Theory Intro

Les Houches

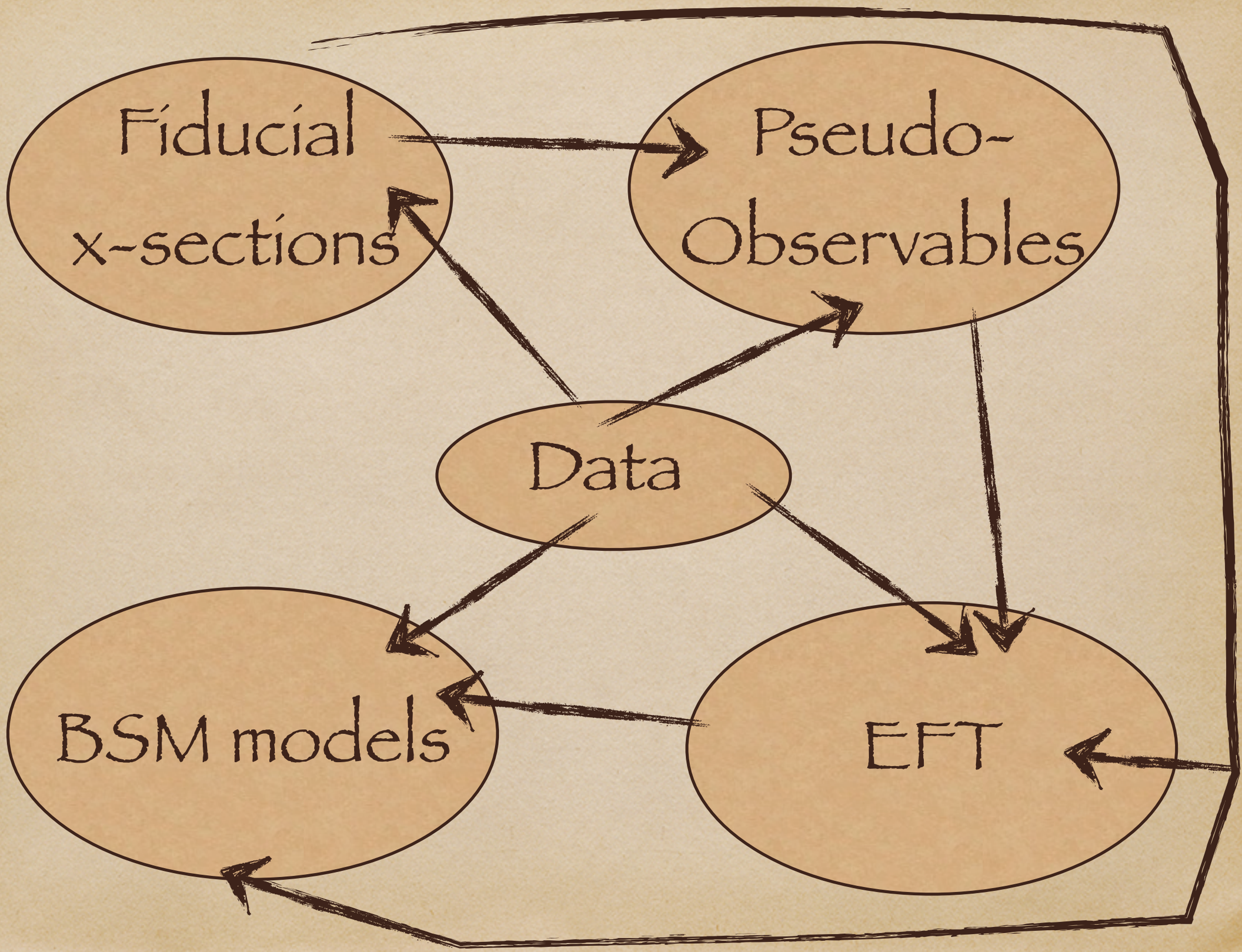
Physics in TeV colliders

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
x-sections
Pseudo-
Observables
Data
BSM models
EFT

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, $\Lambda >> v$, 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 LHCHXSWG 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)xSU(2)xU(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

$$\text{CP even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg}$$

$$\text{CP odd}: \quad \tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg}$$

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

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

$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

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

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>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

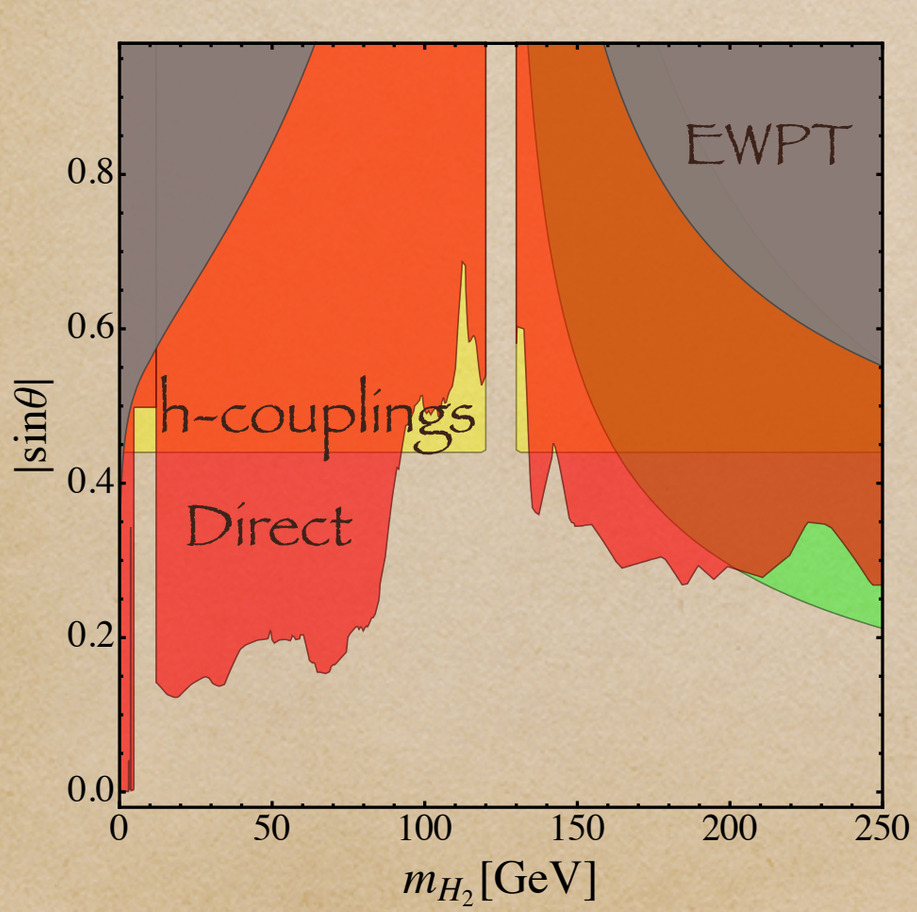
How to do it in practice, in a way that is not prohibitively complicated

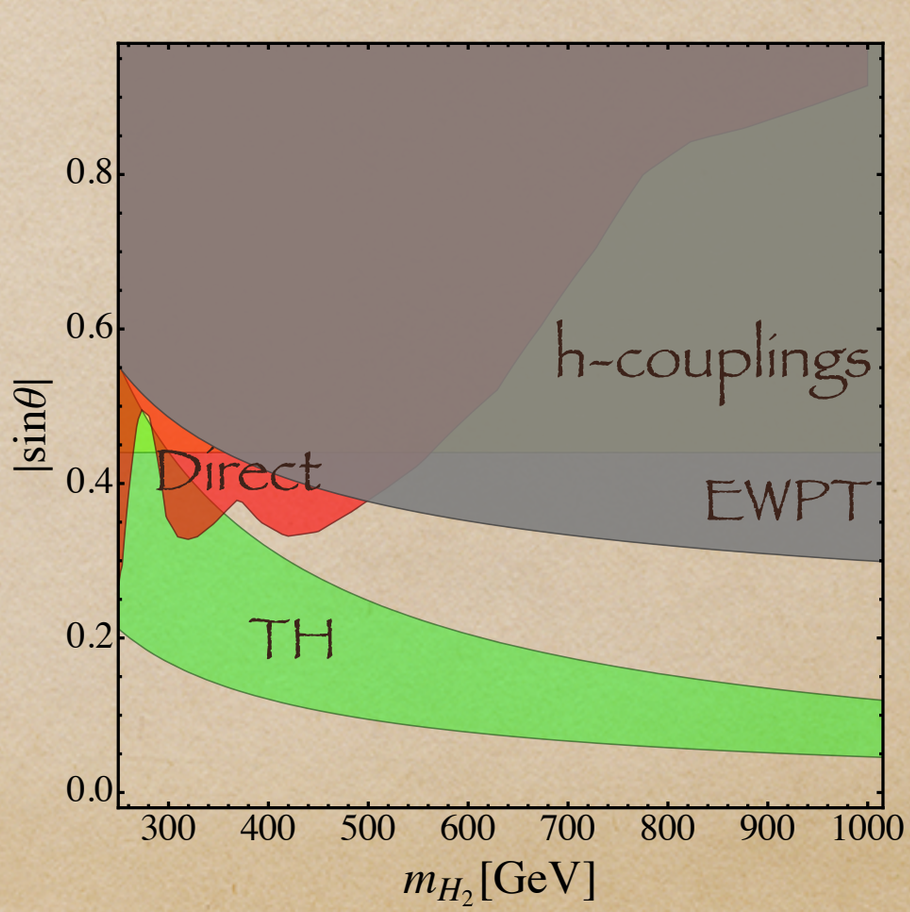
Higgs Partners

- 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. The Alamo of BSM. Probably best motivation for precision Higgs physics. New signatures for Higgs?
- Relaxion. Any signatures in Higgs physics? Any signature at all?