The Last Talk with Nothing New to Say

Tilman Plehn

Universität Heidelberg

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Last Talk

Tilman Plehn

Questions

Couplings

Operators

BSM Higgs

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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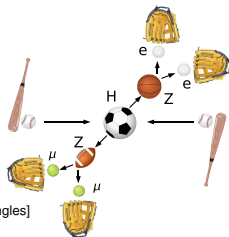### 2. What are the coupling values?   [SFitter]

– 'coupling' after fixing operator basis

– Standard Model Higgs vs anomalous couplings

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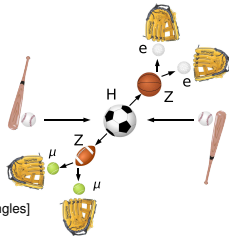– ask flavor colleagues [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]
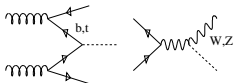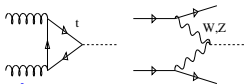
2. What are the coupling values? [SFitter]

– '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,...

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Naive Higgs Couplings

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

– assume: narrow CP-even scalar
         Standard Model operators
         couplings proportional to masses?

– couplings from production & decay rates

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

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\hline
\end{array}
$$

Total width

– non-trivial scaling

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

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]

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Now and in the future

– 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 help: $\Delta_H, \Delta_V, \Delta_f$

L=4.6-5.1(7 TeV)+12-21(8 TeV) fb^{-1}, 68% CL: ATLAS + CMS

$g_x = g_x^{SM}(1+\Delta_x)$

SM exp.
data
data ($+\Delta_\gamma$)

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Higgs portal   [Michael's talk]

– model–specific fits next step

– why not Higgs portal
mixing angle vs invisible width

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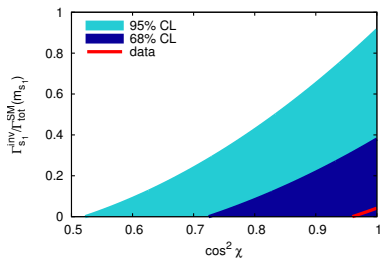– six couplings and ratios from data

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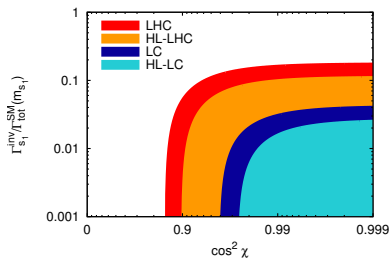– six couplings and ratios from data

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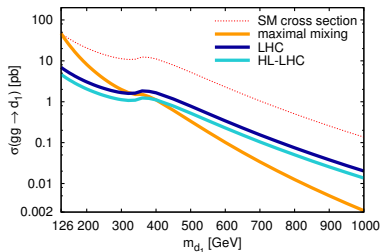– six couplings and ratios from data
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Higgs portal [Michael's talk]

– model–specific fits next step
– why not Higgs portal
  mixing angle vs invisible width
– translated into heavy Higgs rate
– direct invisible searches numerically irrelevant
$\Rightarrow$ remember your model hypothesis

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2HDM as a consistent UV completion

How to think of coupling measurements [constant couplings, see Spanno's talk]

– $\Delta_x \neq 0$ 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

– $\Delta_V \leftrightarrow (\beta - \alpha)$ $\qquad \Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$ $\qquad \Delta_\gamma \leftrightarrow m_{H^\pm}$

– 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
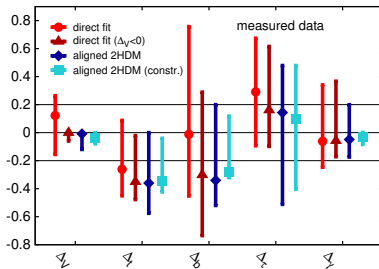
– 2HDM close to perfect at tree level
– $\Delta_W \neq \Delta_Z > 0$ through loops
– ignote constraints on UV completion
⇒ free SM couplings well defined

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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 ⊗ Gaussian: half width added in quadrature

– Gaussian/Poisson ⊗ flat: linear

– flat ⊗ flat: linear

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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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$$\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger H \right) \partial_\mu \left(H^\dagger H \right) + \frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right)$$

$$- \frac{c_6 \lambda}{f^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right)$$

$$+ \frac{i c_W g}{2 m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2 m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu})$$

$$+ \frac{i c_{HW} g}{16 \pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i c_{HB} g'}{16 \pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$+ \frac{c_\gamma {g'}^2}{16 \pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16 \pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu} .$$

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$$- \frac{c_6}{(3f)^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.} \right)$$

$$+ \frac{i c_W}{(16f)^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B}{(16f)^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu})$$

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

$$+ \frac{c_\gamma}{(256f)^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g}{(256f)^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu} .$$

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- – light state if protected by Goldstone's theorem [Georgi & Kaplan]
- – interesting if $v \ll f < 4\pi f \sim m_\rho$ [little Higgs $v \sim g^2 f/(2\pi)$]
- – collider phenomenology of mostly ($H^\dagger H$) terms

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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

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

– plus e-w precision data and triple gauge couplings

– remember what Lagrangian you assume

– not best approach for renormalizable models

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Extended Higgs sectors

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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– dark singlet

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

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$$1 + \Delta_x = \cos\theta = \sqrt{1 - \xi^2} \qquad\qquad \mu_{p,d} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

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– composite Higgs

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

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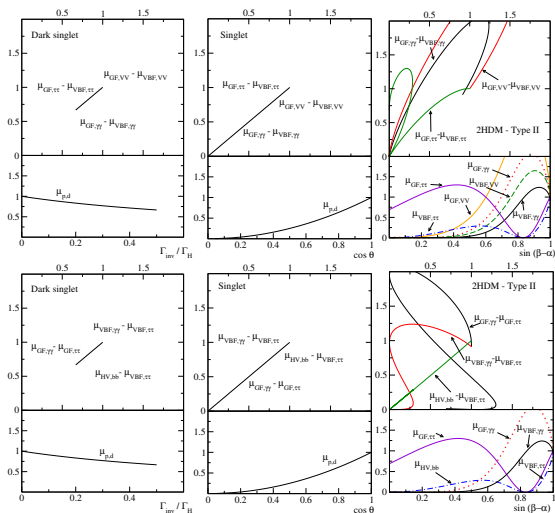– additional doublet [type-X fermion sector]

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

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– additional doublet [type-X fermion sector]

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

– MSSM [plus $\tan\beta$]

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

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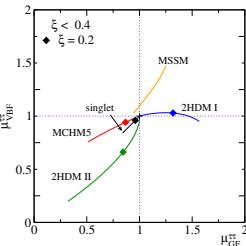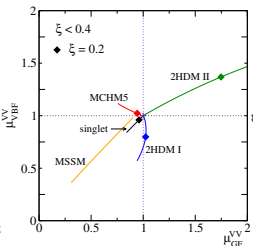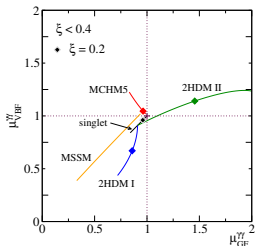Operators

BSM Higgs

Extended Higgs sectors

Effect on signal strengths

– decay–diagonal and production–diagonal correlations
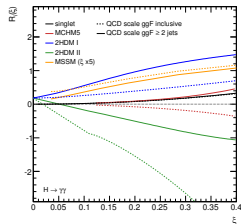– for dark singlet
  for mixing singlet
  for type-II 2HDM

Last Talk

Tilman Plehn

Questions
Couplings
Operators
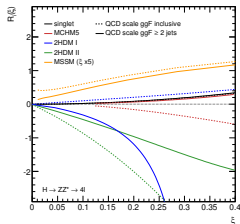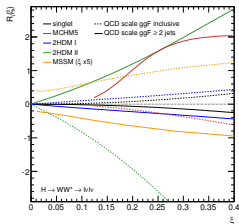BSM Higgs

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– robustness against theory uncertainties

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- $\Rightarrow$ only for illustration at this stage...

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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?