Global Fits Beyond the SM

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in collaboration with

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based on [PRL 109 (2012) 241802], [JHEP07 (2013) 118]

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CKM fitter package

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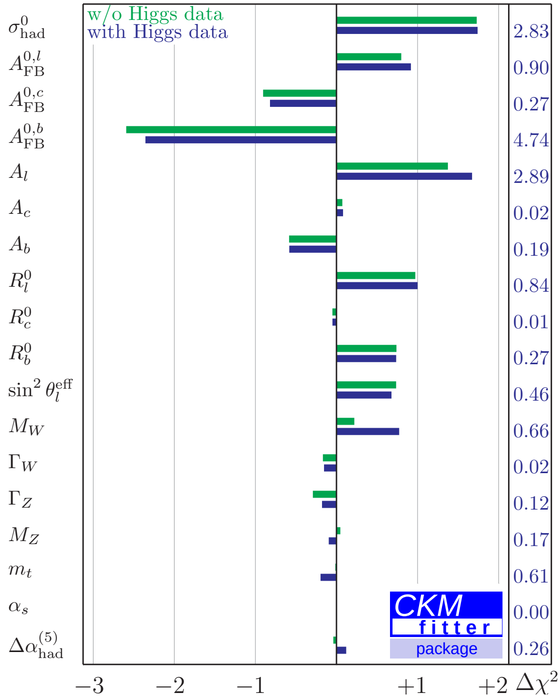
SM Electroweak Fit

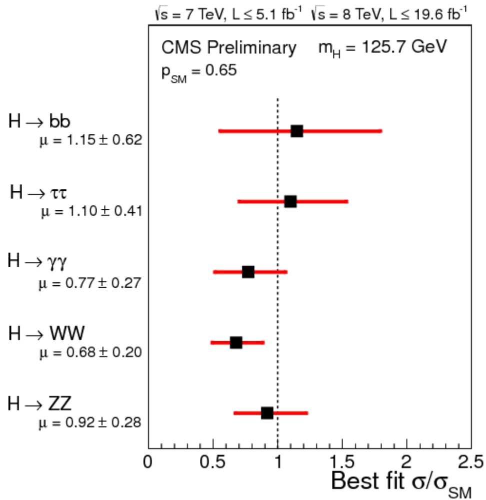
- Fits were used in the LEP era to determine the free parameters of the SM.
- With the Higgs discovery the last free parameter of the SM has been measured directly.
- The SM electroweak fit determines these Parameters from the electroweak precision observables (EWPOs). →
- The influence of this measurement on the SM electroweak fit is relatively small.

[PRL 109 (2012) 241802]



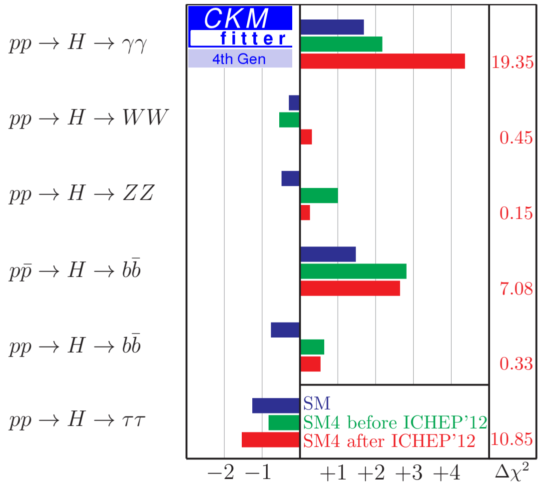
Higgs Signal Strengths

- The EWPOs also severely constrain many models beyond the SM.
- Constraints from the observed Higgs signal strengths can already be equally powerful.
- Combined fits of both types of data can (and should) be used to study models beyond the SM, but. . .
- the statistical interpretation of the fits can be (conceptually and technically) less trivial for models beyond the SM.



The Case of the 4th Generation

- Direct searches push us in a region where the 4G fermions have large Yukawa couplings.
- Virtual corrections to the Higgs couplings modify the Higgs signal strengths.
  [Denner, Dittmaier, Mück, Passarino, Spira, Sturm, Uccirati, Weber; arXiv:1111.6395]
- EWPOs constrain the mass splittings inside the $SU(2)$ doublets.
- Combined fit gives $\Delta\chi^2 = 38$.



Chi-squares and *p*-values

- The usual analytic relation between $\Delta\chi^2$ and the *p*-value (Wilks' theorem) requires nested models.
- The additional fermions of the SM4 do not decouple.

⇒ You cannot obtain the SM3 as a limiting case of the SM4.

⇒ The computation of the *p*-value requires a very expensive numerical simulation, which is unfeasible without special simulation methods.

- These methods were implemented in the public code *my*Fitter (`http://myfitter.hepforge.org`) and documented in [CPC 184 (2013) 2438].
- The SM4 is excluded at 5.3 standard deviations.
  (Wilks' theorem gives 3.5 standard deviations.)

2HDM Fits

The 2HDM of type II

- Two scalar SU(2) doublets.
- A softly broken $\mathbb{Z}_2$ symmetry which forbids FCNCs.
- No Higgs-sector CP violation.
- Scalar particle content: h, H, A, $H^\pm$.
- Independent sets of real parameters are
  - $v_2/v_1 \equiv \tan\beta$, m_{12}^2, λ_1, λ_2, λ_3, λ_4 ,λ_5
  - $\tan\beta$, $\beta-\alpha$, m_{12}^2, m_h, m_H, m_A, $m_{H^\pm}$
- This time we have a decoupling limit: $\beta-\alpha=\pi/2$, $m_H, m_A, m_{H^\pm} \gg m_h$.
- The map between the two parametrisations near the decoupling limit is not very smooth.

Theoretical Constraints

- The Higgs potential must be bounded from below

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

- 'Our' minimum of the Higgs potential must be the global minimum

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

- The Higgs self-couplings must be perturbative:

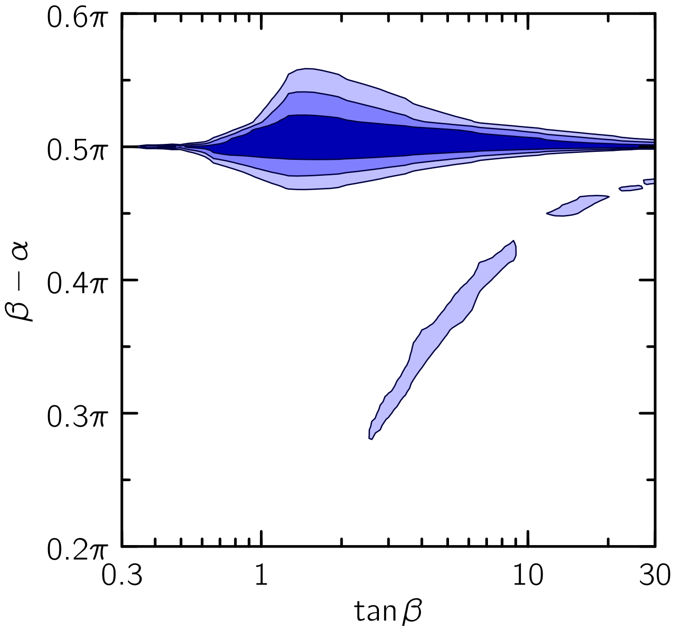
$$|\text{Eigenvalues of } \phi\phi \to \phi\phi \text{ scattering matrix}| < 2\pi \quad .$$

$\Rightarrow$ Fit requires optimisation under non-linear constraints.

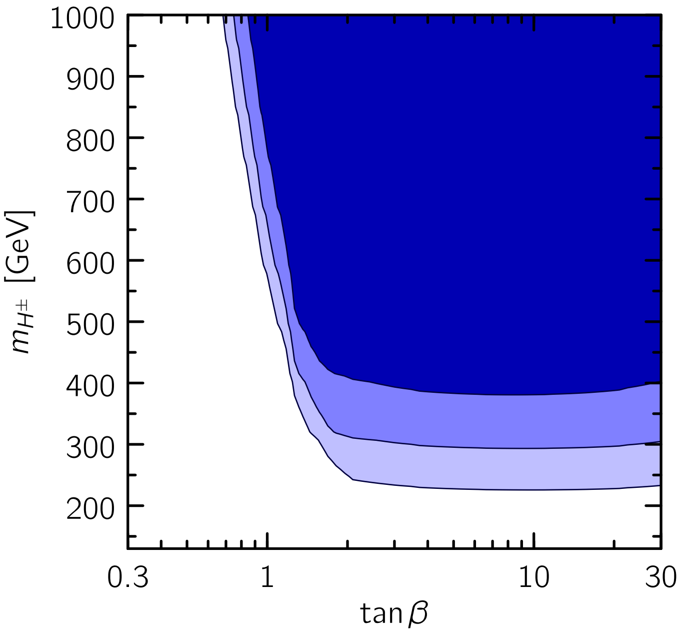
Experimental Constraints

- Full set of electroweak precision observables (no S, T, U).
- Signal strengths of the light Higgs boson (including correlations between different production mechanisms).
- Limits on heavy $H \to WW, ZZ$ and $H \to \tau\tau$ resonances.
- Flavour observables relevant for the low $\tan\beta$ region: Δm_{B_s} and $\mathrm{Br}(\bar{B} \to X_s \gamma)$.

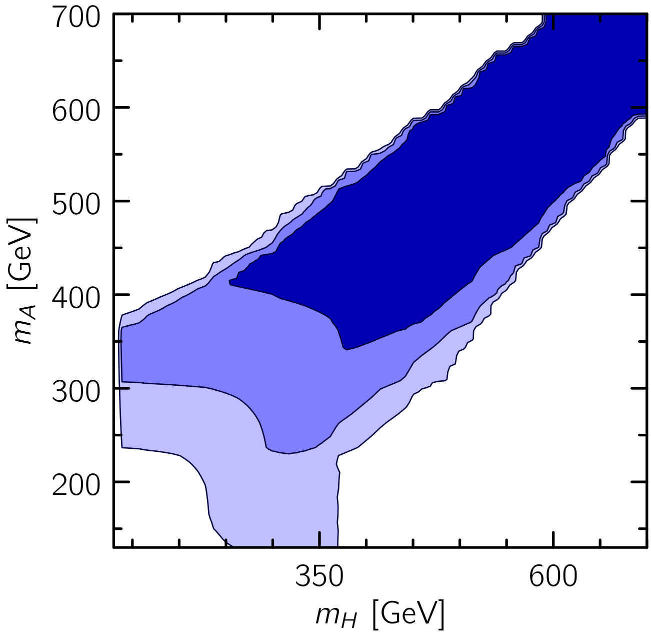
$\tan\beta$ vs. $\beta - \alpha$



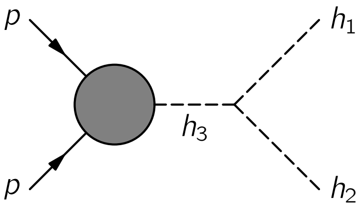
$\tan\beta$ vs. $m_{H^\pm}$



m_H vs. m_A, $m_{H^\pm}$ free



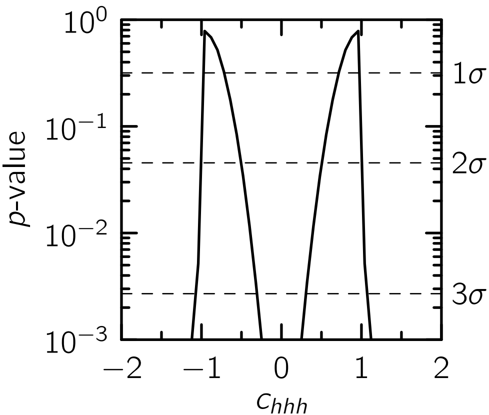
Triple Higgs Couplings



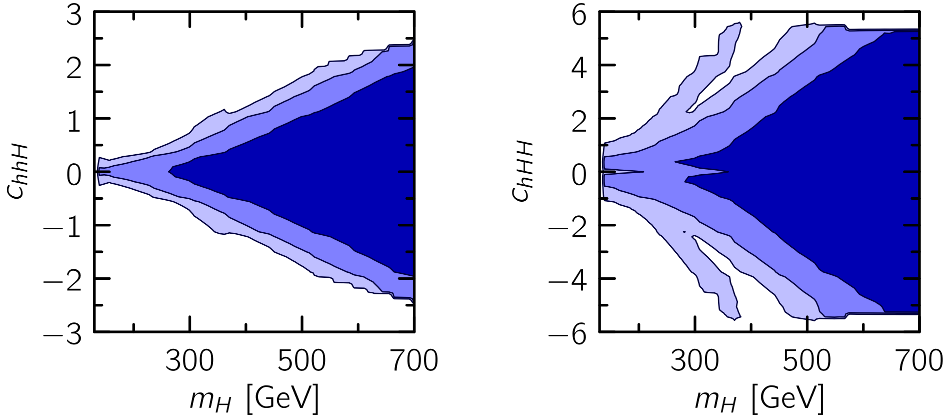
$$c_{h_1 h_2 h_3} = \frac{g^{\text{2HDM}}_{h_1 h_2 h_3}}{g^{\text{SM}}_{HHH}\big|_{m_H = 126\text{ GeV}}}$$

For $\beta - \alpha = \pi/2$:

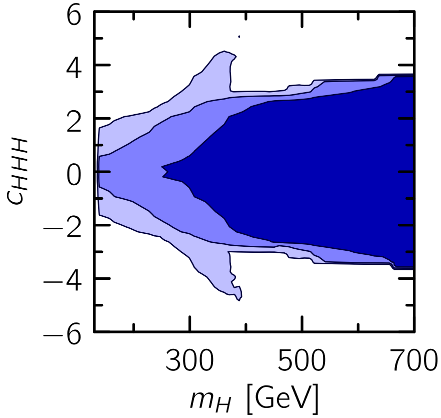
$$c_{hhh} = 1 \quad ,$$
$$c_{hhH} = 0 \quad .$$

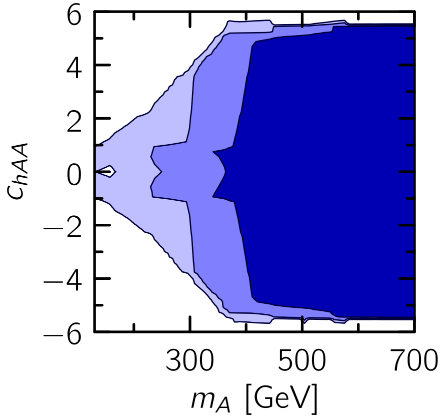


Triple Higgs Couplings



Triple Higgs Couplings





Conclusions (SM4)

- SM with a sequential fourth generation is ruled out by a combination of Higgs and electroweak precision data.
- Computation of p-values in non-decoupling models is non-trivial and requires numerical simulations which become unfeasible for small p-values.
- Importance sampling techniques as implemented in *my*Fitter can speed things up considerably.

Conclusions (2HDM)

- Best-fit scenario of the type-II 2HDM is the decoupling limit.
- Scenarios with non-SM-like h couplings are allowed by Higgs data but disfavoured (at 2σ) by flavour observables (for tight perturbativity bound).
- Scenarios with m_H and m_A below 300 GeV are ruled out at 2σ.
- hhh coupling can only be reduced.
- $c_{hhH} < 1$ for $m_H \lesssim 500$ GeV.
- $c_{hHH}, c_{HHH} < 2$ for $m_H \lesssim 400$ GeV.
- $c_{hAA} < 5$ for $m_A \lesssim 400$ GeV.
- Be careful with purely scan-based analyses. They don't necessarily give you the full picture.