How many doublets?

Constraining new physics with Higgs data

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Introduction

Accountant's approach to new physics:
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No theoretical reason for three fermion generations!
Can there be a fourth generation (SM4), with new heavy fermions t', b', ℓ_4, ν_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

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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.

Fourth generation

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, γ, 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)

$\Rightarrow$ Only degenerate doublets are ruled out.

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

Electroweak precision data perfectly allow simultaneously positive ΔS and ΔT. Kribs et al. (2007)

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

Higgs data

LHC: experimental information on signal strengths

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

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

The production cross section $\sigma(gg \to H)$ 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?

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Does this rule out the SM4?
No: Effect can be compensated by a large $B(H \to \nu_4\overline{\nu}_4) \equiv \Gamma(H \to \nu_4\overline{\nu}_4)/\Gamma_{\text{tot}}$, because the invisible width $\Gamma(H \to \nu_4\overline{\nu}_4)$ dominates Γ_{tot} for $m_{\nu_4} < M_H/2$.

Global fit

Global fit of electroweak precision data, five LHC Higgs signal strengths and $\hat{\mu}(p\bar{p} \to H \to Vb\bar{b})$ 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		HU Berlin
UN	theory	KIT
Martin Wiebusch	theory	KIT

Phys.Rev. D86 (2012) 013011
Phys.Rev. D86 (2012) 074014
Phys.Rev.Lett. 109 (2012) 241802

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 χ^2 function for both theories,

$$\chi^2_{\mathrm{NP,min}}(O_i) = \min \chi^2(x_1, \ldots x_{n+k}) \quad \text{and}$$

$$\chi^2_{\mathrm{SM,min}}(O_i) = \min \chi^2(x_1, \ldots x_n, 0, \ldots 0).$$

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

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$$p = 1 - P_{k/2}\left(\frac{1}{2}\Delta\chi^2\right).$$

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Lower incomplete Γ function.

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:

Step 1: Fit both theories to the measured observables O_i by minimising the χ^2 function,

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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 5σ, a p-value of $5.7 \cdot 10^{-7}$ must be calculated.

$\Rightarrow$ Need several million minimisations...

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. . . 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).

$\Rightarrow$ Speedup of a factor of 100-1000.

M.Wiebusch, *myFitter*, arXiv:1207.1446, http://myfitter.hepforge.org

Result

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

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

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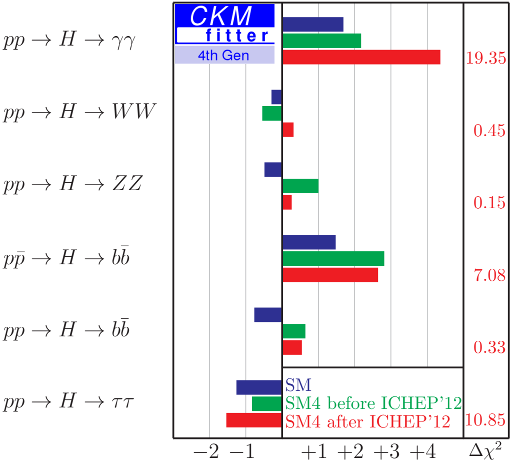
Comment of a colleague:

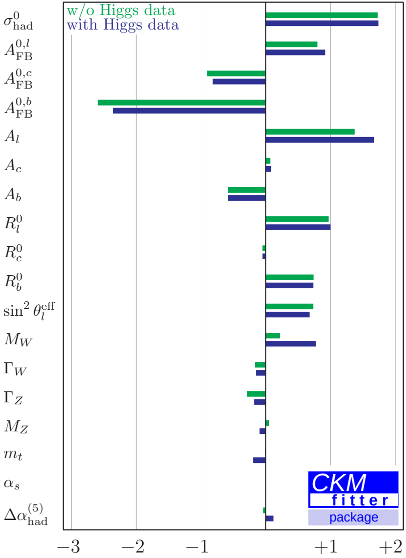
Why don't you rule out the third generation next?"

Higgs signal strengths



PRL 109 (2012) 241802 also contains the first combined fit to Higgs signal strengths and electroweak precision observables (EWPO) after the Higgs discovery within the SM3. 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.

Donovan Crow

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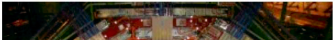
by Donovan Crow

Limited Number of Fermions in Standard Model show 12 Matter Particles Suffice in Nature

Friday December, 2012 *in* Quantum Physics

Matter particles, also called fermions, are the elementary components of the universe. They make up everything we see on earth or through telescopes. “For a long time, however, it was not clear whether we know all components,” explains Ulrich Nierste, Professor at KIT. The standard model of particle physics knows 12 fermions. Based on their similar properties, they are divided into three



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: $(\Phi_1, \Phi_2) \to (-\Phi_1, \Phi_2)$

CP-conserving potential: may choose all parameters real

$$\begin{aligned} V = \quad & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] \end{aligned}$$

Yukawa couplings:

Only $\left\{ \begin{array}{c} \Phi_1 \\ \Phi_2 \end{array} \right\}$ couples to $\left\{ \begin{array}{c} \text{down-type} \\ \text{up-type} \end{array} \right\}$ 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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Trade m_{11}^2 and m_{22}^2 for vacuum expectation values v_1 and v_2 and express all λ_i in terms of Higgs masses to choose

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

as parameters in a global analysis.

Here α is the h-H mixing angle:

$$H = \left(\sqrt{2}\mathrm{Re}\,\Phi_1^0 - v_1\right)\cos\alpha + \left(\sqrt{2}\mathrm{Re}\,\Phi_2^0 - v_2\right)\sin\alpha$$

$$h = -\left(\sqrt{2}\mathrm{Re}\,\Phi_1^0 - v_1\right)\sin\alpha + \left(\sqrt{2}\mathrm{Re}\,\Phi_2^0 - v_2\right)\cos\alpha$$

Fit input: theoretical constraints

i) Higgs potential bounded from below:

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

Gunion,Haber 2002

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Gunion,Haber 2002

ii) stability of "our" vacuum with $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV:

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

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

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

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iv) flavour constraints: mass difference Δm_{B_s} in the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ system and $B(B \to X_s\gamma)$.

Remarks on the flavour constraints:

- $B_s - \overline{B}_s$ mixing is only relevant for $\tan\beta \lesssim 2$.
- $\mathcal{B}(B \to X_s\gamma)$ places the bound $m_{H^+} \geq 322\,\text{GeV}$ (@2σ), 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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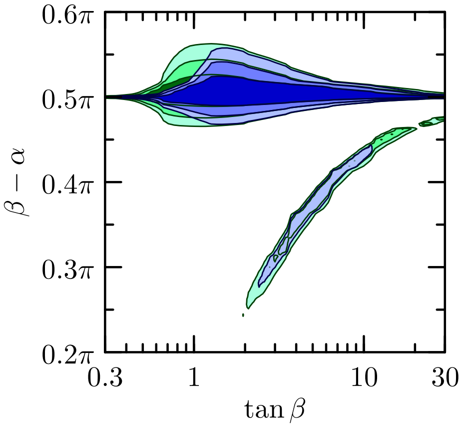
A satisfactory explanation of $B \to \tau\nu$, $B \to D\tau\nu$, and $B \to D^*\tau\nu$ can be achieved with a minimal modification of the Yukawa sector of the considered type-II model.

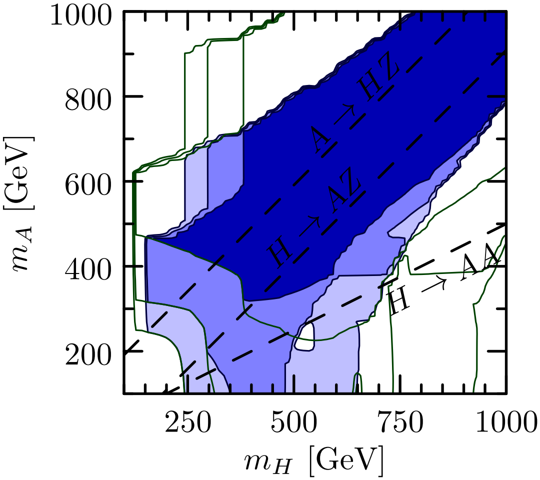
Crivellin, Greub, Kokulu 2012



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?

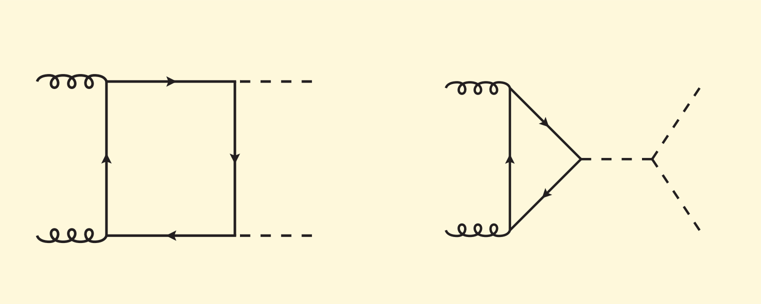
In the "alignment limit" $\beta - \alpha = \pi/2$ the VVh (with $V = W, Z, \gamma$) and $\bar{f}fh$ couplings are SM-like while all other VV-Higgs couplings vanish.

Triple-Higgs couplings

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 ab^{-1} at 14 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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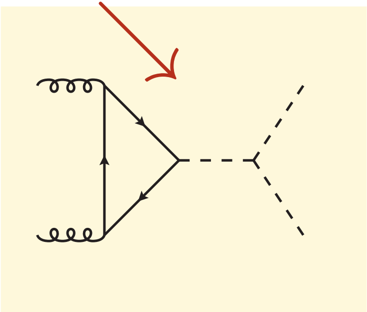
Study:

To which extent can g_{hhh} deviate from its SM value?

To which extent can $gg \to hh$ 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}:

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

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 $\beta - \alpha = \frac{\pi}{2}$:

$$c_{hhh} = 1, \quad c_{hhH} = 0, \quad c_{hXX} \neq 0, \; c_{HXX} \neq 0 \;\; \text{for } X = H, A, H^+$$

Result of the global fit:

At the 3σ level c_{hhh} cannot exceed 1!

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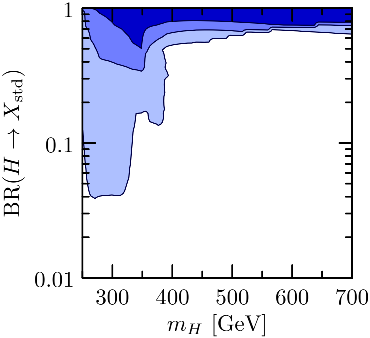
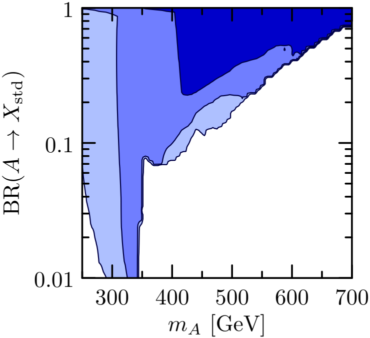
A large branching ratio $B(H \to hh)$ implies smaller branching ratios in the standard search channels
$H \to \gamma\gamma, WW, ZZ, Z\gamma, t\bar{t}, b\bar{b}, \tau\bar{\tau}, gg \ldots$.
Could a spectacularly enhanced h pair production cross section be the only signature of the 2HDM of type 2?

To suppress also standard search channels for A look for regions in the parameter space with large $B(A \to Zh)$ or large $B(A \to ZH)$.

Sum of standard branching ratios:





At the 2σ level $B(H \to X_{\rm std})$ can be as low as 40% and $B(A \to X_{\rm std})$ 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 $A \to ZH$ and $H \to hh$.

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Even for $M_A > 2m_t$ one can have $B(A \to X_{\rm std}) < 0.08$, for $M_A \gtrsim 400\,\text{GeV}$ the channel $A \to H^\pm W^\mp$ 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.