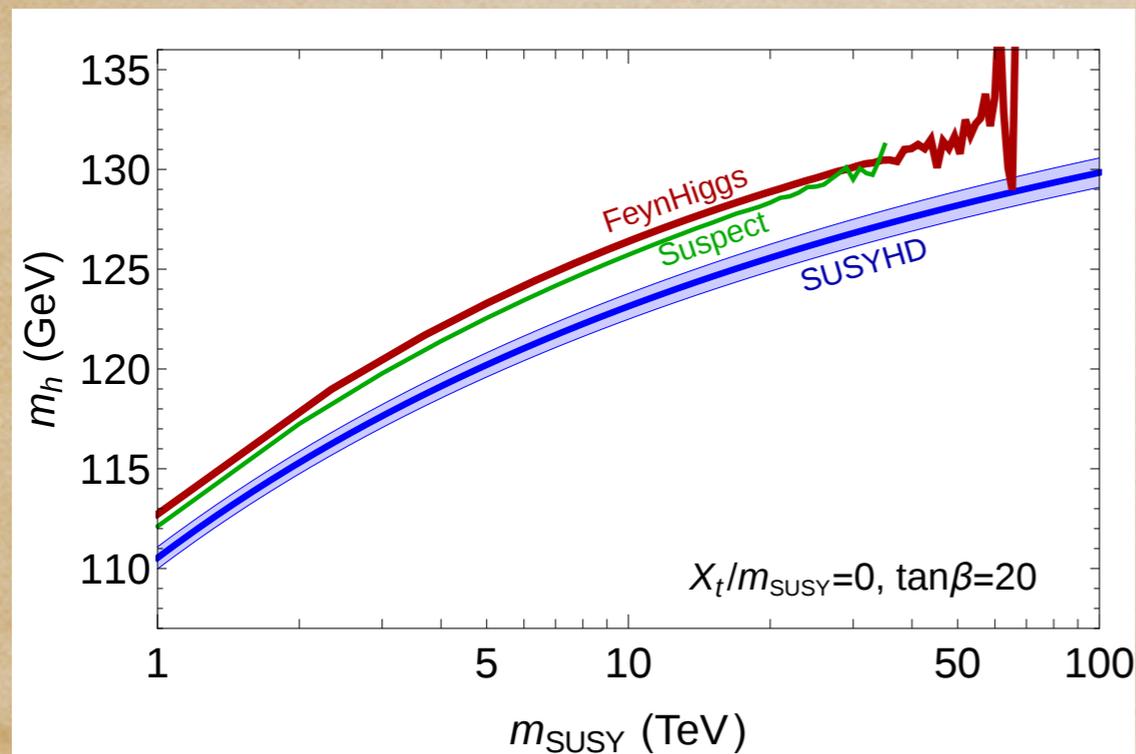
EFT at NLO

- ◆ Currently we can barely constrain Wilson coefficients to be within EFT regime, so tree level $D=6$ EFT corrections perfectly adequate for experimental analysis of Higgs data
- ◆ But in the long run, it may be necessary to go to NLO, at least for some observables/distributions
- ◆ Also, NLO may be important to match measured EFT parameters to underlying BSM model parameters

How to do it in practice, in a way that is not prohibitively complicated

Higgs and SUSY

- ◆ Here probably everything said and done
- ◆ So instead, let me show a plot that inspires strong emotions

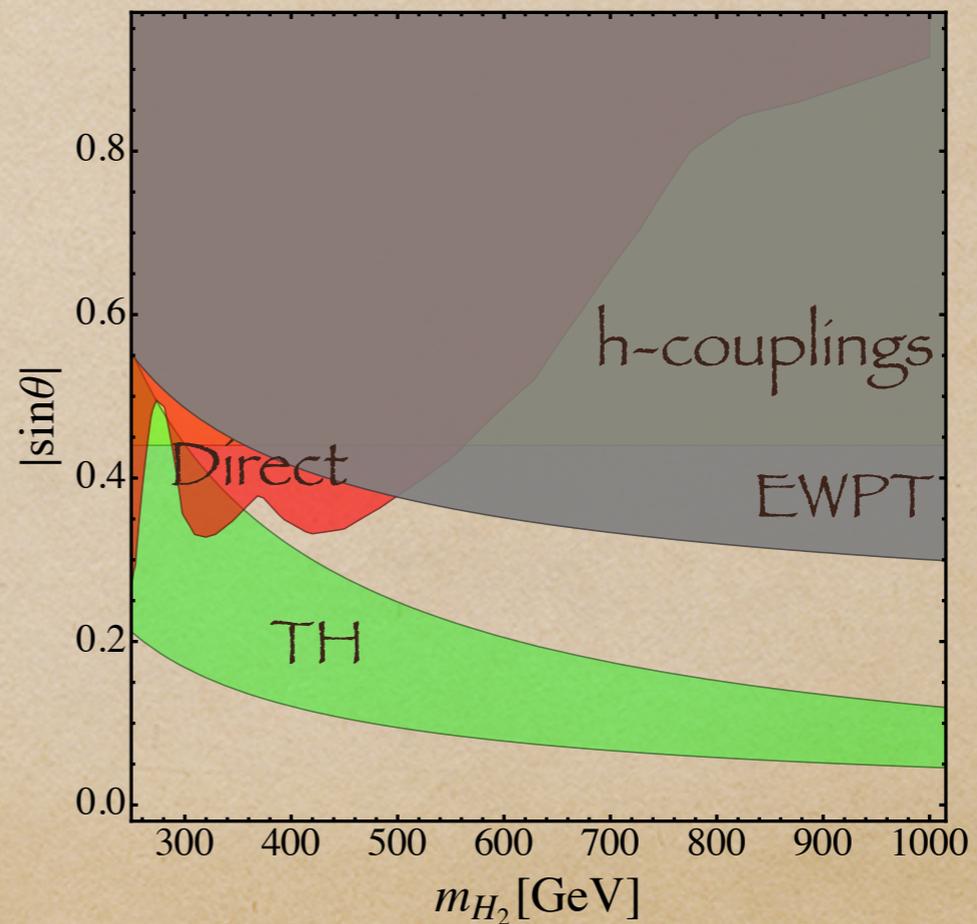
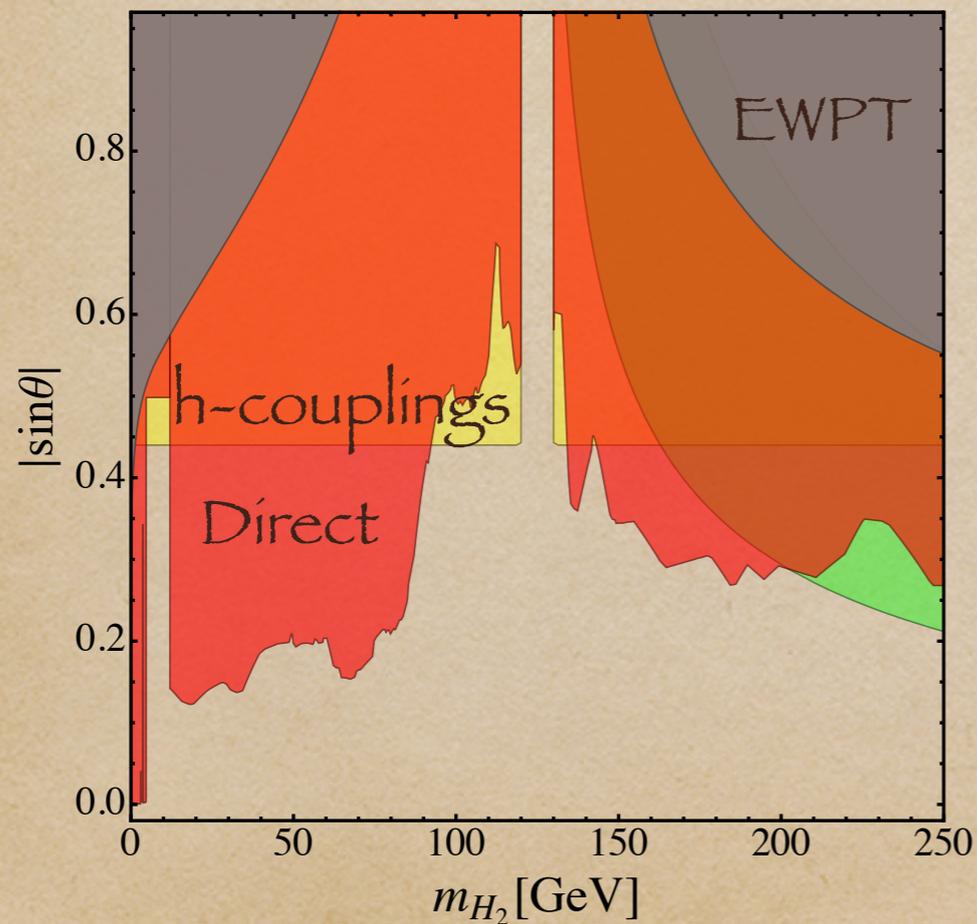


Higgs Partners

- ◆ Is there enough experimental information to constrain different multi-Higgs models
- ◆ How to present constraints for more complicated models with many parameters
- ◆ Any interesting final states that are not being explored?
- ◆ Benchmarks for experimentalists

Higgs Partners

- ◆ Interplay of direct and indirect limits
- ◆ Example, SM+singlet



New ideas for naturalness

- ◆ Neutral naturalness. A la mo of particle physics. Probably best motivation for precision Higgs physics.
- ◆ Relaxion. Any signatures in Higgs physics? Any signature at all?

Anomalies

- ◆ B-meson anomalies in LHCb et al
(B to $K^* \mu \mu$, R_K , B to $D^* \tau \nu$)
- ◆ Diboson resonance excesses in ATLAS
and CMS

Any possible relation to Higgs particles?