Remember the Question when Looking at the Answer

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Higgs Questions

1. What is the ‘Higgs’ Lagrangian?
   
   – psychologically: looked for Higgs, so found a Higgs
   – CP-even spin-0 scalar expected, which operators?
     spin-1 vector unlikely
     spin-2 graviton unexpected
   – ask flavor colleagues  [Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles]
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2. What are the coupling values?
   - ‘coupling’ after fixing operator basis
   - Standard Model Higgs vs anomalous couplings
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2. What are the coupling values?
   – ‘coupling’ after fixing operator basis
   – Standard Model Higgs vs anomalous couplings

3. What does all this tell us?  [review 1403.7191]
   – strongly interacting models
   – TeV-scale new physics
   – weakly interacting extended Higgs sectors
   – Higgs portal, link to baryogenesis, dark matter,...  [Amherst Workshop last week]
Observed Higgs couplings

**Standard Model operators**  [SFitter: Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

- assume: narrow CP-even scalar
- Standard Model operators
- renormalizable plus non-decoupling operators

- couplings from production & decay rates

\[
g_{HXX} = g_{HXX}^{SM} (1 + \Delta X)
\]
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\]

**Total width**

- non-trivial scaling

\[
N = \sigma \text{BR} \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2 \sum \Gamma_i(g^2)} + \Gamma_{\text{unobs}}
\]

\[g^2 \rightarrow 0 \quad = 0\]

gives constraint from \[\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \rightarrow \Gamma_H|_{\text{min}}\]
- \(WW \rightarrow WW\) unitarity: \[g_{WWH} < g_{WWH}^{\text{SM}} \rightarrow \Gamma_H|_{\text{max}}\]  [HiggsSignals]
- SFitter assumption \[\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j\]  [plus generation universality]
Now and in the future

**Now** [Aspen/Moriond 2013; Lopez-Val, TP, Rauch]

- focus SM-like [secondary solutions possible]
- tree couplings consistent in loops
- six couplings and ratios from data
  \[g_g \text{ vs } g_t\] not yet good
  
  [similar: Ellis et al, Djouadi et al, Strumia et al, Grojean et al]
- assumptions change everything
  \[\Delta_H, \Delta_V, \Delta_f\]
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– LHC extrapolations unclear
– interplay in loop-induced couplings
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**Future**

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- theory correlations protecting ratios?

\[
g_x = g_x^{SM} (1 + \Delta_x)
\]
Now and in the future

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**Future**

- LHC extrapolations unclear
- interplay in loop-induced couplings
- theory correlations protecting ratios?
- obvious ILC case:
  - unobserved decays avoided
  - width measured from rates including \( \sigma_{ZH} \)
  - \( H \rightarrow c\bar{c} \) accessible
  - invisible decays hugely improved
  - QCD theory error bars avoided
2HDM as a consistent UV completion

How to think of coupling measurements

- $\Delta x \neq 0$ violating renormalization, unitarity, ...
- EFT approach:
  1. define consistent 2HDM, decouple heavy states
  2. fit 2HDM model parameters, plot range of SM couplings
  3. compare to free SM couplings fit
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Yukawa-aligned 2HDM  [Branco etal, HHG, Pich & Tuzon]

- $\Delta V \leftrightarrow (\beta - \alpha)$  $\Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$  $\Delta_{\gamma} \leftrightarrow m_{H\pm}$
- $\Delta g$ not free parameter, top partner?
  custodial symmetry built in at tree level $\Delta V < 0$
- Higgs-gauge quantum corrections
  enhanced $\Delta V < 0$
- fermion quantum corrections
  large for $\tan \beta \ll 1$
  $\Delta_W \neq \Delta_Z > 0$ possible
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UV-complete vs SM coupling fits

- 2HDM close to perfect at tree level
- $\Delta_W \neq \Delta_Z > 0$ through loops
- Ignore constraints on UV completion
  $\Rightarrow$ free SM couplings well defined
Error analysis

Sources of uncertainty [Cranmer, Kreiss, Lopez-Val, TP]

- statistical error: Poisson
- systematic error: Gaussian, if measured
- theory error: not Gaussian [no statistical interpretation, just a range]

- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong

- theory likelihood flat centrally and zero far away

- profile likelihood construction: RFit [CKMFitter]

\[-2 \log \mathcal{L} = \chi^2 = \tilde{\chi}_d^T C^{-1} \tilde{\chi}_d\]

\[\chi_{d,i} = \begin{cases} 
0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\
|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})}
\end{cases}\]

\[\sigma_i^{(\text{exp})}\]
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\end{cases} \]

Combination in profile likelihood  [RFit, CKMfitter]

- Gaussian $\otimes$ Gaussian: half width added in quadrature
- Gaussian/Poisson $\otimes$ flat: linear
- flat $\otimes$ flat: linear
Higher-dimensional operators

**Light Higgs as a Goldstone boson**  [Contino, Giudice, Grojean, Pomarol, Rattazzi]

- strongly interacting models predicting heavy broad resonance(s)
- light state if protected by Goldstone’s theorem  [Georgi & Kaplan]
- interesting if $\nu \ll f < 4\pi f \sim m_{\rho}$  [little Higgs $\nu \sim g^2 f/(2\pi)$]
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\[
\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D^\mu} H \right) \left( H^\dagger \overleftrightarrow{D^\mu} H \right) - \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H f_L H f_R + \text{h.c.} \right) \\
+ \frac{i c_W g}{2m_\rho^2} \left( H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) \left( D^\nu W_{\mu\nu} \right)^i + \frac{i c_B g'}{2m_\rho^2} \left( H^\dagger \overleftrightarrow{D^\mu} H \right) \left( \partial^\nu B_{\mu\nu} \right) \\
+ \frac{i c_{HW} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i c_{HB} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
+ \frac{c_\gamma g'^2}{16\pi^2 f^2} \frac{g_\rho^2}{g_S^2} H^\dagger H B_{\mu\nu} B_{\mu\nu} + \frac{c_9 g_S^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}.
\]
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$$- \frac{c_6}{(3f)^2} (H^\dagger H)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H \tilde{f}_L \tilde{f}_R + \text{h.c.} \right)$$

$$+ \frac{i c_{W}}{(16f)^2} (H^\dagger \sigma^i \overleftrightarrow{D^\mu} ) (D^\nu W_{\mu\nu})^i + \frac{i c_{B}}{(16f)^2} (H^\dagger \overleftrightarrow{D^\mu} H) (\partial^\nu B_{\mu\nu})$$

$$+ \frac{i c_{H W}}{(16f)^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i c_{H B}}{(16f)^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$+ \frac{c_7}{(256f)^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_8}{(256f)^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}.$$
Higher-dimensional operators

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**Anomalous Higgs couplings**  [Hagiwara et al; Corbett, Eboli, Gonzalez-Fraile, Gonzales-Garcia]

- assume Higgs is largely Standard Model
- additional higher-dimensional couplings

\[
\mathcal{L}_{\text{eff}} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} (\Phi^\dagger \Phi) G_{\mu\nu} G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2} \Phi^\dagger W_{\mu\nu} W^{\mu\nu} \Phi \\
+ \frac{f_W}{\Lambda^2} (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) + \frac{f_B}{\Lambda^2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) + \frac{f_{WWW}}{\Lambda^2} \text{Tr}(W_{\mu\nu} W^{\nu\rho} W_\rho) \\
+ \frac{f_b}{\Lambda^2} (\Phi^\dagger \Phi)(\bar{Q}_3 \Phi d_{R,3}) + \frac{f_\tau}{\Lambda^2} (\Phi^\dagger \Phi)(\bar{L}_3 \Phi e_{R,3})
\]

- plus e-w precision data and triple gauge couplings
- remember what Lagrangian you assume
- best approach for renormalizable models?
Actual models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

- decoupling defined through the massive gauge sector

$$\frac{g_V}{g^\text{SM}_V} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \quad \Leftrightarrow \quad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$
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- dark singlet

\[
\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \quad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1
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- mixing singlet [no anomalous decays]
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  1 + \Delta x = \cos \theta = \sqrt{1 - \xi^2} \quad \mu_{p,d} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1
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- composite Higgs
  $$\xi = \frac{v}{f} \quad \mu_{WBF,d} = \frac{(1 - \xi^2)^2}{(1 - 2\xi^2)^2} = 1 + 2\xi^2 + \mathcal{O}(\xi^3) > 1$$
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- additional doublet [type-X fermion sector]

$$1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2}$$
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  \[ \frac{g_V}{g^*_V} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \quad \Leftrightarrow \quad \Delta V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3) \]

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- additional doublet [type-X fermion sector]
  \[ 1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2} \]

- MSSM [plus $\tan \beta$]
  \[ \xi^2 \approx \frac{m^2_h (m^2_Z - m^2_h)}{m^2_A (m^2_H - m^2_h)} \sim \frac{m^4_Z \sin^2(2\beta)}{m^4_A} \]
Extended Higgs sectors

Effect on signal strengths

- decay–diagonal and production–diagonal correlations
- new physics scenarios in 2 dimensions
Extended Higgs sectors

Effect on signal strengths

– decay–diagonal and production–diagonal correlations
– new physics scenarios in 2 dimensions

– theory uncertainties with direction
⇒ robustness measure
Longitudinal $WW$ scattering

$WW$ scattering at high energies  
[Tao etal; Dawson]

- historically alternative to light Higgs
- $WW$ scattering at high energies  
  [via Goldstones] \[ g \nu H \left( a_L V_{\nu\mu} V^\nu_L + a_T V_{\nu\mu} V^\nu_T \right) \]
- still useful after Higgs discovery?
Longitudinal WW scattering

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- **WW** scattering at high energies  [via Goldstones]
  \[ g_V H \left( a_L V_{L\mu} V^\mu_L + a_T V_{T\mu} V^\mu_T \right) \]
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**Tagging jet observables** [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta
  \[
  P_T(x, p_T) \sim \frac{1 + (1 - x)^2}{x} \frac{p_T^3}{(1 - x) m_W^2 + p_T^2} \\
  P_L(x, p_T) \sim \frac{1 - x}{x} \frac{2(1 - x) m_W^2 p_T}{((1 - x) m_W^2 + p_T^2)^2}
  \]
Longitudinal $WW$ scattering

$WW$ scattering at high energies \cite{Tao et al; Dawson}

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- $WW$ scattering at high energies \cite{via Goldstones}

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Tagging jet observables \cite{Brehmer, Jäckel, TP}

- polarization defined in Higgs frame
- transverse momenta
- azimuthal angle

\[ A_\phi = \frac{\sigma(\Delta \phi_{jj} < \frac{\pi}{2}) - \sigma(\Delta \phi_{jj} > \frac{\pi}{2})}{\sigma(\Delta \phi_{jj} < \frac{\pi}{2}) + \sigma(\Delta \phi_{jj} > \frac{\pi}{2})} \]
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$WW$ scattering at high energies  
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Tagging jet observables  
[Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta
- azimuthal angle
- total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

⇒ simple question, clear answer
Width measurements

- SM-like Higgs: $\Gamma \sim m/30000$ not reconstructable \[ at \text{LHC or LC}\]
- LC trick $\Gamma \propto (\sigma \times \text{BR})/\sigma$
- LHC trick [Caola & Melnikov]
  peak cross section vs off-shell interference in $H \rightarrow ZZ$

$$
\sigma_{\text{peak}} \sim \frac{g_{gg}^2 g_Z^2}{(s - m^2)^2 + m^2 \Gamma^2} = \frac{g_{gg}^2 g_Z^2}{m^2 \Gamma^2} \quad \sigma_{\text{off}}(g_{gg} g_Z) \sim \sigma_{\text{cont}} - \frac{A_{\text{int}} g_{gg} g_Z}{s - m^2} + \frac{A_H g_{gg}^2 g_Z^2}{(s - m^2)^2}
$$

- control of $\sigma_{\text{cont}} \sim \sigma_{\text{off}}$ the problem

$\Rightarrow \Gamma \lesssim 10 \Gamma_{\text{SM}}$ from rates
Higgs width

**Width measurements**

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\]

- control of $\sigma_{\text{cont}} \sim \sigma_{\text{off}}$ the problem
\[\Rightarrow \Gamma \lesssim 10 \Gamma_{\text{SM}} \text{ from rates}\]

**Model independent?** [Englert, Spannowsky]

- $g_g(p_1^2, p_2^2, p_H^2)$ from quantum effects
- only single number for $p_H^2 = m^2$
- additional scalar loop [$m_\phi = m_t$]

\[
\frac{\mathcal{M}_\phi}{\mathcal{M}_t} \sim \frac{1 + 2m_t^2 C_0(s, m_t)}{(s - 4m_t^2)C_0(s, m_t) - 2}
\]

\[\Rightarrow \text{‘model independent’ not applicable to Higgs@LHC}\]
Questions

Big questions

– what is the Higgs Lagrangian?
– what are the coupling values?
– what does all this tell us?

Small questions

– what are good alternative model hypotheses?
– go for renormalizable or EFT completions?
– how can we improve the couplings fit precision?
– how can we measure the quark Yukawas?
– how can we measure the Higgs self coupling?
– how do we avoid theory dominating uncertainties
– who wants to work on backgrounds?
– can QCD be fun?

Much of this work was funded by the BMBF Theorie-Verbund which is ideal for relevant LHC work
Higgs Questions
Tilman Plehn

Questions
Couplings
Operators
BSM Higgs

$WW \rightarrow WW$

Higgs width