Fitting the two-loop renormalized Two-Higgs-Doublet model

Warsaw, 6 December 2015

Otto Eberhardt

in collaboration with D. Chowdhury

JHEP 1511 (2015) 052, arXiv:1503.08216

Istituto Nazionale di Fisica Nucleare, Sezione di Roma

European Research Council
Established by the European Commission
Supporting top researchers from anywhere in the world

INFN Istituto Nazionale di Fisica Nucleare

Motivation

All couplings of the 125 GeV h seem to be SM like, but:

- How do we interpret the EW vacuum metastability in the SM?
- What about the hierarchy problem?

Model

$$
\begin{aligned}
V_H^{\text{2HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\
& + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]
\end{aligned}
$$

Model

$$
\begin{aligned}
V_H^{\text{2HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\
& + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]
\end{aligned}
$$

Assume an additional Z_2 symmetry to avoid tree-level FCNC's

t couples to Φ_2,
- b to Φ_2,
  - τ to Φ_2 “type I”
  - τ to Φ_1 “type X”
- b to Φ_1,
  - τ to Φ_2 “type Y”
  - τ to Φ_1 “type II”

Model

$$
\begin{aligned}
V_H^{\mathrm{2HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\
& + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]
\end{aligned}
$$

Assume an additional Z_2 symmetry to avoid tree-level FCNC's

t couples to Φ_2,
- b to Φ_2,
  - τ to Φ_2 "type I"
  - τ to Φ_1 "type X"
- b to Φ_1,
  - τ to Φ_2 "type Y"
  - τ to Φ_1 "type II"

Parameters

The 8 potential parameters can be translated into 8 physical parameters:

$$v = 246 \text{ GeV}, \quad m_h = 125 \text{ GeV},$$

$$m_H, \quad m_A, \quad m_{H^+}, \quad m_{12}^2, \quad \tan\beta, \quad \beta - \alpha$$

Parameters

The 8 potential parameters can be translated into 8 physical parameters:

$v = 246$ GeV, $\quad m_h = 125$ GeV,

$m_H, \quad m_A, \quad m_{H^+}, \quad m_{12}^2, \quad \tan\beta, \quad \beta - \alpha$

Alignment limit: $\quad (\beta-\alpha) - \frac{\pi}{2} \to 0$

Decoupling limit: $\quad (\beta-\alpha) - \frac{\pi}{2} \ll 1$ and $m_H \approx m_A \approx m_{H^+} \gg m_h$

[Gunion, Haber '02]

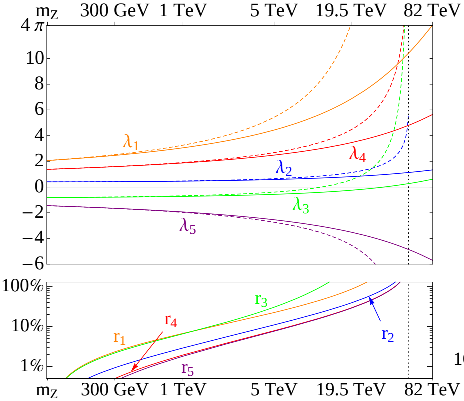
NLO RGE

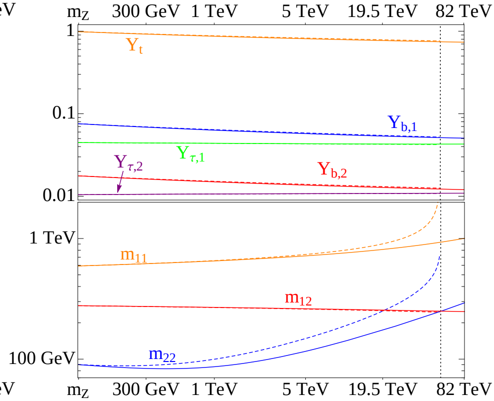
We get the NLO RGE using PyR@TE.
[Lyonnet, Schienbein, Staub, Wingerter '13]
(http://pyrate.hepforge.org/)

Benchmark point from [Baglio, OE, Nierste, Wiebusch '14]:

$m_H = 600$ GeV, $m_A = 658$ GeV, $m_{H^+} = 591$ GeV,
$\tan\beta = 4.28$, $\beta - \alpha = 0.513\pi$ and $m_{12}^2 = (277.3 \text{ GeV})^2$

Benchmark point – potential parameters



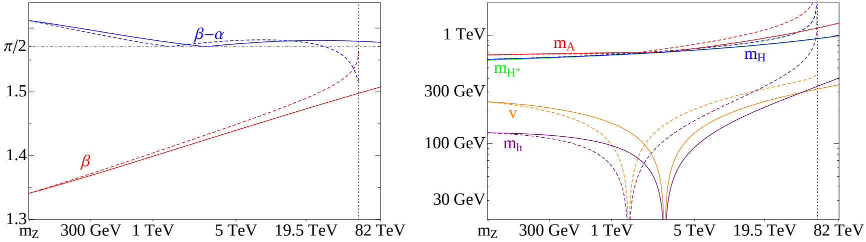


$$r_i = \left| \frac{\lambda_i^{\mathbf{LO}} - \lambda_i^{\mathbf{NLO}}}{\lambda_i^{\mathbf{NLO}}} \right|$$

- - - - - LO RGE

——— NLO RGE

Benchmark point – physical parameters



[Chowdhury, OE '15]

- - - - - LO RGE

——— NLO RGE

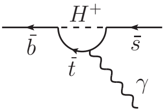
Potential stability bounds

- Positivity of the scalar potential [Deshpande, Ma '78]
- Unitarity of the $\phi_i\phi_j \to \phi_i\phi_j$ S-matrix ($\|S_{\phi_i\phi_j \to \phi_i\phi_j}\| < \frac{1}{8}$)
  [Nierste, Riesselmann '96; Ginzburg, Ivanov '05; Baglio, OE, Nierste, Wiebusch '14]
- Global minimum at 246 GeV [Barroso, Ferreira, Ivanov, Santos '13]

Define the largest scale which is compatible with the stability criteria as cut-off $\mu_{\text{stability}}$.

Flavour and electroweak observables

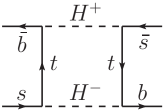
$\mathcal{B}(b \to s\gamma)$



[Hermann, Misiak, Steinhauser '12; Misiak et al. '15; HFAG '14]

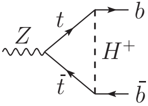
Δm_{B_s}

[Deschamps et al. '09; LHCb '13]

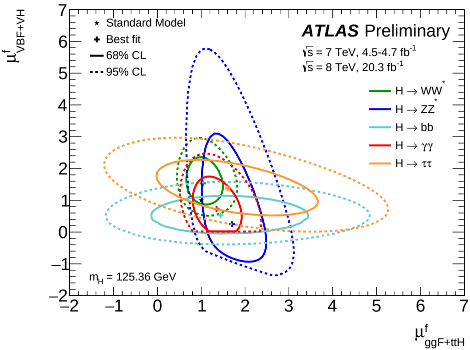


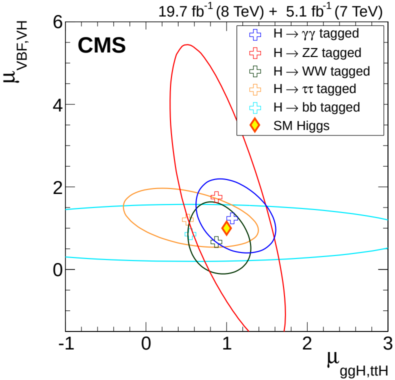
$M_W,\ \Gamma_W,\ \Gamma_Z,\ \sin^2\theta_l^{\mathrm{eff}},\ \sigma^0_{\mathrm{had}},\ A^{0,l}_{\mathrm{FB}},\ A^{0,c}_{\mathrm{FB}},\ A^{0,b}_{\mathrm{FB}},\ A_l,\ A_c,\ A_b,\ R^0_l,\ R^0_c,\ R^0_b$

[Zfitter '90,'01,'06; LEP & SLD '06]



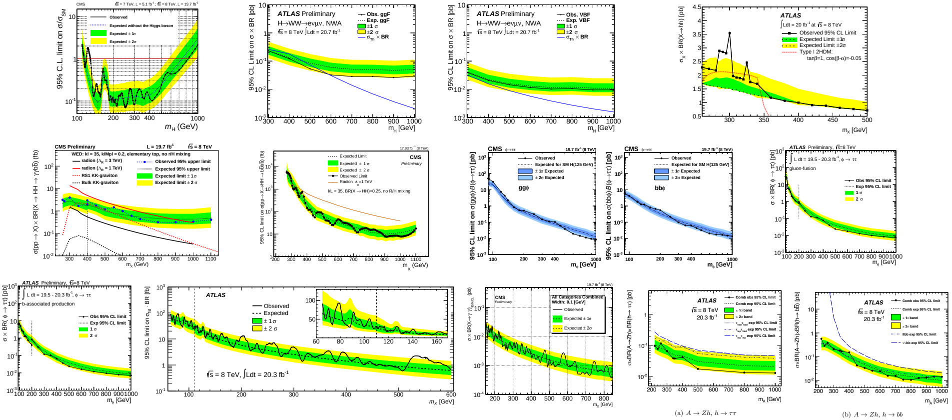
Light Higgs signal strengths





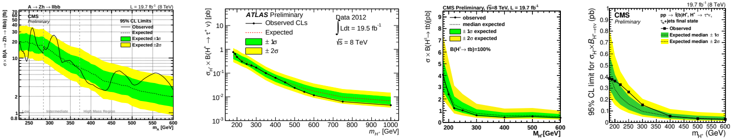
[ATLAS '15; CMS '15]

Heavy Higgs searches



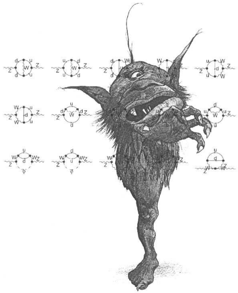
(a) $A \to Zh,\ h \to \tau\tau$

(b) $A \to Zh,\ h \to bb$



[LHC '15]

Framework



FeynArts 3.8

FormCalc 8

LoopTools 2.8

Pyr@te

Python Renormalization Group Equations @ Two-Loop for Everyone

ZFITTER
The Fortran Package ZFITTER

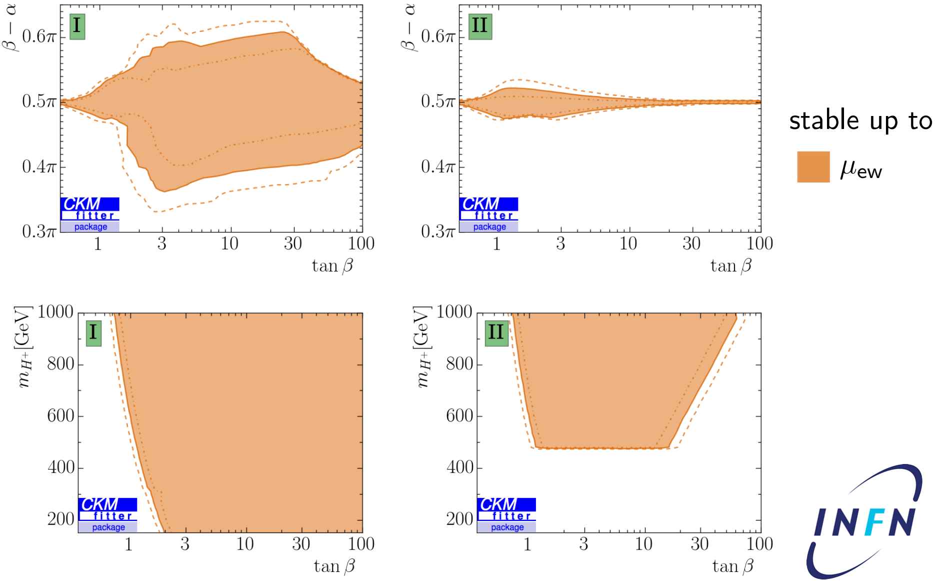
FeynRules 2.0

HDECAY

MADGRAPH 5

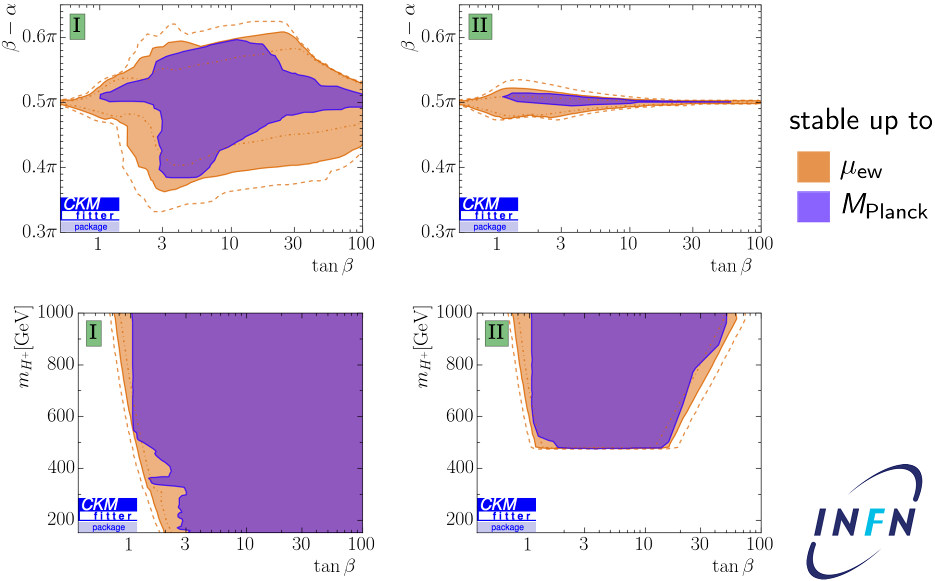
CKM fitter package

Fit results



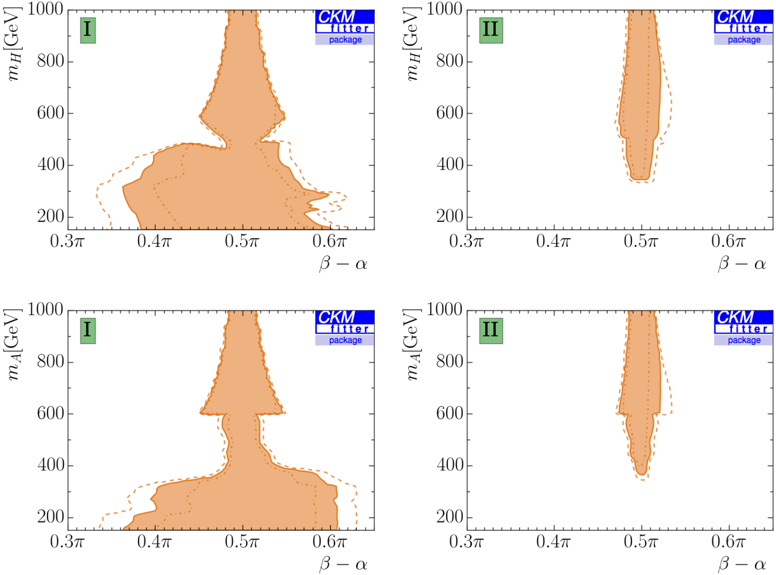
I
II
$\beta - \alpha$
0.6π
0.5π
0.4π
0.3π
1
3
10
30
100
$\tan\beta$
m_{H^+}[GeV]
1000
800
600
400
200
CKM fitter package
stable up to
μ_{ew}

Fit results



I
II
$\beta - \alpha$
0.6π
0.5π
0.4π
0.3π
1
3
10
30
100
tan β
m_{H^+}[GeV]
1000
800
600
400
200
CKM fitter package
stable up to
μ_{ew}
M_{Planck}

Fit results

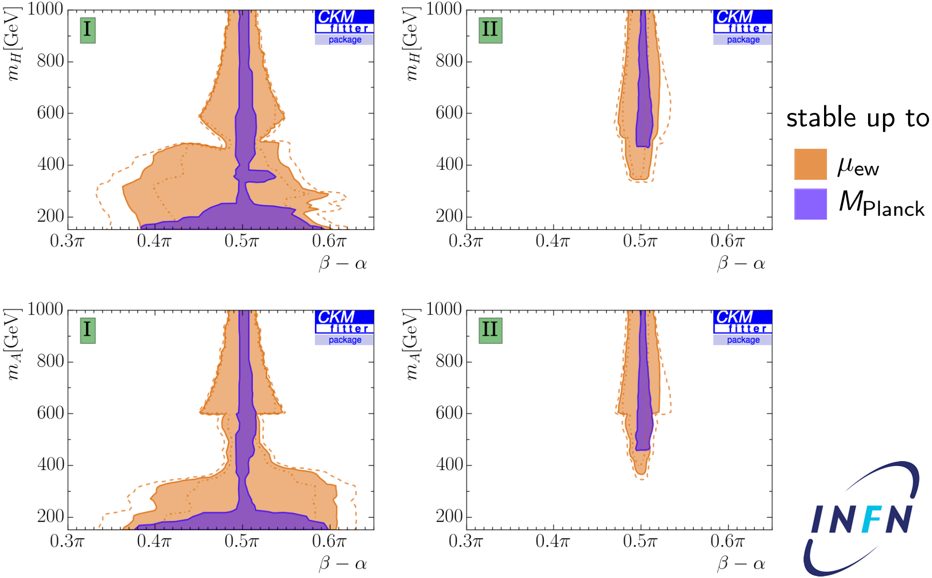


stable up to

μ_{ew}

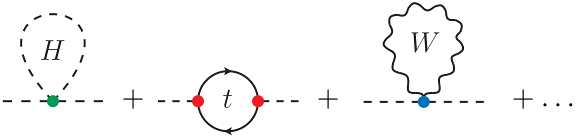
INFN

Fit results


I
II
CKM fitter package
1000
800
600
400
200
m_H[GeV]
m_A[GeV]
0.3π
0.4π
0.5π
0.6π
$\beta - \alpha$
stable up to
μ_{ew}
M_{Planck}

Naturalness

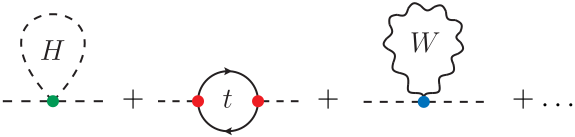
$$\delta m_h^2 =$$



$$= \frac{\mu_{\text{nat}}^2}{16\pi^2}\left[\sum_{n=0}^{\infty} f_n(\lambda_i, Y_i, g_i)\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)^n\right] + \mathcal{O}\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)$$

Naturalness

$$\delta m_h^2 =$$

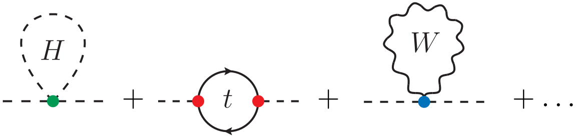


$$= \frac{\mu_{\text{nat}}^2}{16\pi^2} \left[\sum_{n=0}^{\infty} f_n(\color{green}{\lambda_i}, \color{red}{Y_i}, \color{blue}{g_i}) \left(\ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}} \right)^n \right] + \mathcal{O}\left(\ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}} \right)$$

$$\approx \frac{\mu_{\text{nat}}^2}{16\pi^2} f_0(\lambda_i, Y_i, g_i) \left[1 + \sum_{n=1}^{\infty} \prod_{\ell=1}^{n} k_\ell \right]$$

$$\text{with} \quad k_n = \frac{f_n(\lambda_i, Y_i, g_i)}{f_{n-1}(\lambda_i, Y_i, g_i)} \ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}$$

Naturalness

$\delta m_h^2 =$ 

$$= \frac{\mu_{\text{nat}}^2}{16\pi^2}\left[\sum_{n=0}^{\infty} f_n(\lambda_i, Y_i, g_i)\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)^n\right] + \mathcal{O}\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)$$

$$\approx \frac{\mu_{\text{nat}}^2}{16\pi^2} f_0(\lambda_i, Y_i, g_i)\left[1 + \sum_{n=1}^{\infty}\prod_{\ell=1}^{n} k_\ell\right]$$

$$\text{with} \quad k_n = \frac{f_n(\lambda_i, Y_i, g_i)}{f_{n-1}(\lambda_i, Y_i, g_i)} \ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}$$

Assuming $\mu_{\text{nat}} = \mu_{\text{stability}}$, $|k_1|, |k_2| \leq 1$ and $|\delta m_h^2| \leq m_h^2$:

$$\boxed{|f_0(\lambda_i, Y_i, g_i)| < 6 \text{ and } \mu_{\text{nat}} \lesssim 5 \text{ TeV}}$$

Conclusions

- 2HDM NLO RGE in arXiv:1503.08216
- $\tan\beta > 1$ with $\mu_{\text{stability}}$ at M_{Planck}
- $\left|\beta - \alpha - \frac{\pi}{2}\right| < \begin{matrix} 0.14\pi \\ 0.12\pi \end{matrix}$ with $\mu_{\text{stability}}$ at $\begin{matrix} m_Z \\ M_{\text{Planck}} \end{matrix}$ in type I

  $\left|\beta - \alpha - \frac{\pi}{2}\right| < \begin{matrix} 0.026\pi \\ 0.016\pi \end{matrix}$ with $\mu_{\text{stability}}$ at $\begin{matrix} m_Z \\ M_{\text{Planck}} \end{matrix}$ in type II
- Perturbative naturalness of m_h is only possible for μ_{nat} in the TeV range.

Future outlook

HEPfit project (https://github.com/silvest/HEPfit)
Bayesian open-source fits of the SM and beyond, including:

- ✔ 2HDMs as presented here with
  - ✔ Stability constraints
  - ✔ S, T, U
  - ✔ Higgs constraints (LO)
  - ✔ $b \to s\gamma$ (NNLO), Δm_{B_s} (LO), $B \to \tau\nu$ (LO)
  - ✘ Further flavour observables (LO)
  - ✘ EWPO
  - ✘ RGE (NLO)
- ✘ $m_H = 125$ GeV
- ✘ CP violation in the scalar potential
- ✘ Other types of 2HDMs (inert, BGL, type III)

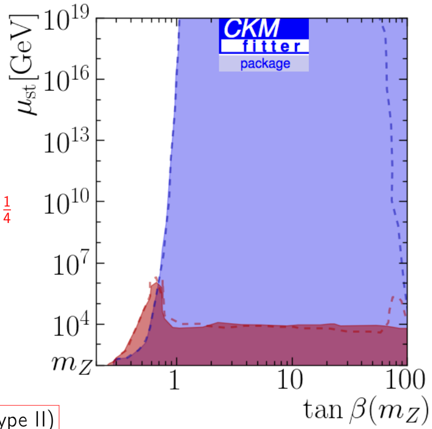
First HEPfit release planned this winter – stay tuned!

Back-up

Limits on $\beta - \alpha$, $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$

		Type I	Type II
$\mu_{\text{st}} = \mu_{\text{ew}}$	$\beta - \alpha$	$[1.14; 1.91]$	$[1.49; 1.64]$
		$[0.36\pi; 0.61\pi]$	$[0.47\pi; 0.52\pi]$
	$\cos(\beta - \alpha)$	$[-0.33; 0.42]$	$[-0.068; 0.081]$
	$\sin(\beta - \alpha)$	$[0.908; 1]$	$[0.997; 1]$
$\mu_{\text{st}} = \mu_{\text{Pl}}$	$\beta - \alpha$	$[1.21; 1.87]$	$[1.55; 1.62]$
		$[0.39\pi; 0.60\pi]$	$[0.493\pi; 0.516\pi]$
	$\cos(\beta - \alpha)$	$[-0.30; 0.36]$	$[-0.044; 0.018]$
	$\sin(\beta - \alpha)$	$[0.934; 1]$	$[0.999; 1]$

Why do we use $\|S_{\phi_i\phi_j\to\phi_i\phi_j}\| < \frac{1}{8}$



$\max(\|S_{\phi_i\phi_j\to\phi_i\phi_j}\|) < \frac{1}{8}$

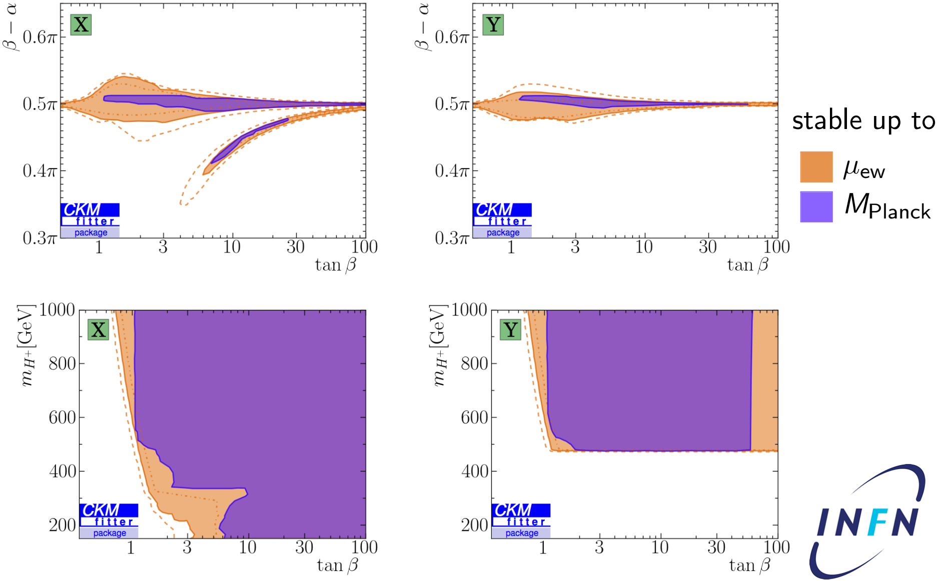
$\frac{1}{8} < \max(\|S_{\phi_i\phi_j\to\phi_i\phi_j}\|) < \frac{1}{4}$

If $\mu_{\text{stability}} = M_{\text{Planck}}$:

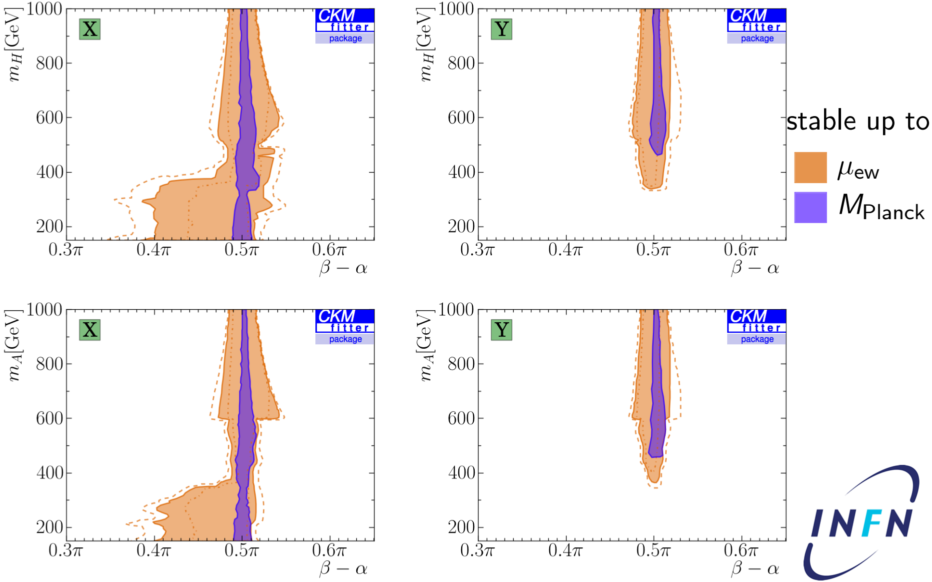
$\|S_{\phi_i\phi_j\to\phi_i\phi_j}\| \lesssim \frac{1}{20}$

$\tan\beta > 1$ (and < 60 in type II)

Fit results for the types X and Y



Fit results for the types X and Y



$f_n(\lambda_i, Y_i, g_i)$

$$\delta m_h^2 = \frac{\mu_{\text{nat}}^2}{16\pi^2}\left[\sum_{n=0}^{\infty} f_n(\lambda_i, Y_i, g_i)\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)^n\right] + \mathcal{O}\left(\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)$$

$$\approx \frac{\mu_{\text{nat}}^2}{16\pi^2} f_0(\lambda_i, Y_i, g_i)\left[1 + \sum_{n=1}^{\infty}\prod_{\ell=1}^{n}\underbrace{\left(\frac{f_\ell(\lambda_i, Y_i, g_i)}{f_{\ell-1}(\lambda_i, Y_i, g_i)}\ln\frac{\mu_{\text{nat}}}{\mu_{\text{ew}}}\right)}_{k_\ell}\right]$$

$$f_0(\lambda_i, Y_i, g_i) = \frac{3}{2}\lambda_1 + \frac{3}{2}\lambda_2 - \frac{3}{2}\cos(2\alpha)(\lambda_1 - \lambda_2) + 2\lambda_3 + \lambda_4$$
$$- \cos^2(\alpha)\left(6Y_b^2 + 6Y_t^2 + 2Y_\tau^2\right) + \frac{3}{4}g_1^2 + \frac{9}{4}g_2^2$$

$$f_{n+1}(\lambda_i, Y_i, g_i) = \frac{1}{n+1}\sum_{L\in\{\lambda_i, Y_i, g_i\}}\beta_L\frac{\partial}{\partial L}f_n(\lambda_i, Y_i, g_i)$$

Literature

[ATLAS '15] – ATLAS Collaboration, ATLAS-CONF-2015-007

[Baglio, OE, Nierste, Wiebusch '14] – J. Baglio, O. Eberhardt, U. Nierste and M. Wiebusch, Phys.Rev. D90 (2014) 015008

[Barroso, Ferreira, Ivanov, Santos '13] – A. Barroso, P. Ferreira, I. Ivanov and R. Santos, JHEP 1306 (2013) 045

[Chowdhury, OE '15] – D. Chowdhury, O. Eberhardt, JHEP 1511 (2015) 052

[CMS '15] – CMS Collaboration, Eur.Phys.J. C75 (2015) 212

[Deschamps et al. '09] – O. Deschamps, S. Descotes-Genon, S. Monteil, V. Niess, S. T'Jampens and V. Tisserand, Phys.Rev. D82 (2010) 073012

[Deshpande, Ma '78] – N. G. Deshpande and E. Ma, Phys.Rev. D18 (1978) 2574

[Ginzburg, Ivanov '05] – I. Ginzburg and I. Ivanov, Phys.Rev. D72 (2005) 115010

Literature (continued)

[Gunion, Haber '02] – J. F. Gunion and H. E. Haber, Phys.Rev. D67 (2003) 075019

[Hermann, Misiak, Steinhauser '12] – T. Hermann, M. Misiak, and M. Steinhauser, JHEP 1211 (2012) 036

[HFAG '14] – Heavy Flavor Averaging Group http://www.slac.stanford.edu/xorg/hfag/rare/2014/radll/OUTPUT/HTML/radll_table3.html

[LEP & SLD '06] – ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group, S. Schael et al., Phys.Rept. 427 (2006) 257-454

[LHC '15] – various ATLAS and CMS measurements, see [Chowdhury, OE '15]

[LHCb '13] – LHCb Collaboration, New J.Phys. 15 (2013) 053021

Literature (continued)

[Lyonnet, Schienbein, Staub, Wingerter '13] – F. Lyonnet, I. Schienbein, F. Staub, A. Wingerter, Comput.Phys.Commun. 185 (2014) 1130-1152

[Misiak et al. '15] – M. Misiak, H.M. Asatrian, R. Boughezal, M. Czakon, T. Ewerth, A. Ferroglia, P. Fiedler, P. Gambino, C. Greub, U. Haisch T. Huber, M. Kaminski, G. Ossola, M. Poradzinski, A. Rehman, T. Schutzmeier, M. Steinhauser and J. Virto, arXiv:1503.01789

[Nierste, Riesselmann '96] – U. Nierste and K. Riesselmann, Phys.Rev. D53 (1996) 6638-6652

[Zfitter '90,'01,'06] – D. Y. Bardin, M. S. Bilenky, T. Riemann, M. Sachwitz and H. Vogt, Comput.Phys.Commun. 59 (1990) 303-312; D. Y. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, T. Riemann, Comput.Phys.Commun. 133 (2001) 229-395; A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M.W. Grunewald, K. Mönig, S. Riemann, T. Riemann, Comput.Phys.Commun. 174 (2006) 728-758