

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

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in collaboration with O. Eberhardt

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SUSY 2015

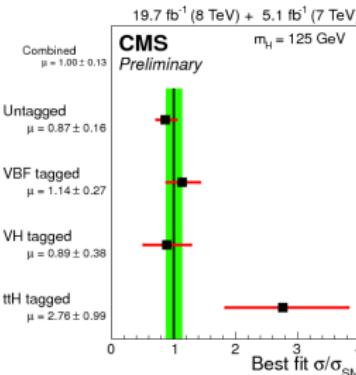
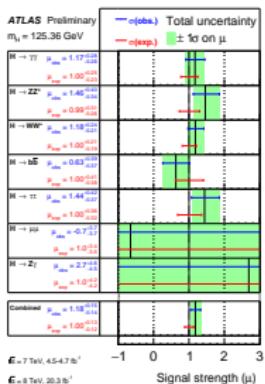
Lake Tahoe

Aug 24 2015



Higgs Discovery at LHC

- Mass of the Higgs is around 125 GeV.
- Higgs is parity even and spin-0.
- Higgs properties in Run-1 look “SM-like”.
- Measurements are in reasonable agreement with SM-predictions.



Motivation

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

- Why spin-0 content is minimal while spin- $\frac{1}{2}$ is not?
- No evidence of any degrees of freedom which could ensure the naturalness of the Higgs mass.

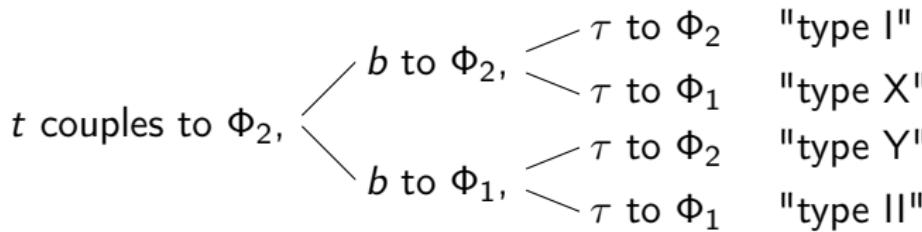
Model

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

Model

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

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



Parameters

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

$$\begin{aligned} v &\approx 246 \text{ GeV}, \quad m_h = 125 \text{ GeV}, \\ m_H, \quad m_A, \quad m_{H^+}, \quad m_{12}^2, \quad \tan \beta, \quad \beta - \alpha \end{aligned}$$

Parameters

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$$\nu \approx 246 \text{ GeV}, \quad m_h = 125 \text{ GeV}, \\ m_H, \quad m_A, \quad m_{H^+}, \quad m_{12}^2, \quad \tan \beta, \quad \beta - \alpha$$

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

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

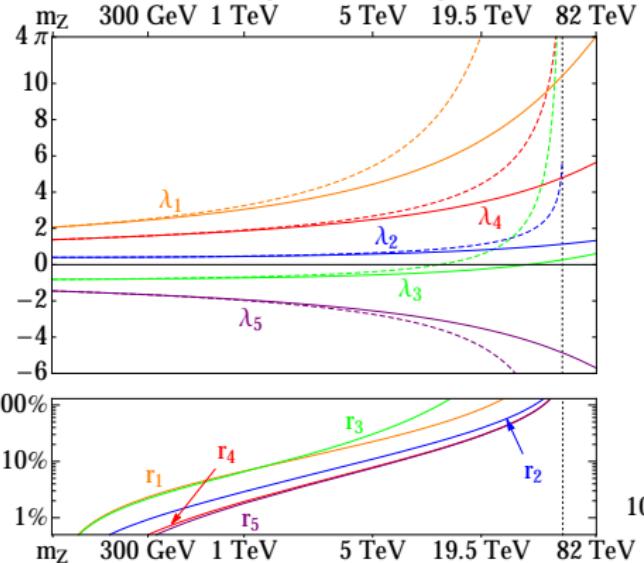
[Gunion, Haber '02, Craig et al. '13, Carena et al. '13]

NLO RGE

- We are interested to see whether the 2HDM can be extended to high-scale as a theory beyond the SM.
- In the analysis we employ 2-loop RGEs of the 2HDM parameters.
- To see the effect of NLO RGE we use the a benchmark point from [\[Baglio, Eberhardt, Nierste, Wiebusch '14\]](#):

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

Benchmark point – potential parameters

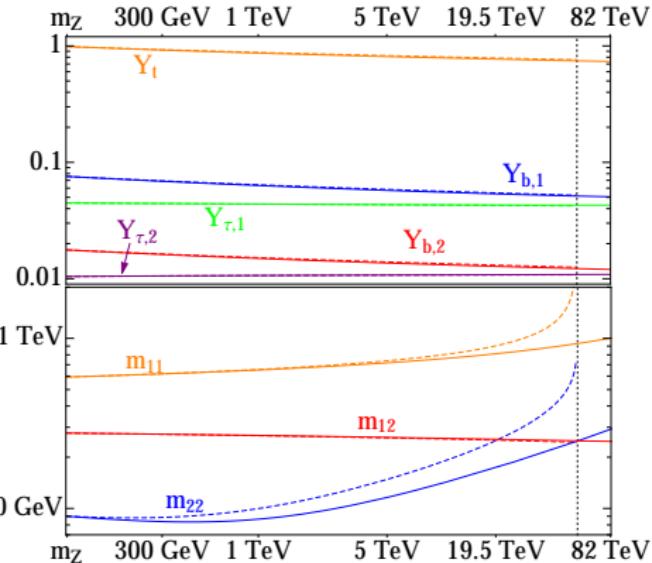


$$r_i = \left| \frac{\lambda_i^{\text{LO}} - \lambda_i^{\text{NLO}}}{\lambda_i^{\text{NLO}}} \right|$$

— LO RGE
— NLO RGE

✓ 2-loop RGEs softens the running.

✓ Cut-off scale is pushed to higher values with 2-loop RGEs.



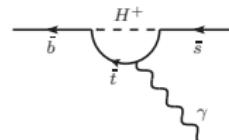
Potential stability bounds

- Positivity of the scalar potential [Deshpande, Ma '78]
- Unitarity of the $\phi_i\phi_j \rightarrow \phi_i\phi_j$ S-matrix ($\|S_{\phi_i\phi_j \rightarrow \phi_i\phi_j}\| < \frac{1}{8}$)
[Nierste, Riesselmann '96; Ginzburg, Ivanov '05;
Baglio, Eberhardt, 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

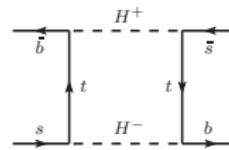
$$\mathcal{B}(b \rightarrow s\gamma)$$



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

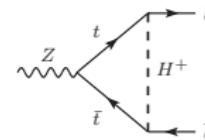
$$\Delta m_{B_s}$$

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

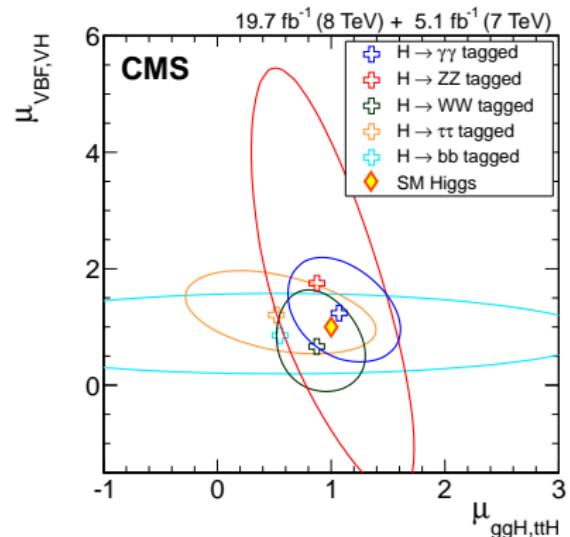
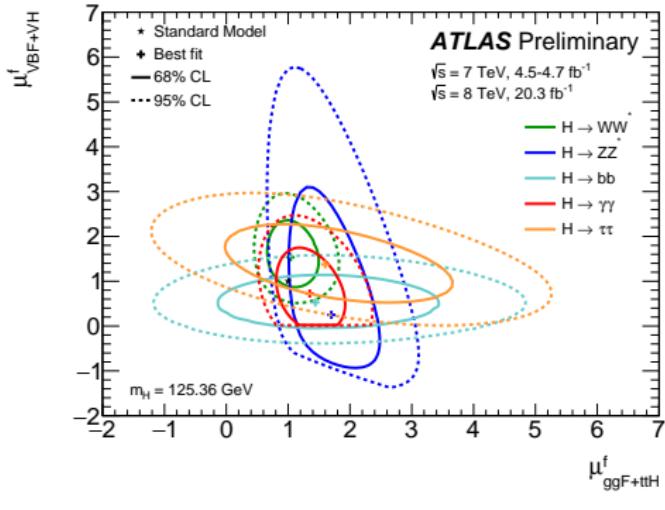


$$M_W, \Gamma_W, \Gamma_Z, \sin^2 \theta_I^{\text{eff}}, \sigma_{\text{had}}^0, A_{\text{FB}}^{0,I}, A_{\text{FB}}^{0,c}, A_{\text{FB}}^{0,b}, A_I, A_c, A_b, R_I^0, R_c^0, R_b^0$$

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

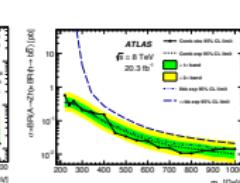
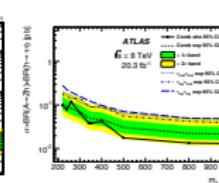
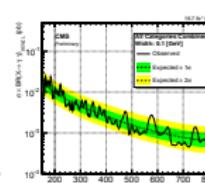
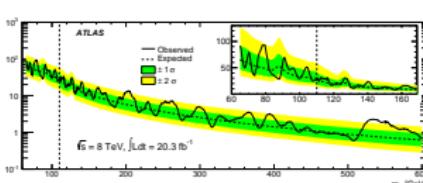
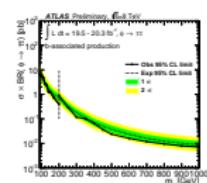
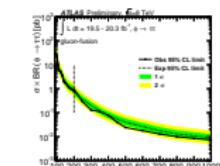
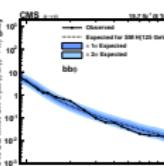
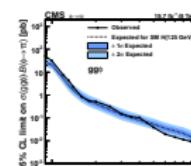
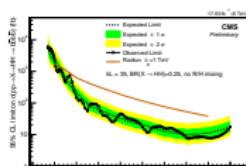
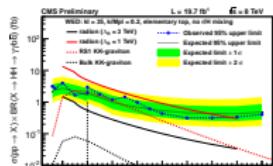
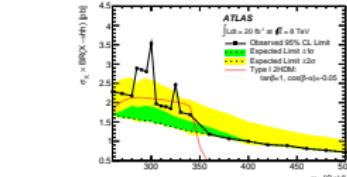
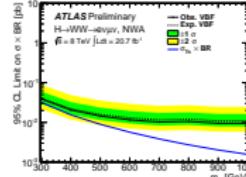
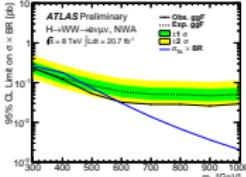
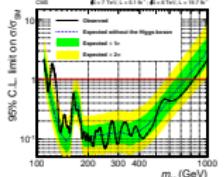
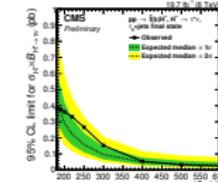
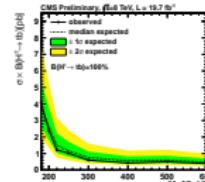
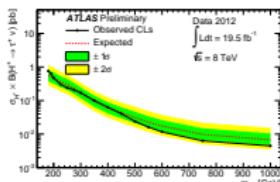
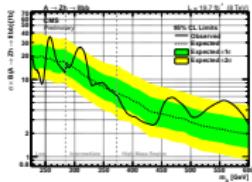


Light Higgs signal strengths



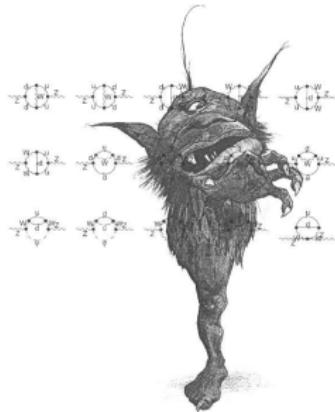
[ATLAS '15; CMS '15]

Heavy Higgs searches

(a) $A \rightarrow Z h, h \rightarrow \tau\tau$ (b) $A \rightarrow Z h, h \rightarrow b\bar{b}$ 

[LHC '15]

Framework



FeynArts 3.8

FormCalc 8

LoopTools 2.8



Python Renormalization Group Equations @ Two-Loop for Everyone



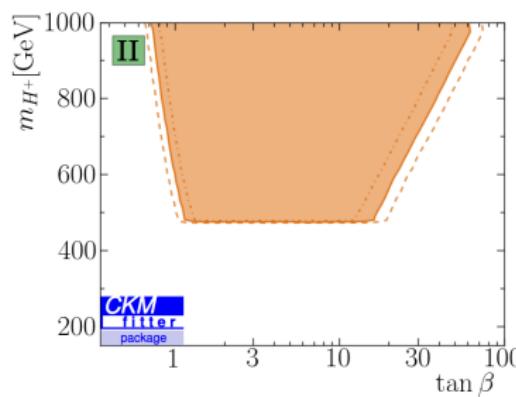
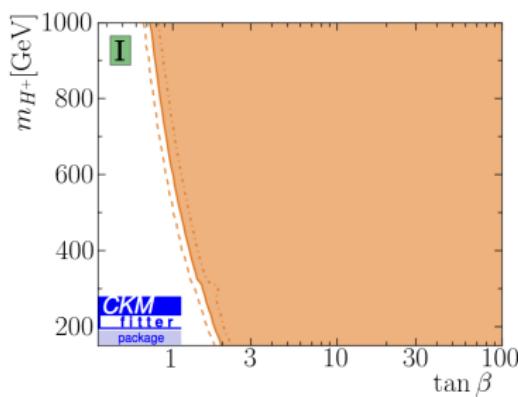
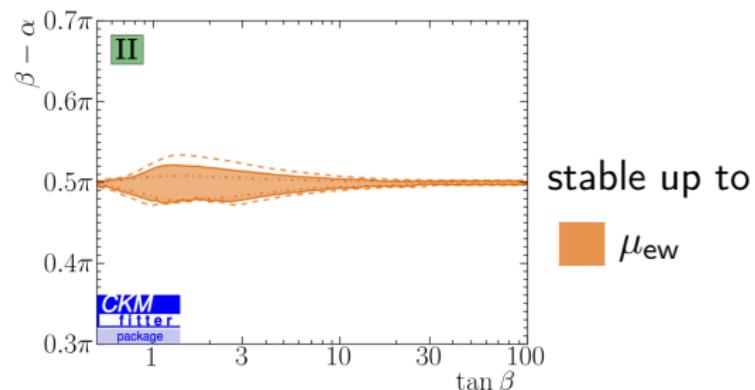
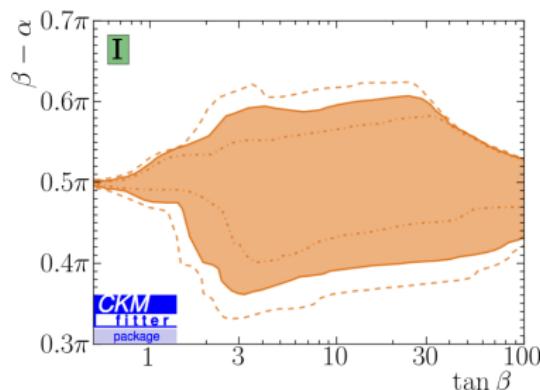
FEYNRULES 2.0



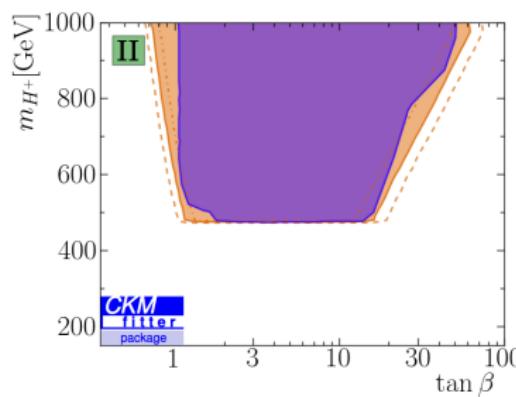
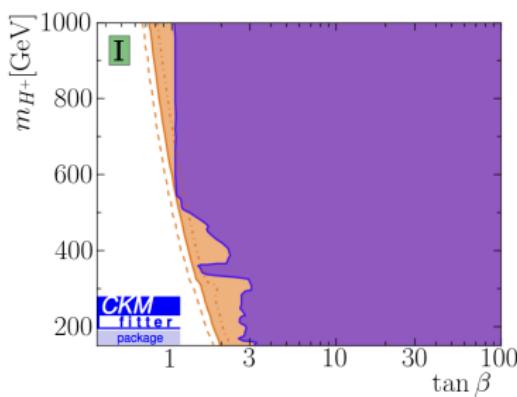
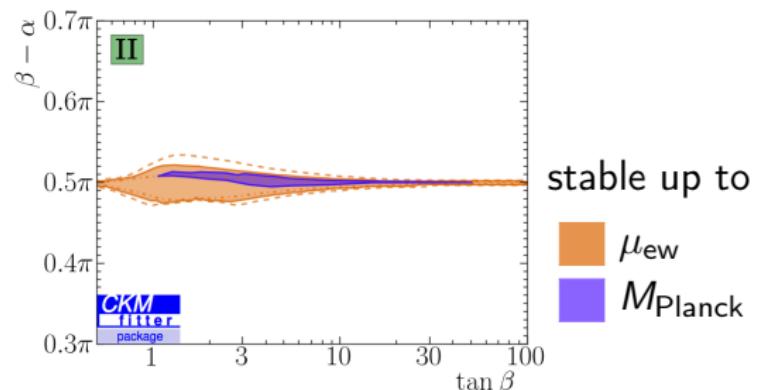
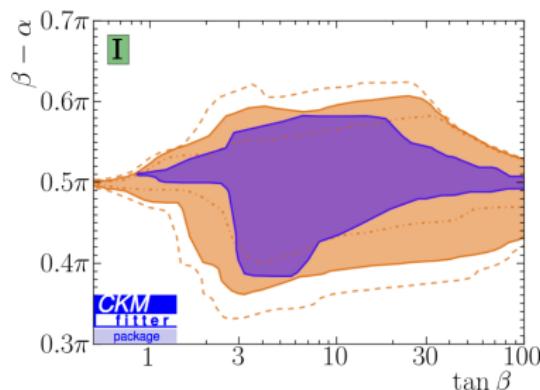
HDECAY



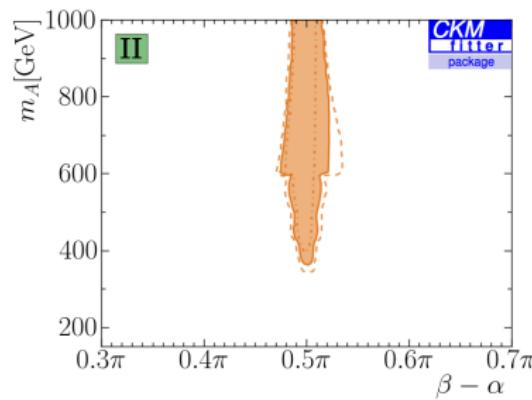
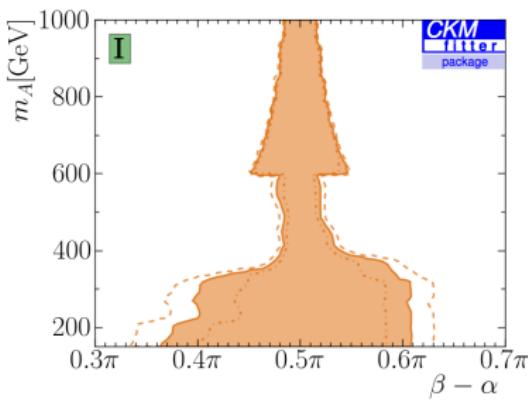
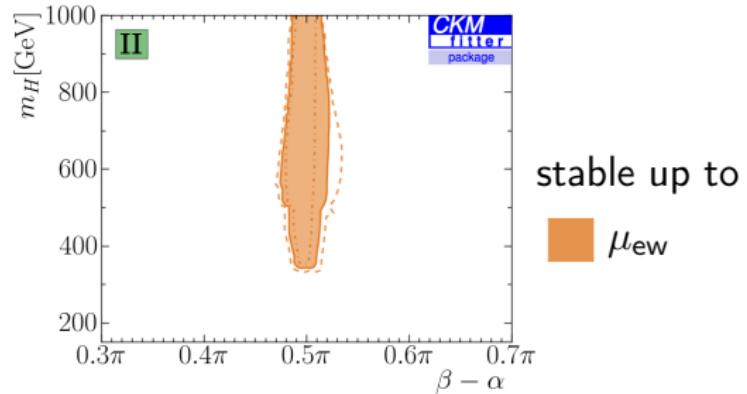
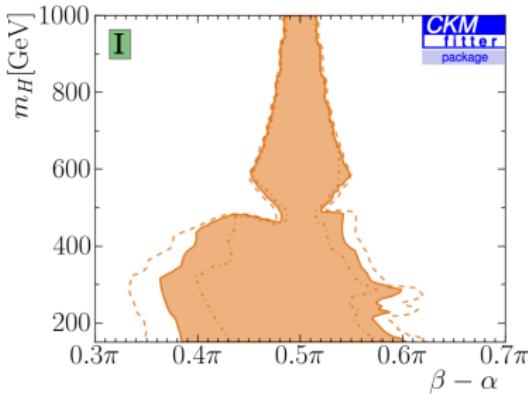
Fit results



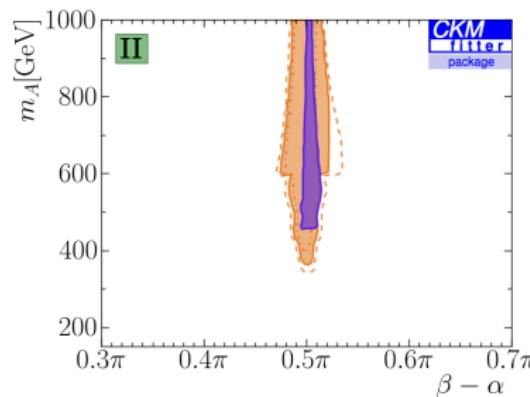
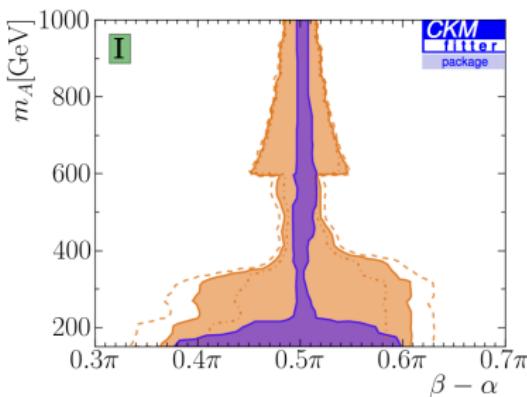
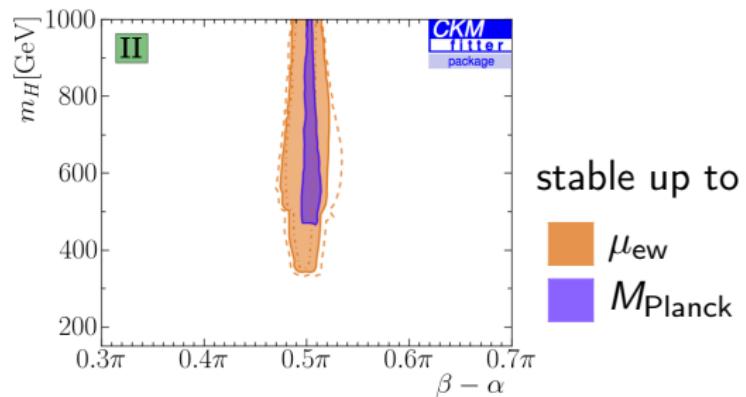
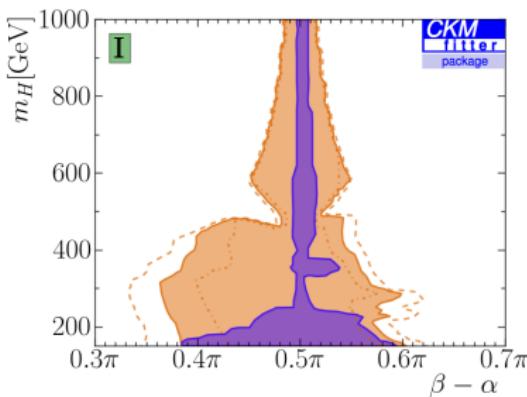
Fit results



Fit results



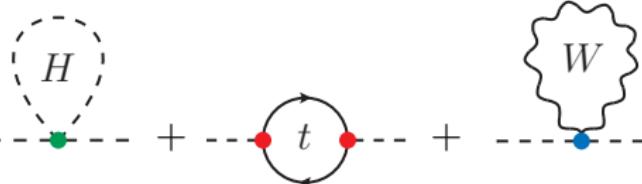
Fit results



Naturalness

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

Naturalness



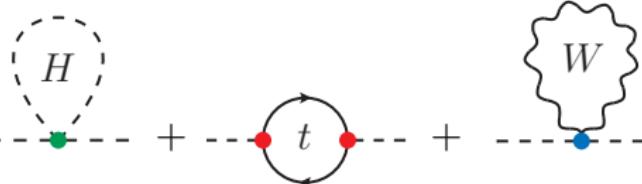
$$\delta m_h^2 = \text{---} \circlearrowleft \text{---} + \text{---} \circlearrowright \text{---} + \text{---} \circlearrowup \text{---} + \dots$$

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

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

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

Naturalness



$$\delta m_h^2 = \text{---} \cdot \text{---} + \text{---} \circlearrowleft t \circlearrowright \text{---} + \text{---} \cdot \text{---} + \dots$$

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

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

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

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

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

Conclusions

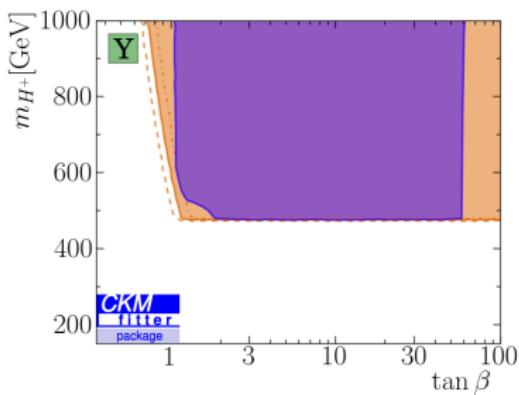
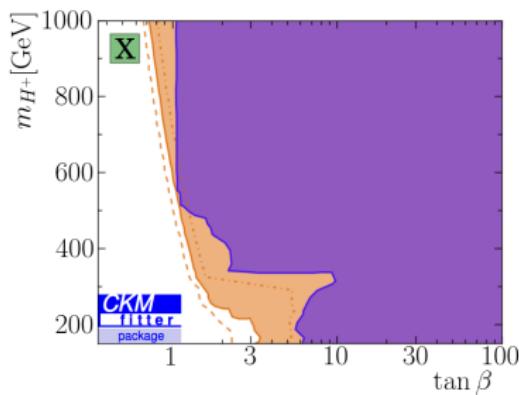
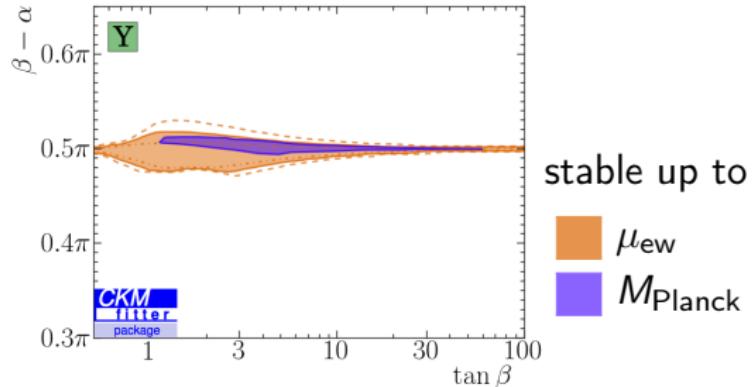
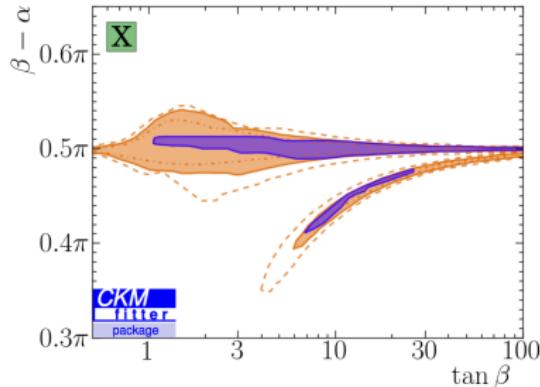
- 2HDM NLO RGE in arXiv:1503.08216
- $\tan \beta > 1$ with $\mu_{\text{stability}}$ at M_{Planck}
- $|\beta - \alpha - \frac{\pi}{2}| < \frac{0.14\pi}{0.12\pi}$ with $\mu_{\text{stability}}$ at $\frac{m_Z}{M_{\text{Planck}}}$ in type I
- $|\beta - \alpha - \frac{\pi}{2}| < \frac{0.025\pi}{0.014\pi}$ with $\mu_{\text{stability}}$ at $\frac{m_Z}{M_{\text{Planck}}}$ in type II
- Perturbative naturalness of m_h is only possible for μ_{nat} in the TeV range.

Back-up

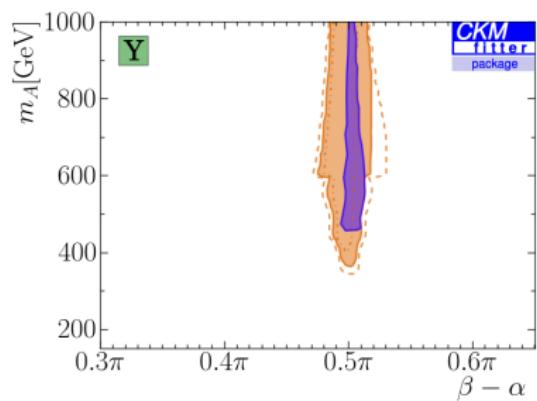
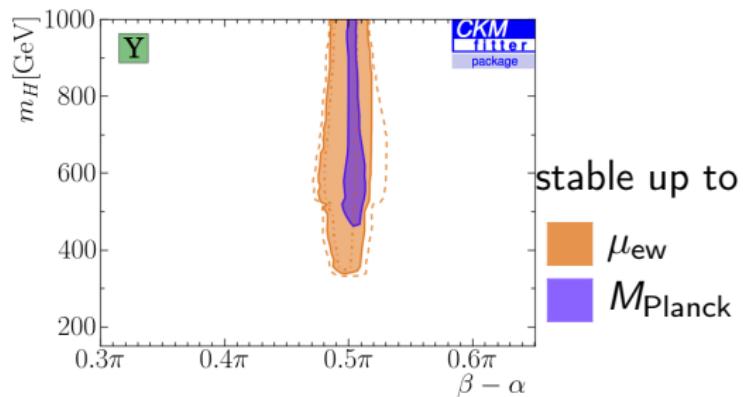
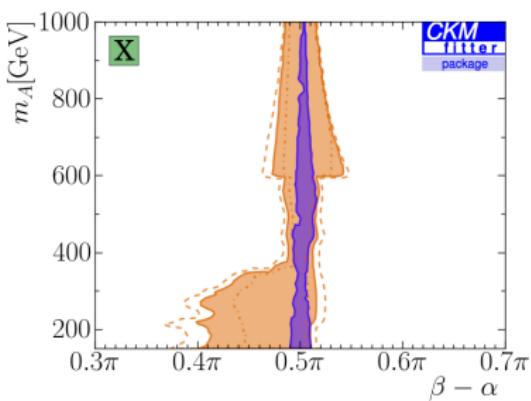
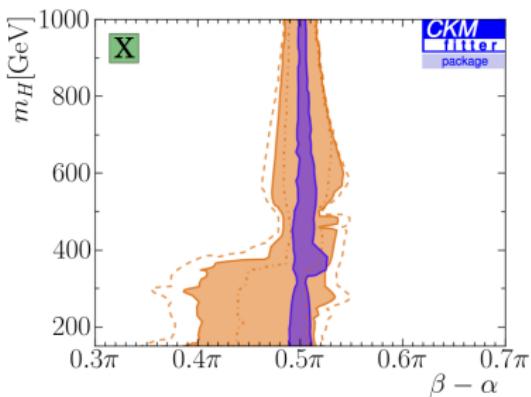
Limits on $\beta - \alpha$, $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$

		Type I	Type II
$\mu_{\text{st}} = \mu_{\text{ew}}$	$\beta - \alpha$	$[1.136; 1.909]$ $[0.362\pi; 0.608\pi]$	$[1.491; 1.640]$ $[0.475\pi; 0.522\pi]$
	$\cos(\beta - \alpha)$	$[-0.332; 0.421]$	$[-0.069; 0.080]$
	$\sin(\beta - \alpha)$	$[0.907; 1]$	$[0.997; 1]$
$\mu_{\text{st}} = \mu_{\text{Pl}}$	$\beta - \alpha$	$[1.207; 1.87]$ $[0.384\pi; 0.595\pi]$	$[1.555; 1.614]$ $[0.495\pi; 0.514\pi]$
	$\cos(\beta - \alpha)$	$[-0.258; 0.36]$	$[-0.043; 0.016]$
	$\sin(\beta - \alpha)$	$[0.935; 1]$	$[0.999; 1]$

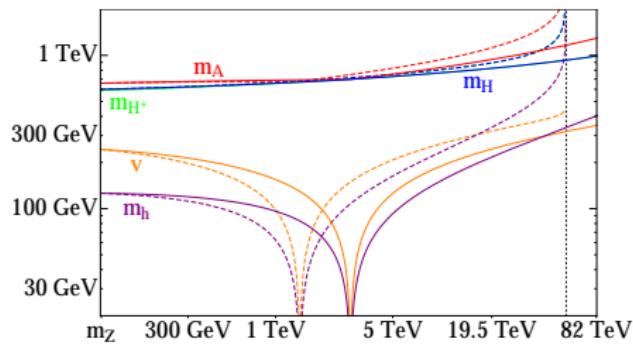
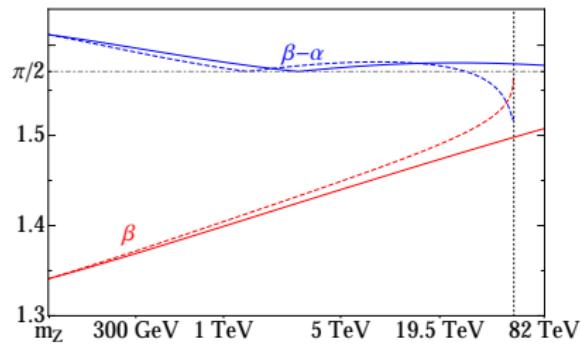
Fit results



Fit results



Benchmark point – physical parameters

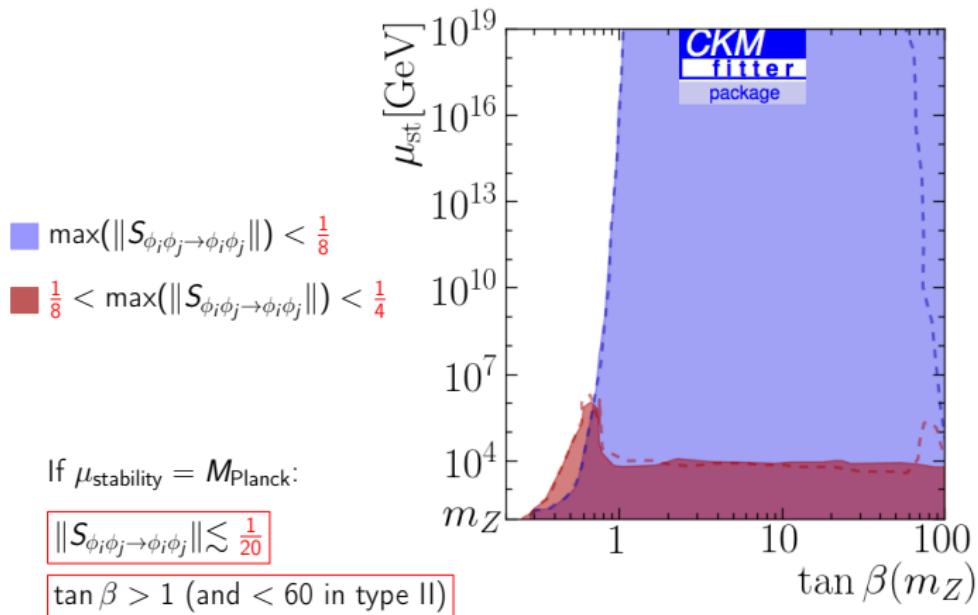


[DC, Eberhardt '15]

- - - - - LO RGE

— — — NLO RGE

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



$$f_n(\lambda_i, Y_i, g_i)$$

$$\begin{aligned}\delta m_h^2 &= \frac{\mu_{\text{nat}}^2}{16\pi^2} \left[\sum_{n=0}^{\infty} f_n(\lambda_i, Y_i, g_i) \left(\ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}} \right)^n \right] + \mathcal{O} \left(\ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}} \right) \\ &\approx \frac{\mu_{\text{nat}}^2}{16\pi^2} f_0(\lambda_i, Y_i, g_i) \left[1 + \sum_{n=1}^{\infty} \underbrace{\prod_{\ell=1}^n \left(\frac{f_\ell(\lambda_i, Y_i, g_i)}{f_{\ell-1}(\lambda_i, Y_i, g_i)} \ln \frac{\mu_{\text{nat}}}{\mu_{\text{ew}}} \right)}_{k_\ell} \right]\end{aligned}$$

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

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

Literature

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

[Baglio, Eberhardt, 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

[DC, Eberhardt '15] – D. Chowdhury, O. Eberhardt, arXiv:1503.08216

[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 [DC, Eberhardt '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. Ferroglio, 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