Remember the Question when Looking at the Answer

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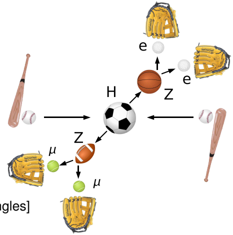
Universität Heidelberg

Pheno, May 2014

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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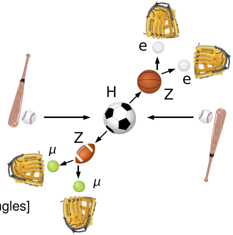

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- 'coupling' after fixing operator basis
- Standard Model Higgs vs anomalous couplings

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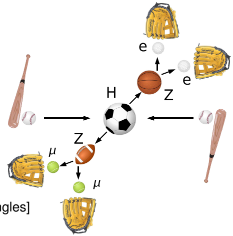

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3. What does all this tell us? [review 1403.7191]

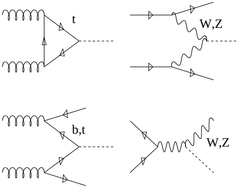
– strongly interacting models

– 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

$$\begin{array}{|l|}\hline gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \\ \hline\end{array} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \;(1 + \Delta_X)} \quad \longleftrightarrow \quad \begin{array}{|l|}\hline H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ \hline\end{array}$$

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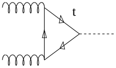

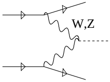

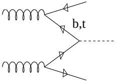

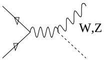

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Total width

- non-trivial scaling

$$N = \sigma \, BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \; \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2 \dfrac{\sum \Gamma_i(g^2)}{g^2} + \Gamma_{\text{unobs}}} \stackrel{g^2 \to 0}{\longrightarrow} = 0$$

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

Now and in the future

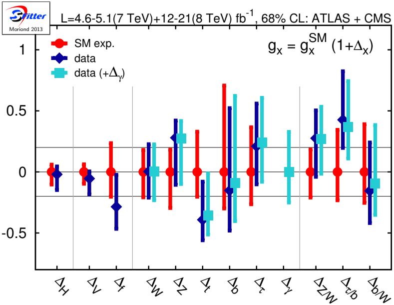
Now [Aspen/Moriond 2013; Lopez-Val, TP, Rauch]

- focus SM-like [secondary solutions possible]
- tree couplings consistent in loops
- six couplings and ratios from data

  g_g vs g_t not yet good

  [similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]
- assumptions change everything

  $\Delta_H, \Delta_V, \Delta_f$



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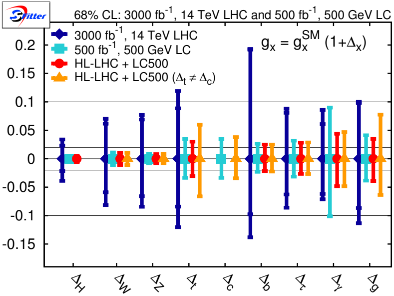

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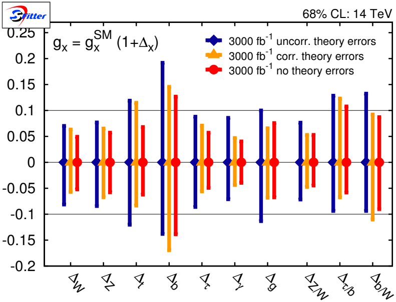

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– obvious ILC case:

unobserved decays avoided
width measured from rates including σ_{ZH}
$H \to c\bar{c}$ 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]

- $\Delta_V \leftrightarrow (\beta - \alpha)$ $\Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$ $\Delta_\gamma \leftrightarrow m_{H\pm}$
- Δ_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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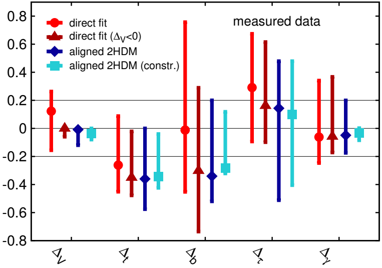
UV-complete vs SM coupling fits

- 2HDM close to perfect at tree level
- $\Delta_W \neq \Delta_Z > 0$ through loops
- ignote 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]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \, C^{-1} \, \vec{\chi}_d$$

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

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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 $v \ll f < 4\pi f \sim m_\rho$ [little Higgs $v \sim g^2 f/(2\pi)$]

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$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \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}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{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^i_{\mu\nu} + \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^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
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& - \frac{c_6}{(3f)^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
& + \frac{i c_W}{(16f)^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B}{(16f)^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW}}{(16f)^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB}}{(16f^2)} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma}{(256f)^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g}{(256f)^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
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Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

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

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

– 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

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

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$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \qquad\qquad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

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$$\xi = \frac{v}{f} \qquad\qquad \frac{\mu_{\text{WBF},d}}{\mu_{\text{GF},d}} = \frac{(1 - \xi^2)^2}{(1 - 2\xi^2)^2} = 1 + 2\xi^2 + \mathcal{O}(\xi^3) > 1$$

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$$1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2}$$

– MSSM [plus tan β]

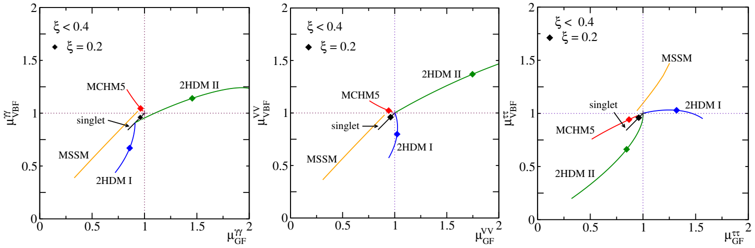
$$\xi^2 = \simeq \frac{m_h^2 \, (m_Z^2 - m_h^2)}{m_A^2 (m_H^2 - m_h^2)} \sim \frac{m_Z^4 \, \sin^2(2\beta)}{m_A^4}$$

Extended Higgs sectors

Effect on signal strengths

– decay–diagonal and production–diagonal correlations

– new physics scenarios in 2 dimensions



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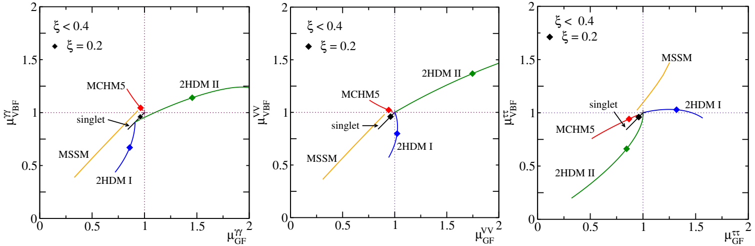
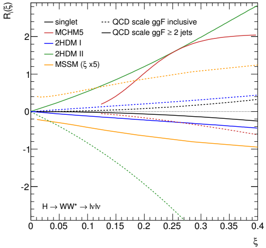


– theory uncertainties with direction

⇒ 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]

$$g_V \; H \; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

– still useful after Higgs discovery?

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– high energy signal reduced by Higgs

– tagging jets as Higgs pole observables instead

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- still useful after Higgs discovery?
- high energy signal reduced by Higgs
- tagging jets as Higgs pole observables instead

Tagging jet observables [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta

$$P_T(x, p_T) \sim \frac{1+(1-x)^2}{x} \; \frac{p_T^3}{((1-x)m_W^2 + p_T^2)^2}$$

$$P_L(x, p_T) \sim \frac{1-x}{x} \; \frac{2(1-x)m_W^2 p_T}{((1-x)m_W^2 + p_T^2)^2}$$

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

– historically alternative to light Higgs

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– 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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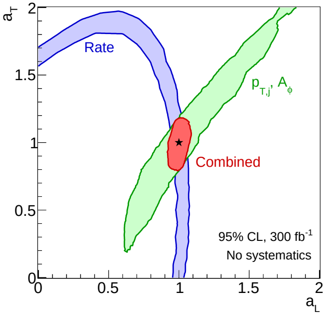
– total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

$\Rightarrow$ simple question, clear answer



Higgs width

Width measurements

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

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

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

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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 [$m_\phi = m_t$]

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

m_ϕ	μ_{peak}	$\Gamma/\Gamma_{\text{SM}}$	$\mu_{\text{off},H}$
70 GeV	1.0	5	0.98
170 GeV	1.0	4.7	1.8
170 GeV	1.0	1.7	1.06

$\Rightarrow$ ‘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

Bundesministerium für Bildung und Forschung