How many doublets?
Constraining new physics with Higgs data

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Can there be a fourth generation (SM4), with new heavy fermions $t', b', \ell_4, \nu_4$?
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No theoretical reason for three fermion generations! Can there be a fourth generation (SM4), with new heavy fermions $t', b', \ell_4, \nu_4$?

No theoretical reason for a minimal Higgs sector! Can there be a second Higgs doublet?
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The non-standard Higgs bosons of a two-Higgs-doublet model (2HDM) decouple with increasing masses, reproducing the Standard Model in the decoupling limit.
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As long as experimental data comply with the SM expectations a **decoupling** model of new physics cannot be excluded, while

the calculation of the statistical significance for the exclusion of a **non-decoupling** model of new physics is difficult: The SM and the new-physics model are **non-nested**, meaning that the SM is not recovered for specific parameter choices of the new-physics model.
My theory colleagues: Rather boring subject. But: more than 500 papers on the subject in the last 10 years.
Oblique electroweak corrections

New physics with particle masses well above $M_Z$, no extra gauge bosons and no $Z$-vertex corrections affect electroweak precision observables through the parameters $S$, $T$, and $U$, calculated from self-energy diagrams of $Z$, $\gamma$, and $W$.

The non-decoupling of heavy chiral fermions from $S$ lead to a premature obituary notice of the SM4 in the Particle Data Table.
But: Contribution of \((t', b')\) to \(S\):

\[
\Delta S = \frac{1}{2\pi} \left[ 1 - \frac{1}{3} \ln \frac{m_{t'}}{m_{b'}} \right]
\]

Peskin, Takeuchi (1991)

⇒ Only degenerate doublets are ruled out.

\[
\Delta T \approx \frac{1}{12\pi \sin^2 \theta_W \cos^2 \theta_W} \frac{(m_{t'}^2 - m_{b'}^2)^2}{m_{b'}^2 M_Z^2} \quad \text{for } |m_{t'}^2 - m_{b'}^2| \ll m_{b'}^2.
\]

Electroweak precision data perfectly allow simultaneously positive \(\Delta S\) and \(\Delta T\).

Kribs et al. (2007)

Other freedom: Permit fermion mixing, but then must deal with non-oblique corrections to \(Z \rightarrow b\bar{b}\).
Higgs data

LHC: experimental information on signal strengths

$$\hat{\mu}(pp \rightarrow H \rightarrow Y) = \frac{\sigma(pp \rightarrow H)B(H \rightarrow Y)_{SM4}}{\sigma(pp \rightarrow H)B(H \rightarrow Y)_{SM3}}$$

with $$Y = \gamma\gamma, WW^*, ZZ^*, Vb\overline{b}, \tau\tau$$.

The production cross section $$\sigma(gg \rightarrow H)$$ in the SM4 is 9 times larger than in the SM3 and essentially independent of $$m_{t'}$$, $$m_{b'}$$.

Does this rule out the SM4?
Higgs data

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Does this rule out the SM4?

No: Effect can be compensated by a large \( B(H \to \nu_4\bar{\nu}_4) \equiv \Gamma(H \to \nu_4\bar{\nu}_4)/\Gamma_{\text{tot}}, \) because the invisible width \( \Gamma(H \to \nu_4\bar{\nu}_4) \) dominates \( \Gamma_{\text{tot}} \) for \( m_{\nu_4} < M_H/2 \).
Global fit of electroweak precision data, five LHC Higgs signal strengths and $\hat{\mu}(p\bar{p} \rightarrow H \rightarrow Vb\bar{b})$ from Tevatron using CKMfitter.

Otto Eberhardt  theory  KIT
Geoffrey Herbert  ATLAS  HU Berlin
Heiko Lacker  ATLAS  HU Berlin
Alexander Lenz  theory  CERN/Durham
Andreas Menzel  theory  HU Berlin
UN  theory  KIT
Martin Wiebusch  theory  KIT

To quantify the level at which a theory is disfavoured with respect to the SM one performs a likelihood ratio test. Choose SM parameters $x_1, \ldots x_n$ and new-physics (NP) parameters $x_{n+1}, \ldots x_{n+k}$ such that $x_{n+1} = \ldots x_{n+k} = 0$ in the SM. Fit the theories to the observables $O_i$:

**Step 1:** Minimise $\chi^2$ function for both theories,

- $\chi^2_{\text{NP, min}}(O_i) = \min \chi^2(x_1, \ldots x_{n+k})$ and
- $\chi^2_{\text{SM, min}}(O_i) = \min \chi^2(x_1, \ldots x_n, 0, \ldots 0)$.

$\Delta \chi^2(O_i) := \chi^2_{\text{SM, min}}(O_i) - \chi^2_{\text{NP, min}}(O_i)$. 


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Does not work for the SM4!
The SM4 and SM3 are non-nested models, i.e. one cannot recover the SM3 from the SM4 by fixing its extra parameters, due to the non-decoupling property. Instead:

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**Step 3:** Fit both theories for each set of toy measurements and compute $\Delta \chi^2(O'_i) := \chi_{\text{SM4,min}}^2(O'_i) - \chi_{\text{SM,min}}^2(O'_i)$. 
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**Step 4:** The statistical significance of the SM4 is the fraction of toy measurements with $\Delta \chi^2(O'_i) \geq \Delta \chi^2(O_i)$. 
Challenge: To rule out a theory at $5\sigma$, a p-value of $5.7 \cdot 10^{-7}$ must be calculated.

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Challenge: To rule out a theory at $5\sigma$, a p-value of $5.7 \cdot 10^{-7}$ must be calculated.

⇒ Need several million minimisations... ... if toy measurements follow Gaussian distribution.

Idea: Importance sampling: Modify the probability function of the toy Monte-Carlo in such way that the central region of the Gaussian (corresponding to few standard deviations) is avoided (i.e. fit only to the tail of the Gaussian).

⇒ Speedup of a factor of 100-1000.

We find an excellent fit to the SM3. The $p$-value of the SM4 is $p = 1.1 \cdot 10^{-7}$, corresponding to $5.3 \sigma$. Without the Tevatron data on $p\bar{p} \rightarrow Vb\bar{b}$ we find $p = 1.9 \cdot 10^{-6}$, corresponding to $4.8 \sigma$.

The exclusion of the SM4 corresponds to the perturbative regime only.
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The exclusion of the SM4 corresponds to the perturbative regime only.

Comment of a colleague:

"Why don’t you rule out the third generation next?"
Higgs signal strengths

- $pp \rightarrow H \rightarrow \gamma \gamma$
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- $pp \rightarrow H \rightarrow WW$
- $pp \rightarrow H \rightarrow ZZ$
- $pp \rightarrow H \rightarrow b\bar{b}$
- $pp \rightarrow H \rightarrow b\bar{b}$
- $pp \rightarrow H \rightarrow \tau \tau$

SM4 before ICHEP'12
SM4 after ICHEP'12

Delta $\chi^2$
PRL 109 (2012) 241802 also contains the first combined fit to Higgs signal strengths and electroweak precision observables (EWPO) after the Higgs discovery. For the EWPO we have used the Zfitter program.
Deviations of EWPO

Fit results for the SM.

In the past EWPO were used to constrain \( m_t \) and \( m_H \).

With the Higgs discovery a parameter-free test of the SM is possible.
14. Dezember 2012 16:04 Teilchenphysik

Alle Dinge sind drei

Der Zerfall eines Higgs-Boson, wie es sich die Wissenschaftler vorstellen. Anhand der Messdaten des Teilchenbeschleunigers am Cern in Genf, die im Sommer das Higgs-Teilchen offenbart haben, kommen Forscher zu dem Schluss, dass die gesamte Materie aus nur wenigen Elementarbausteinen zusammengesetzt ist. (Foto: dpa)


Von Dirk Eidemüller
Two-Higgs-doublet model of type II

The presented work is based on:

Otto Eberhardt, UN, Martin Wiebusch, JHEP 1307 (2013) 118
Julien Baglio, Otto Eberhardt, UN, Martin Wiebusch, arXiv:1403.1264
**Higgs potential**

**Type II: softly broken $Z_2$ symmetry:** $(\Phi_1, \Phi_2) \rightarrow (-\Phi_1, \Phi_2)$

**CP-conserving potential:** may choose all parameters real

\[
V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2
\]
\[
+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)
\]
\[
+ \frac{1}{2} \lambda_5 \left[ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]
\]

**Yukawa couplings:**

Only \{ $\Phi_1$ \} couples to \{ down-type \}

\{ $\Phi_2$ \} couples to \{ up-type \} fermions.
Higgs spectrum:

- 2 CP-even neutral Higgs fields $h, H$
- 1 CP-odd neutral Higgs field $A$
- 2 charged Higgs fields $H^+, H^-$
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1 CP-odd neutral Higgs field $A$
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Trade $m^2_{11}$ and $m^2_{22}$ for vacuum expectation values $v_1$ and $v_2$
and express all $\lambda_i$ in terms of Higgs masses to choose

$$\tan \beta = v_2/v_1, \quad \beta - \alpha, \quad m^2_{12}, \quad m_H, \quad m_A, \quad m_{H^\pm}$$

as parameters in a global analysis.

Here $\alpha$ is the $h$-$H$ mixing angle:

$$H = \left(\sqrt{2} \text{Re} \Phi^0_1 - v_1\right) \cos \alpha + \left(\sqrt{2} \text{Re} \Phi^0_2 - v_2\right) \sin \alpha$$

$$h = -\left(\sqrt{2} \text{Re} \Phi^0_1 - v_1\right) \sin \alpha + \left(\sqrt{2} \text{Re} \Phi^0_2 - v_2\right) \cos \alpha$$
i) Higgs potential bounded from below:

\[ \lambda_1 > 0 \ , \lambda_2 > 0 \ , \lambda_3 > -\sqrt{\lambda_1 \lambda_2} \ , \ |\lambda_5| < \lambda_3 + \lambda_4 + \sqrt{\lambda_1 \lambda_2} \]

Gunion, Haber 2002
Fit input: theoretical constraints

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\[ \text{Gunion, Haber 2002} \]

ii) stability of “our” vacuum with \( v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \):

\[ m_{12}^2 (m_{11}^2 - m_{22}^2 \sqrt{\lambda_1/\lambda_2}) (\tan \beta - (\lambda_1/\lambda_2)^{1/4}) > 0 \]

\[ \text{Barroso et al. 2013} \]
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Barroso et al. 2013

iii) perturbative couplings:

\[ \| 16\pi S \| < \Lambda_{\text{max}} \]

with \( S \) being the tree-level scattering matrix for Higgs and longitudinal gauge bosons. \( \| \cdot \| \) is the magnitude of the largest eigenvalue.

Lee,Quigg,Thacker 1977
Perturbativity bound:

\[ \|16\pi S\| < \Lambda_{\text{max}} \]

Necessary for tree-level unitarity: \( \Lambda_{\text{max}} = 16\pi \)

SM experience with higher-orders: must impose \( \Lambda_{\text{max}} = 2\pi \) to avoid breakdown of perturbation theory

We have studied both the loose and tight bounds, but quote our results for the tight bound with \( \Lambda_{\text{max}} = 2\pi \).
Fit input: experimental constraints

i) **ATLAS** and **CMS** data on Higgs signal strength

\[ \hat{\mu}(pp \to H \to Y) = \frac{\sigma(pp \to h)B(h \to Y)|_{2HDM}}{\sigma(pp \to h)B(h \to Y)|_{SM3}} \]

with \( Y = \gamma\gamma, WW^*, ZZ^*, Vb\overline{b}, \tau\tau \),
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iii) all electroweak precision observables (EWPO) (as implemented in **Zfitter**),
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ii) CMS exclusion limits for \( H,A \) decays to \( WW,ZZ \), and \( \tau\tau \),

iii) all electroweak precision observables (EWPO) (as implemented in \textit{Zfitter}),

iv) flavour constraints: mass difference \( \Delta m_{B_s} \) in the \( B_s - \bar{B}_s \) system and \( B(B \rightarrow X_s\gamma) \).
Remarks on the flavour constraints:

\(B_s - B_s\) mixing is only relevant for \(\tan \beta \lesssim 2\).

\(B(B \to X_s \gamma)\) places the bound \(m_{H^+} \geq 322\) GeV (@2\(\sigma\)), which (for \(\tan \beta \gtrsim 2\)) is essentially independent of \(\tan \beta\).

Hermann et al., JHEP1211(2912)036.

\(B \to \tau \nu\), \(B \to D \tau \nu\), and \(B \to D^* \tau \nu\) are neither well described by the SM nor the 2HDM of type II. Including these decay modes would not affect the likelihood ratio test for \(\tan \beta \lesssim 50\) and would disfavour the 2HDM of type II for larger values of \(\tan \beta\).
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A satisfactory explanation of $B \to \tau \nu$, $B \to D\tau \nu$, and $B \to D^*\tau \nu$ can be achieved with a minimal modification of the Yukawa sector of the considered type-II model.

Crivellin, Greub, Kokulu 2012
blue: tight perturbativity bound

green: loose perturbativity bound

non-decoupling strip: rather small $m_{H^+}$ in tension with flavour observables, but allowed by Higgs signal strengths
blue: tight perturbativity bound, $1\sigma,$ $2\sigma,$ $3\sigma$ regions,

EWPO demand that either $M_A \sim M_{H^+}$ or $M_H \sim M_{H^+}$, while one of $M_A, M_H$ can be lighter than 200 GeV!
Why is the constraint so far away from the decoupling limit?

In the “alignment limit” $\beta - \alpha = \pi / 2$ the $VVh$ (with $V = W, Z, \gamma$) and $\bar{f}fh$ couplings are SM-like while all other $VV$-Higgs couplings vanish.
The measurement of the $hhh$ coupling $g_{hhh}$ through Higgs pair production is a major goal of future LHC runs and of the ILC.

LHC with $3\, \text{ab}^{-1}$ at $14\, \text{TeV}$: measure $g_{hhh}$ with $40\%$ error.

Barger et al. arXiv:1311.2931
Can one find new physics in this way?
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Study:
To which extent can $g_{hhh}$ deviate from its SM value?
To which extent can $gg \rightarrow hh$ be enhanced with respect to the SM prediction?

both $h$ and $H$ in the $s$ channel
Normalise all triple-Higgs couplings to $g_{hhh}^{SM}$:

$$c_{\phi_1 \phi_2 \phi_3} = \frac{g_{\phi_1 \phi_2 \phi_3}^{2HDM}}{g_{hhh}^{SM}}$$

with $\phi_1, \phi_2, \phi_3 \in \{h, H, A, H^\pm\}$. 
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with $\phi_1, \phi_2, \phi_3 \in \{h, H, A, H^\pm\}$.

In the alignment limit $\beta - \alpha = \frac{\pi}{2}$:

$$c_{hhh} = 1, \quad c_{hhH} = 0, \quad c_{hXX} \neq 0, \quad c_{HXX} \neq 0 \text{ for } X = H, A, H^+$$
Result of the global fit:

At the $3\sigma$ level $c_{hhh}$ cannot exceed 1!

One finds $c_{hhh} \geq \{0.72, 0.56, 0.40\}$ at $\{1\sigma, 2\sigma, 3\sigma\}$. 
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But: The global fit permits large enough $c_{hhH}$ to increase the Higgs pair production cross section by more than a factor of 50 through $gg \rightarrow H \rightarrow hh$!
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But: The global fit permits large enough $c_{hhH}$ to increase the Higgs pair production cross section by more than a factor of 50 through $gg \rightarrow H \rightarrow hh$!

A large branching ratio $B(H \rightarrow hh)$ implies smaller branching ratios in the standard search channels $H \rightarrow \gamma\gamma, WW, ZZ, Z\gamma, t\bar{t}, b\bar{b}, \tau\bar{\tau}, gg \ldots$. Could a spectacularly enhanced $h$ pair production cross section be the only signature of the 2HDM of type 2?
To suppress also standard search channels for $A$ look for regions in the parameter space with large $B(A \rightarrow Zh)$ or large $B(A \rightarrow ZH)$.

Sum of standard branching ratios:
At the $2\sigma$ level $B(H \rightarrow X_{\text{std}})$ can be as low as 40% and $B(A \rightarrow X_{\text{std}})$ can be even suppressed below 1%.

This happens in a narrow strip with $M_{H^+} \sim 320 \text{ GeV} \leq m_A \leq 2m_t$ and $M_H < 260 \text{ GeV}$, with dominant decay modes $A \rightarrow ZH$ and $H \rightarrow hh$. 
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Even for $M_A > 2m_t$ one can have $B(A \rightarrow X_{\text{std}}) < 0.08$, for $M_A \gtrsim 400 \text{ GeV}$ the channel $A \rightarrow H^\pm W^{\mp}$ opens!
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• For an exhaustive study of all triple-Higgs couplings and benchmark scenarios (for collider studies) in the studied 2HDM see arXiv:1403.1264.