NLO unitarity fits of the 2HDM with HEPfit

Lisbon, 7th September 2016

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in collaboration with V. Cacchio, D. Chowdhury and C. Murphy

arXiv:1609.01290

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Outline

Introduction

The quartic couplings of the SM and MSSM Higgs potentials are perturbative; in the 2HDM not necessarily.

How can we tame loop contributions to those couplings in the 2HDM in order to maintain perturbativity?

What is HEPfit?

Flexible open-source C++ code to do calculations with various observables in the SM and beyond:

- Simple user-defined models and/or observables
- Stand-alone or library modes to compute single observables
- Optional Bayesian fitting framework to do global statistical analyses
  (run-time optimized, parallelized; can be replaced by a different, e.g. frequentist set-up)

Our goal: 4S – S much S fast and S precise S possible

Installation and usage

Depends on: ROOT, GSL, Boost, Bayesian Analysis Toolkit (BAT)

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tar zxvf HEPfit-x.x.tar.gz && cd HEPfit-x.x && cmake . -DLOCAL_INSTALL_ALL=ON -DMPIBAT=ON && make && make install
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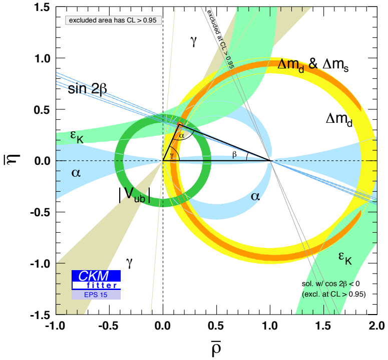
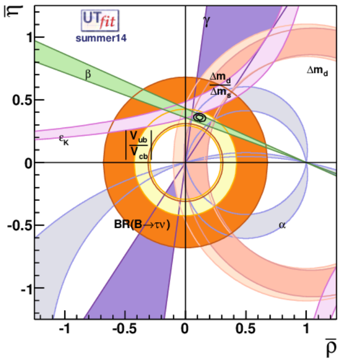
```
./analysis StandardModel.conf MonteCarlo.conf
```

Run time

Unitarity triangle fits with run time of at least a few days



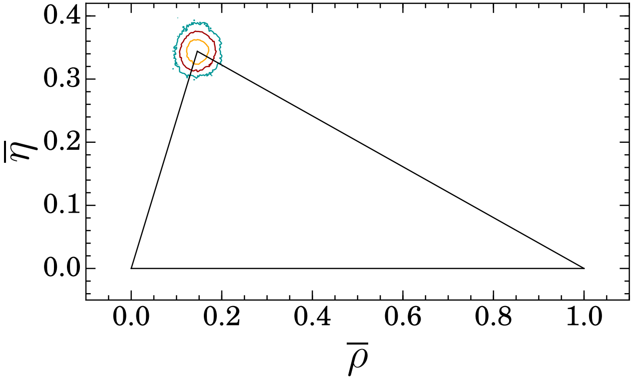
[CKMfitter '15]



[UTfit '14]

Run time

Unitarity triangle fit with HEPfit is possible on a laptop: about 1 hour with eight cores



Models in HEPfit

- SM and generic extensions (arXiv:1512.07157, arXiv:1608.01509)
- 2HDM with softly broken Z_2 (arXiv:1609.01290)
- MSSM with generic flavour structure
- Your model?

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Theory

Scalar Lagrangian:

$$\begin{aligned}\mathcal{L}_H^{\text{2HDM}} = & (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2) \\ & - m_{11}^2 \Phi_1^\dagger \Phi_1 - m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) \\ & - \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 - \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 - \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\ & - \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) - \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right] \\ & - \left\{ \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \right] \left(\Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right\}\end{aligned}$$

assuming Z_2 symmetry and no CP violation: 8 real parameters

Theory

Re-parametrisation:

λ_1		$v \approx 246$ GeV	v.e.v.
λ_2		$m_h \approx 125$ GeV	light CP-even Higgs mass
λ_3		m_H	heavy CP-even Higgs mass
λ_4	$\rightarrow$	m_A	CP-odd Higgs mass
λ_5		m_{H^+}	charged Higgs mass
m_{11}^2		α	diagonalisation angle of the CP-even mass matrix
m_{22}^2		β	diagonalisation angle of the CP-odd and charged mass matrix
m_{12}^2		m_{12}^2	soft Z_2 breaking parameter

Theory

We will use $\tan\beta$ and $\beta-\alpha$ instead of α and β.

Alignment limit: $(\beta-\alpha)-\frac{\pi}{2}\to 0$ $\Rightarrow$All h couplings SM-like

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

[Gunion, Haber '02]

Unitarity

SM (before the h was discovered)

The S-matrix is required to be unitary: $S^\dagger S = \mathbb{1}$

Partial wave decomposition: $|a_\ell^{2\to 2} - \frac{i}{2}|^2 + \sum\limits_{n>2} |a_\ell^{2\to n}|^2 = \frac{1}{4}$

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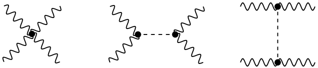
at LO: $a_0^{2\to 2} = -\frac{3\lambda}{8\pi} \quad \Rightarrow \boxed{\lambda \lesssim 4}$



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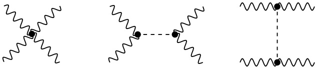
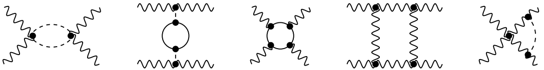


at NLO: $\lambda \lesssim 2.2$ [Durand, Johnson, Lopez '92]



Unitarity

2HDM with softly broken Z_2 $\quad$ $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ instead of one λ

Tree-level unitarity matrix:

$$\frac{1}{8\pi}\begin{pmatrix}
\lambda_1 & \lambda_5 & & & & & & & & & & \\
\lambda_5 & \lambda_2 & & & & & & & & & & \\
& & \lambda_3+\lambda_4 & & & & & & & & & \\
& & & \lambda_3-\lambda_4 & & & & & & & & \\
& & & & \lambda_1 & \lambda_4 & & & & & & \\
& & & & \lambda_4 & \lambda_2 & & & & & & \\
& & & & & & \lambda_3 & \lambda_5 & & & & \\
& & & & & & \lambda_5 & \lambda_3 & & & & \\
& & & & & & & & 3\lambda_1 & 2\lambda_3+\lambda_4 & & \\
& & & & & & & & 2\lambda_3+\lambda_4 & 3\lambda_2 & & \\
& & & & & & & & & & \lambda_3+2\lambda_4 & 3\lambda_5 \\
& & & & & & & & & & 3\lambda_5 & \lambda_3+2\lambda_4
\end{pmatrix}$$

[Casalbuoni, Dominici, Feruglio, Gatto, Giunti; Maalampi, Sirkka, Vilja; Kanemura, Kubota, Takasugi; Akeroyd, Arhrib, Naimi; Ginzburg, Ivanov; Horejsi, Kladiva; '88-'06]

Unitarity

2HDM with softly broken Z_2 $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ instead of one λ

Tree-level unitarity eigenvalues:

$$a^{\text{even,LO}}_{1,1\pm} = \frac{1}{16\pi}\left(\lambda_1 + \lambda_2 \mp \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right)$$

$$a^{\text{odd,LO}}_{1,\frac{1}{2}\pm\frac{1}{2}} = \frac{1}{8\pi}(\lambda_3 \pm \lambda_4)$$

$$a^{\text{even,LO}}_{0,1\pm} = \frac{1}{16\pi}\left(\lambda_1 + \lambda_2 \mp \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right)$$

$$a^{\text{odd,LO}}_{0,1\pm} = \frac{1}{8\pi}(\lambda_3 \mp \lambda_5)$$

$$a^{\text{even,LO}}_{0,0\pm} = \frac{1}{16\pi}\left(3(\lambda_1 + \lambda_2) \mp \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right)$$

$$a^{\text{odd,LO}}_{0,0\pm} = \frac{1}{8\pi}(\lambda_3 + 2\lambda_4 \mp 3\lambda_5)$$

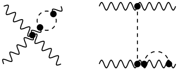
Unitarity

2HDM with softly broken Z_2

NLO unitarity eigenvalues (example):

$$a^{\text{odd,NLO}}_{1,\frac{1}{2}\pm\frac{1}{2}} = -\frac{3}{2}\left(\beta_{\lambda_3} \pm \beta_{\lambda_4}\right) - \frac{1}{16\pi^2}\left(i\pi - 1\right)\left(\lambda_3 \pm \lambda_4\right)^2$$

$$+ \text{ wavefunction renormalization}$$



[Grinstein, Murphy, Uttayarat '15]

Unitarity

2HDM with softly broken Z_2

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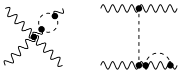


[Cacchio, Chowdhury, OE, Murphy '16]

Unitarity

2HDM with softly broken Z_2

Perturbativity of the NLO contributions:

$$R_1' = \frac{|a^{\text{NLO}}|}{|a^{\text{LO}}|} \leq 1$$

We apply this only if $|a^{\text{LO}}| > 0.02 \approx \frac{1}{16\pi}$.

Unitarity

2HDM with softly broken Z_2

We assure that the implicit assumption $s \gg |\lambda_i| v^2$ is fulfilled by imposing potential stability up to 750 GeV.

Only at this scale we start to apply the unitarity constraints.

Remaining constraints

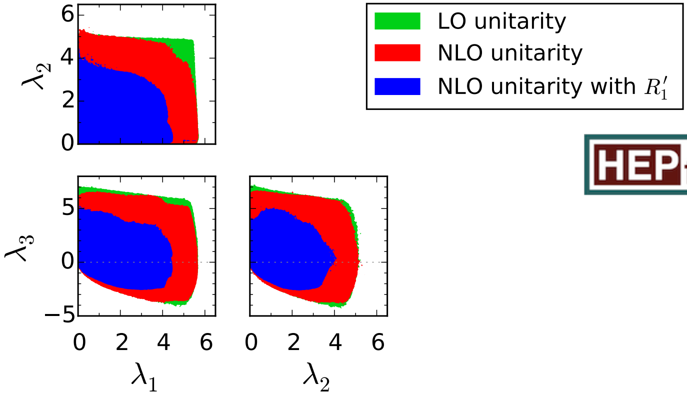
Theory:

- Positivity of the Higgs potential [Deshpande, Ma '78]
- Vacuum stability [Barroso, Ferreira, Ivanov, Santos '13]

Experiment:

- Oblique parameters [Haber '92]
- h signal strengths from LHC Run I
- H and A searches from LHC Run I
- Δm_{B_s} [Geng, Ng '88; Deschamps et al. '09] and $\mathcal{B}(\bar{B} \to X_s \gamma)$ [Hermann, Misiak, Steinhauser '12; Misiak et al. '15]

Quartic couplings – only theory constraints



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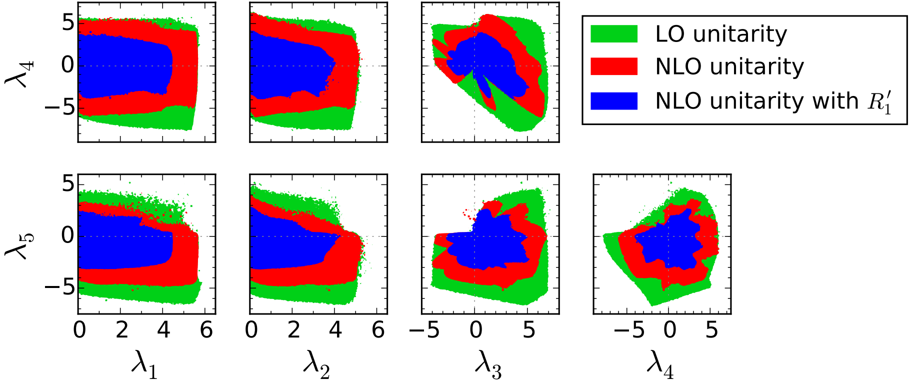

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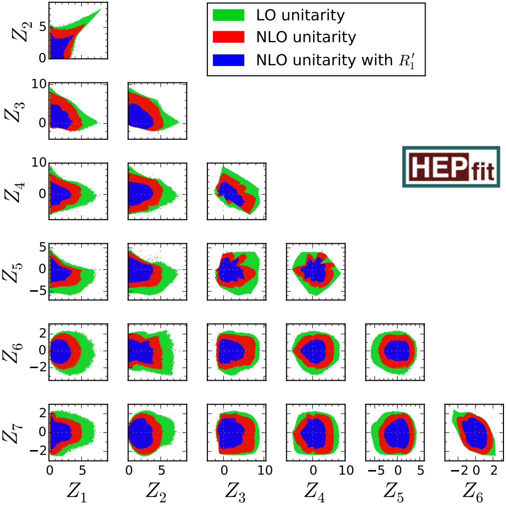
Other planes – only theory constraints



[Cacchio, Chowdhury, OE, Murphy '16]

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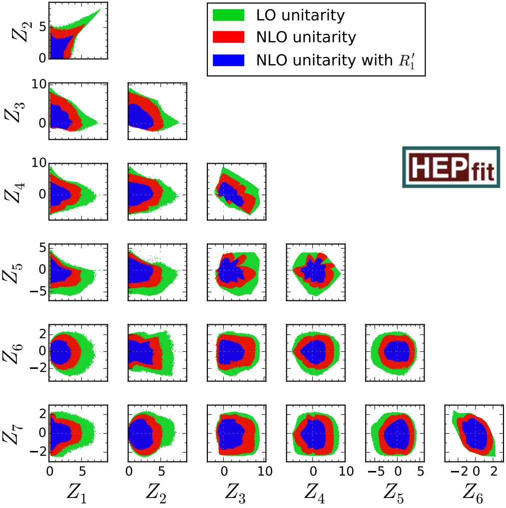
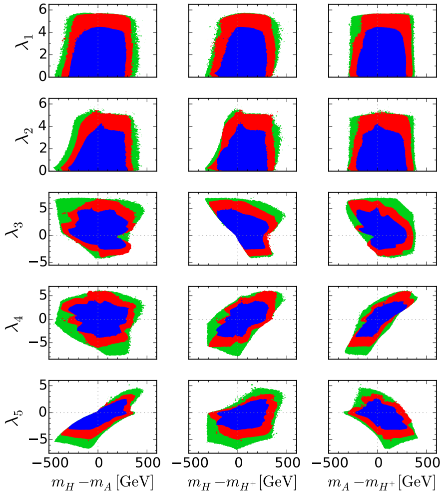
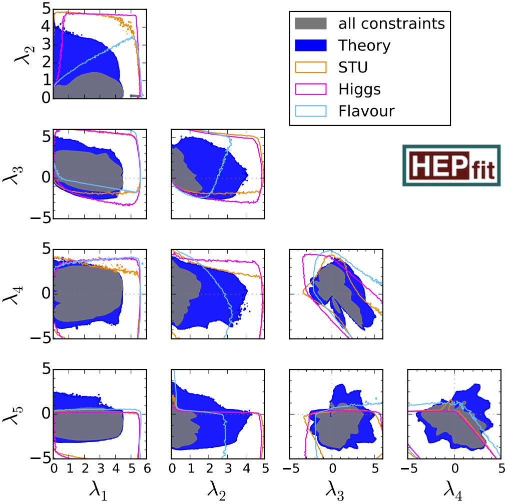




[Cacchio, Chowdhury, OE, Murphy '16]

Fits with all inputs (only type II)



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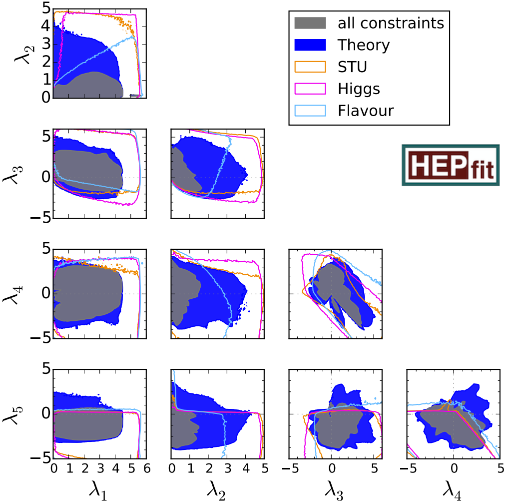
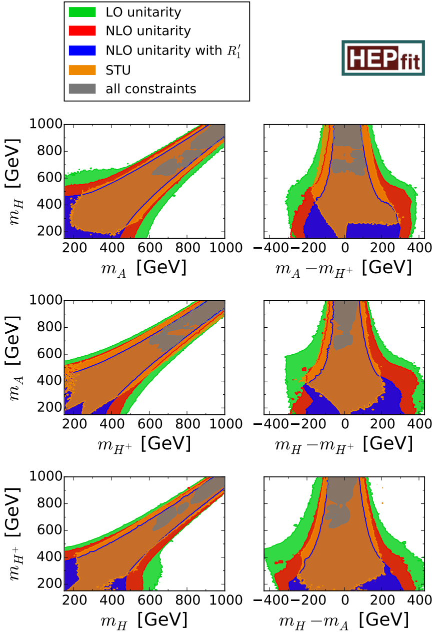




[Cacchio, Chowdhury, OE, Murphy '16]

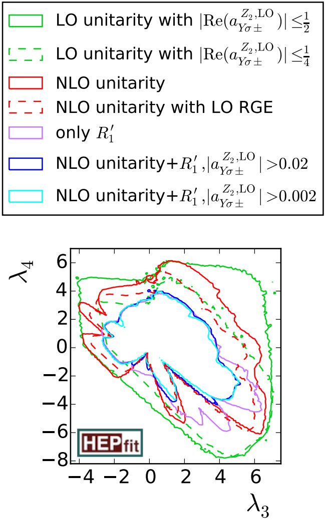
Conclusions

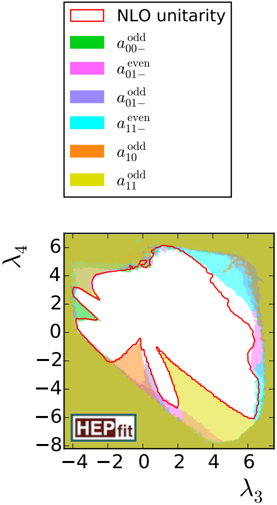
- `HEPfit` will be released soon
- The 2HDM parameters get further constrained by NLO unitarity.
- Using all constraints and with 95.4% probability in type II:

$$0 < \lambda_1 < 4.2 \qquad 0 < \lambda_2 < 1.2$$
$$-1.3 < \lambda_3 < 3.1 \quad -2.5 < \lambda_4 < 2.9 \quad -2.7 < \lambda_5 < 0.5$$
$$m_{H,A,H^+} \gtrsim 650 \text{ GeV}$$
$$m_{12}^2 > (370 \text{ GeV})^2$$

Thank you!

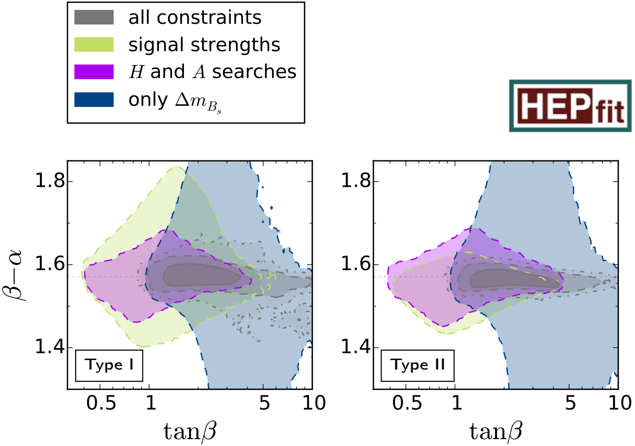
λ_3 vs. λ_4 – only theory constraints





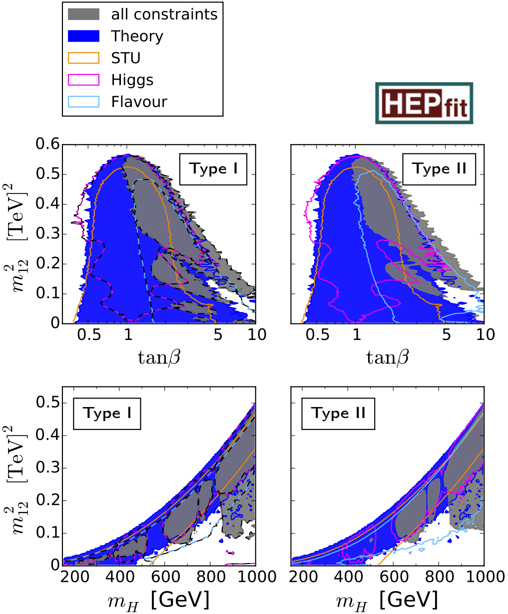
[Cacchio, Chowdhury, OE, Murphy '16]

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



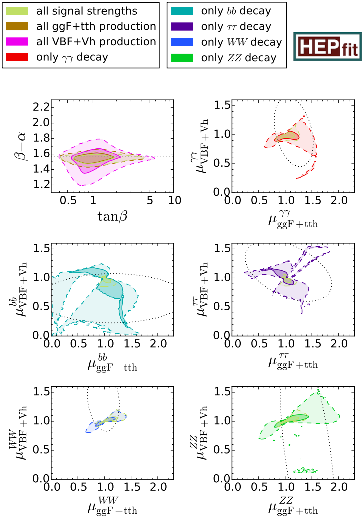
[Cacchio, Chowdhury, OE, Murphy '16]

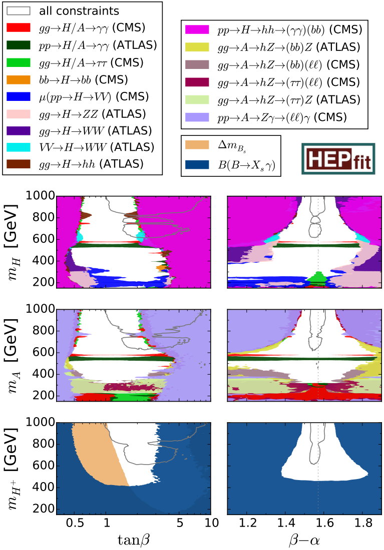
m_{12}^2



[Cacchio, Chowdhury, OE, Murphy '16]

Higgs and flavour observables



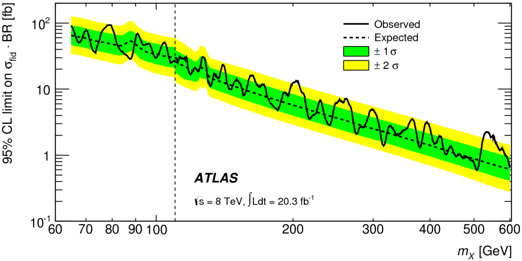


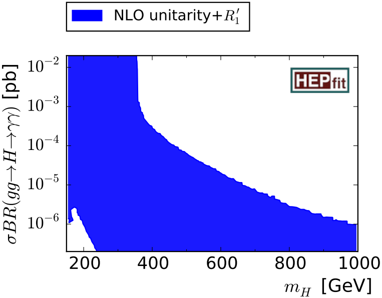
[Cacchio, Chowdhury, OE, Murphy '16]

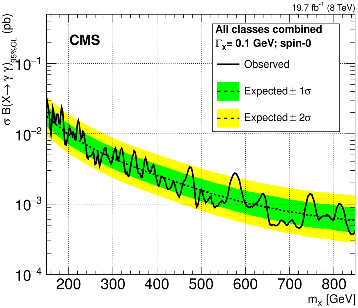
LHC diphoton channels

$$R = \frac{\sigma\mathcal{B}|_{\text{theo}} - (\sigma\mathcal{B}|_{95\%,\text{obs}} - \sigma\mathcal{B}|_{95\%,\text{exp}})}{\sigma\mathcal{B}|_{95\%,\text{exp}}}$$

$$\approx \frac{0-(2.5\,\text{fb}-1\,\text{fb})}{1\,\text{fb}} \text{ around 550 GeV}$$



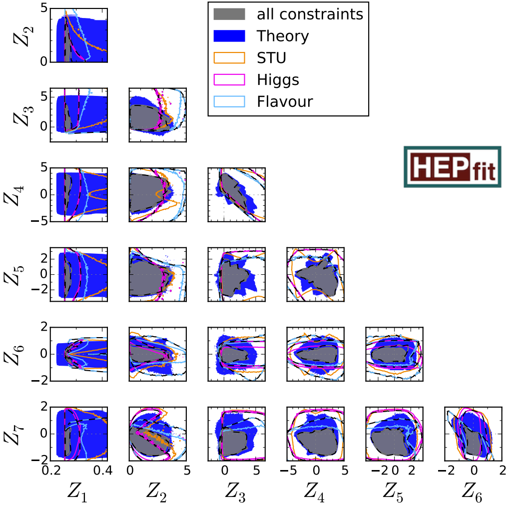




[Cacchio, Chowdhury, OE, Murphy ’16]

[ATLAS, CMS ’14]

Z_i vs. Z_j planes with experimental constraints



[Cacchio, Chowdhury, OE, Murphy '16]

Inputs STU

Pseudo-observable	Value	Correlation matrix		
S	0.09 ± 0.10	1	0.86	-0.54
T	0.10 ± 0.12	0.86	1	-0.81
U	0.01 ± 0.09	-0.54	-0.81	1

[HEPfit '16]

Inputs h signal strengths

Signal strength	Value	Correlation matrix	
$\mu^{\gamma\gamma}_{\text{ggF+tth}}$	1.16 ± 0.26	1	-0.30
$\mu^{\gamma\gamma}_{\text{VBF+Vh}}$	1.05 ± 0.43	-0.30	1
$\mu^{bb}_{\text{ggF+tth}}$	1.15 ± 0.97	1	$4.5 \cdot 10^{-3}$
$\mu^{bb}_{\text{VBF+Vh}}$	0.65 ± 0.30	$4.5 \cdot 10^{-3}$	1
$\mu^{\tau\tau}_{\text{ggF+tth}}$	1.06 ± 0.58	1	-0.43
$\mu^{\tau\tau}_{\text{VBF+Vh}}$	1.12 ± 0.36	-0.43	1
$\mu^{WW}_{\text{ggF+tth}}$	0.98 ± 0.21	1	-0.14
$\mu^{WW}_{\text{VBF+Vh}}$	1.38 ± 0.39	-0.14	1
$\mu^{ZZ}_{\text{ggF+tth}}$	1.42 ± 0.35	1	-0.49
$\mu^{ZZ}_{\text{VBF+Vh}}$	0.47 ± 1.37	-0.49	1

[ATLAS & CMS '16]

Inputs heavy Higgs searches

Channel	Experiment	Mass range (GeV)
$gg \to H/A \to \tau\tau$	ATLAS CMS	90-1000 90-1000
$b\bar{b} \to H/A \to \tau\tau$	ATLAS CMS	90-1000 90-1000
$gg \to H/A \to \gamma\gamma$	ATLAS CMS	65-600 150-850
$b\bar{b} \to H/A \to b\bar{b}$	CMS	100-900
$gg \to H \to WW$	ATLAS	300-1500
$WW/ZZ \to H \to WW$	ATLAS	300-1500
$gg \to H \to ZZ$	ATLAS	140-1000
$WW/ZZ \to H \to ZZ$	ATLAS	140-1000
$pp \to H \to ZZ$	CMS	150-1000
$\vdots$		

Inputs heavy Higgs searches, continued

Channel	Experiment	Mass range (GeV)
$gg \to H \to hh$	ATLAS	260-1000
$pp \to H \to hh[\to (b\bar{b})(\tau\tau)]$	CMS	300-1000
$pp \to H \to hh \to (\gamma\gamma)(b\bar{b})$	CMS	250-1100
$pp \to H \to hh \to (b\bar{b})(b\bar{b})$	CMS	270-1100
$gg \to A \to hZ \to (\tau\tau)(\ell\ell)$	CMS	220-350
$gg \to A \to hZ \to (b\bar{b})(\ell\ell)$	CMS	225-600
$gg \to A \to hZ \to (\tau\tau)Z$	ATLAS	220-1000
$gg \to A \to hZ \to (b\bar{b})Z$	ATLAS	220-1000
$pp \to A \to Z\gamma \to (\ell\ell)\gamma$	CMS	200-1200

[ATLAS & CMS '13-'16]

Inputs flavour observables

Observable	Value
Δm_{B_s}	17.757 ± 0.021 ps^{-1}
$\mathcal{B}(\bar{B} \to X_s \gamma)$	$3.43 \cdot 10^{-4} \pm 0.21 \cdot 10^{-4} \pm 0.07 \cdot 10^{-4}$

[HFAG '16]