Global fits in the Aligned Two-Higgs-Doublet model

Multi-Higgs Workshop

Lisbon, 4th September 2018

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in collaboration with O.Eberhardt and A. Pich

Motivation

- **Standard Model:** Great success but still
  - Strong CP problem
  - CP-violation
  - Dark Matter
  - (...)

- **The Two Higgs Doublet Model**
  - Fulfil all precision electroweak tests
  - New sources of CP-violation
  - Dark Matter candidates
  - Axion phenomenology
  - (...)

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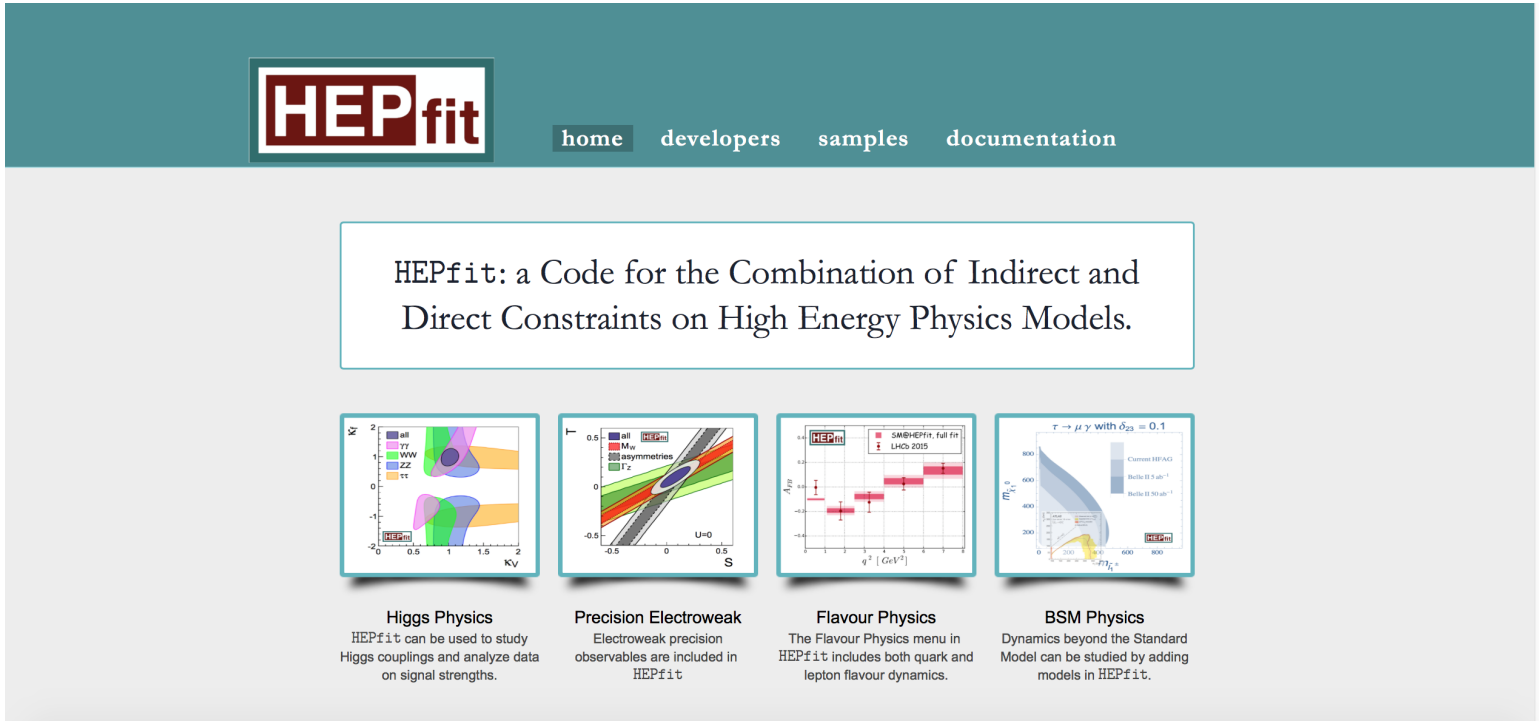
HEPfit



http://hepfit.roma1.infn.it

→ Otto Eberhardt's talk:

Global fits in the Z2 symmetric Two-Higgs Doublet models

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The Two-Higgs-Doublet Model

$$\begin{bmatrix} h \\ H \\ A \end{bmatrix} = \mathcal{R} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \xrightarrow{\text{CP-conserving limit}} \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

$$\begin{aligned} V = {} & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 \left(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 \right) \\ & + \frac{\lambda_1}{2} \left(\phi_1^\dagger \phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\phi_2^\dagger \phi_2 \right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1 \right) \left(\phi_2^\dagger \phi_2 \right) + \lambda_4 \left(\phi_1^\dagger \phi_2 \right) \left(\phi_2^\dagger \phi_1 \right) \\ & + \left[\frac{\lambda_5}{2} \left(\phi_1^\dagger \phi_2 \right)^2 + \lambda_6 \left(\phi_1^\dagger \phi_1 \right) \left(\phi_1^\dagger \phi_1 \right) + \lambda_7 \left(\phi_2^\dagger \phi_2 \right) \left(\phi_1^\dagger \phi_1 \right) + \text{h.c} \right] \end{aligned}$$

$$Y_u = \varsigma_u M_u \,, \qquad Y_d = \varsigma_d M_d \,, \qquad Y_\ell = \varsigma_\ell M_\ell \,.$$

The Two-Higgs-Doublet Model

$$\begin{bmatrix} h \\ H \\ A \end{bmatrix} = \mathcal{R} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \xrightarrow{\text{CP-conserving limit}} \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

$$m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_1, \lambda_2, \lambda_3, \lambda_4 \rightarrow m_H^2,\ m_A^2,\ m_{H^\pm}^2,\ \log\tan\beta$$

$$Y_u = \varsigma_u\, M_u\,, \qquad Y_d = \varsigma_d\, M_d\,, \qquad Y_\ell = \varsigma_\ell\, M_\ell\,.$$

The Two-Higgs-Doublet Model

Parameters of the fit

$v \approx 246\,\text{GeV}$, $m_h \approx 125\,\text{GeV}$,

$\log\tan\beta \in [-3,\, 3]$, $\tilde{\alpha} \in [-\frac{\pi}{2},\, \frac{\pi}{2}]$,

$|\lambda_i| < 10,\ i = 5, 6, 7$, $m_H^2, m_A^2, m_{H^\pm}^2 \in [80,\, 2000]^2\,\text{GeV}^2$,

$\varsigma_u \in [-3,\, 3]$, $\varsigma_d \in [-50,\, 50]$, $\varsigma_\ell \in [-100,\, 100]$.

$\longrightarrow$ 11 parameters

The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Oblique parameters

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The Two-Higgs-Doublet Model – constraints

$$\mu^X = \frac{\sigma(pp \to h)\Gamma(h \to X)}{\sigma(pp \to h)_{\rm SM}\Gamma(h \to X)_{\rm SM}}$$

- h signal strengths
- Flavour observables
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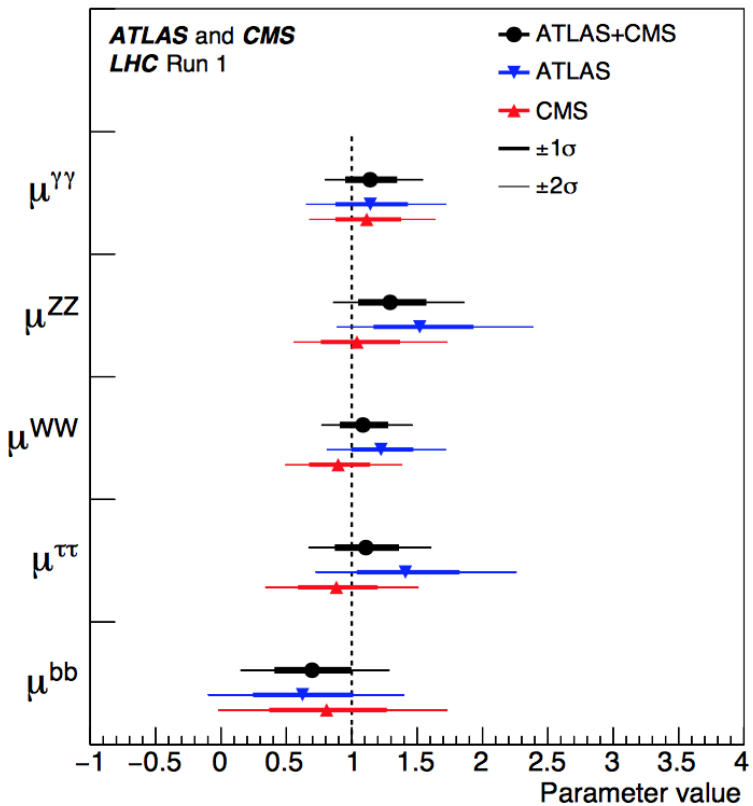
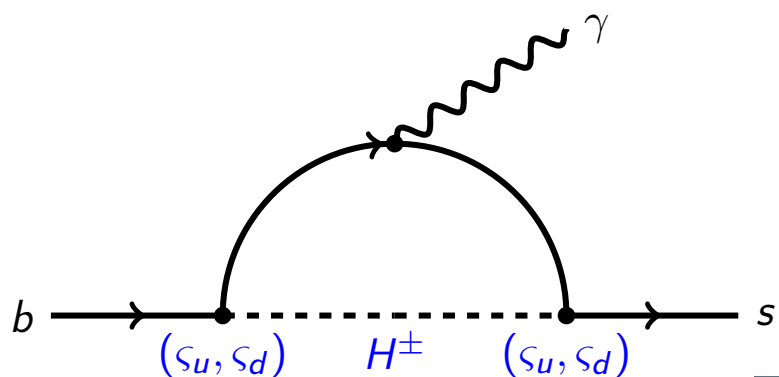


The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables $\longrightarrow$ $\begin{cases} (g-2)_\mu \\ R_b \\ B_s \to \mu^+\mu^- \\ b \to s\gamma \end{cases}$
- Unitarity and stability
- Oblique parameters



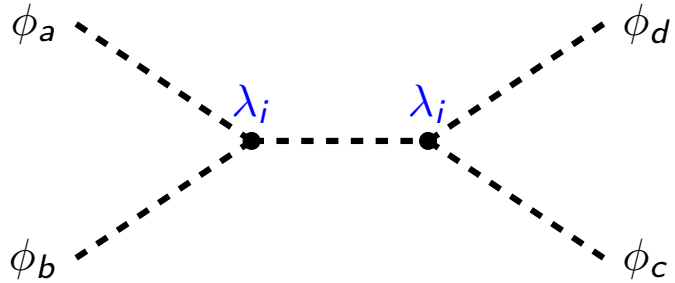
The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Oblique parameters

Unitarity of the S matrix: $S^\dagger S < 1$

$P(\phi_a \phi_b \to \phi_c \phi_d) < 1$

$\to$ At LO $\left(a_j^{(0)}\right)^2 < \frac{1}{4}$



Stability = potential bounded from below

$\downarrow$

bounds on λ_i

The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
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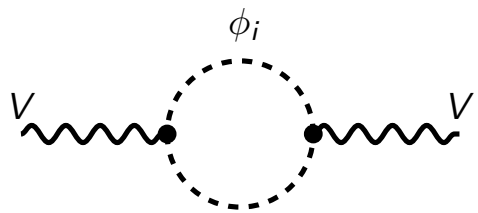
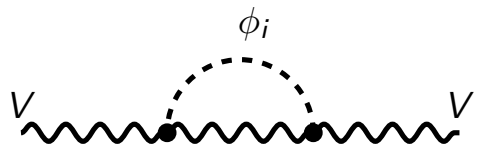
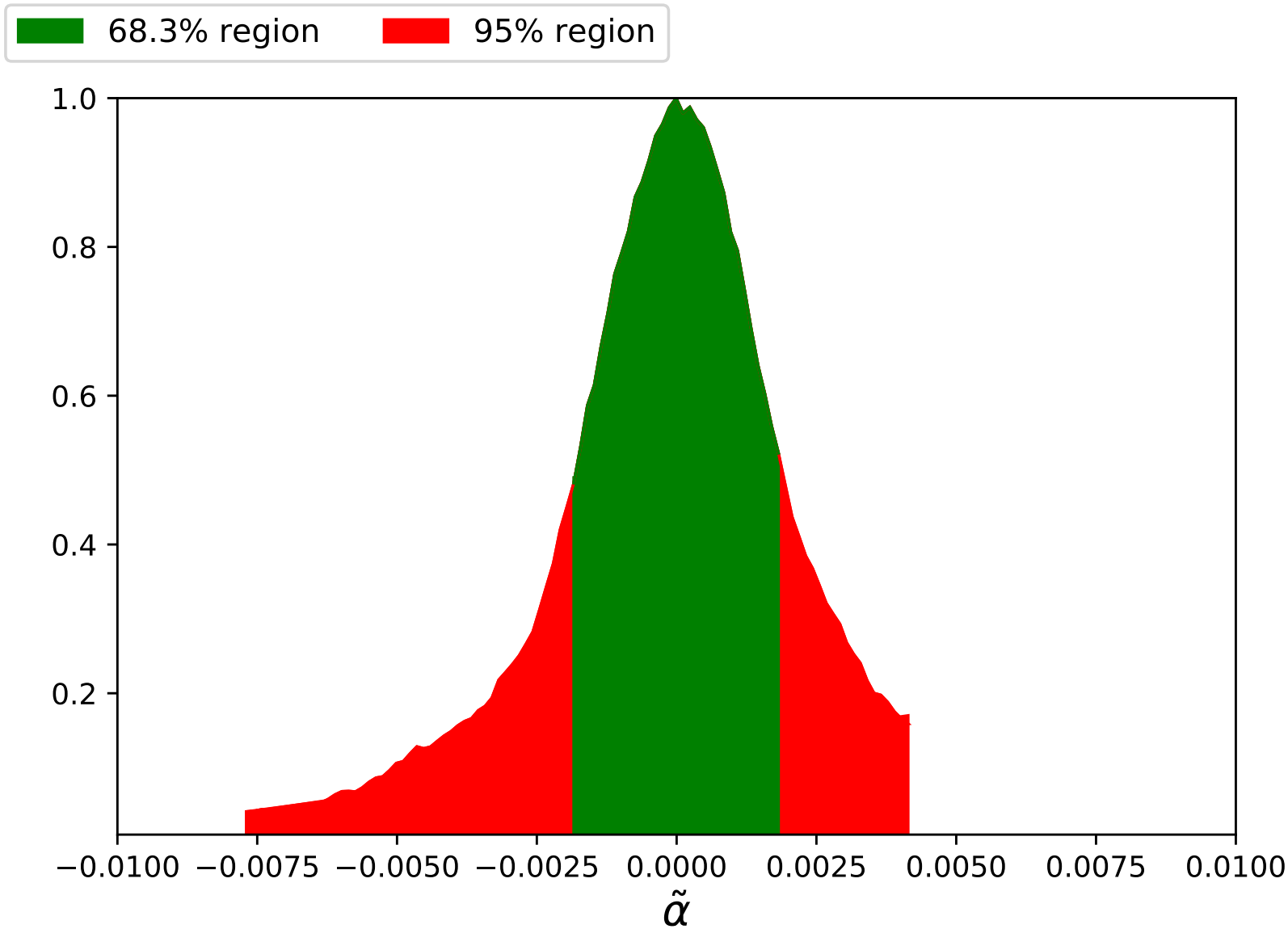
- Oblique parameters

S, T, U: Electroweak precision observables





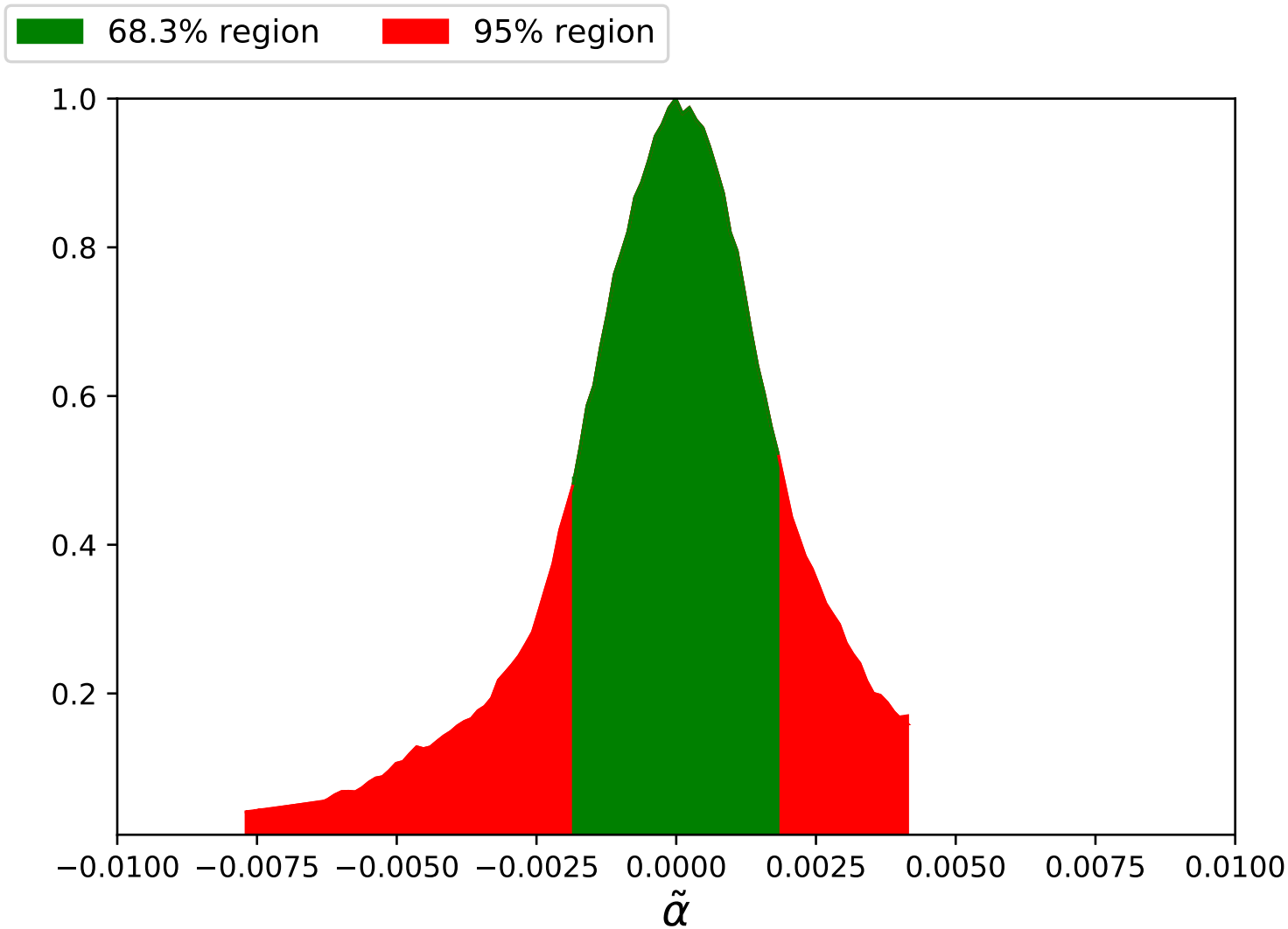
Results-h signal strengths



Results-h signal strengths

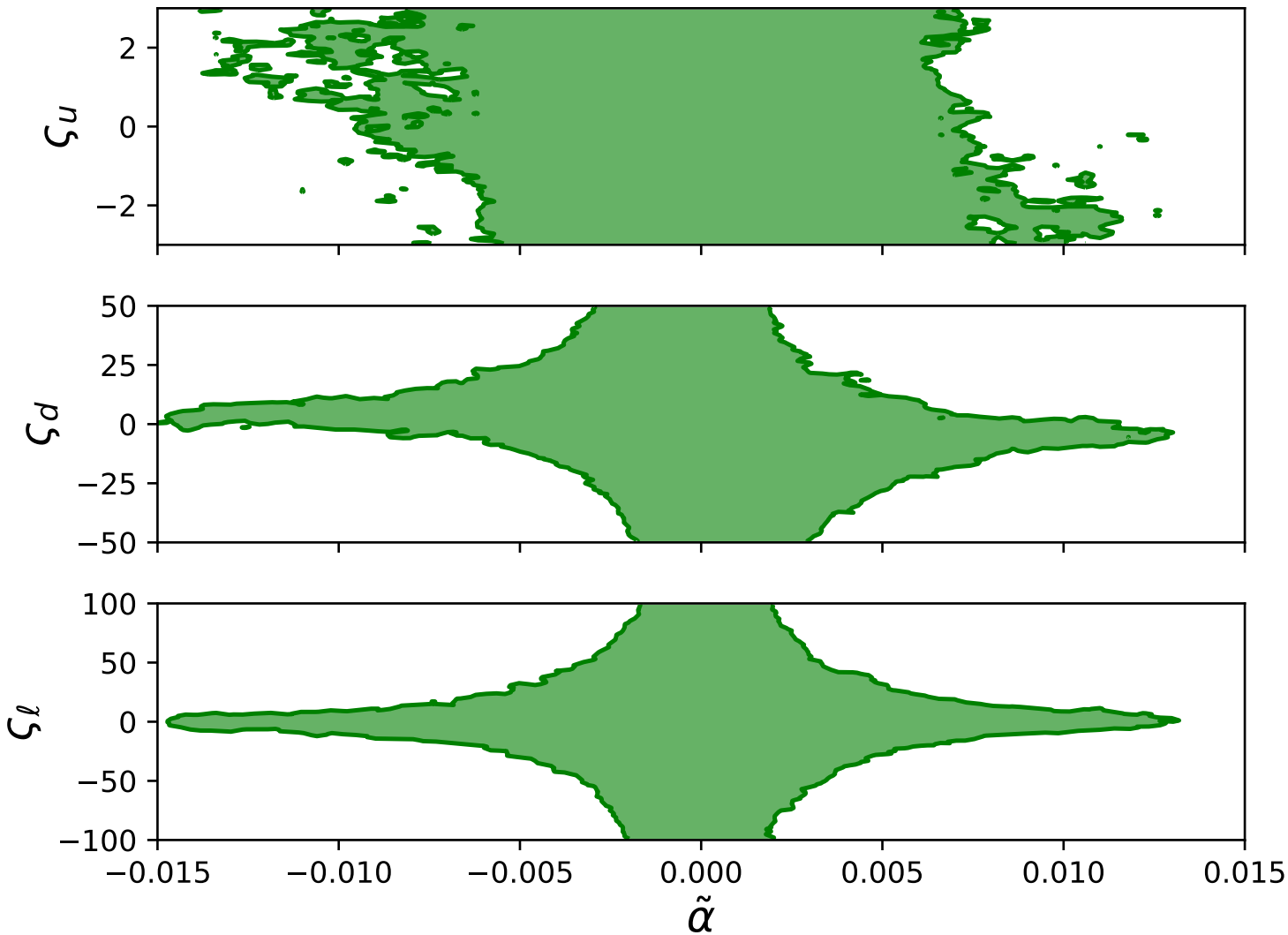
Flavour observables. Allowed at 95%

$$h = \cos\tilde{\alpha} S_1 + \sin\tilde{\alpha} S_2$$
$$H = -\sin\tilde{\alpha} S_1 + \cos\tilde{\alpha} S_2$$



Results-h signal strengths

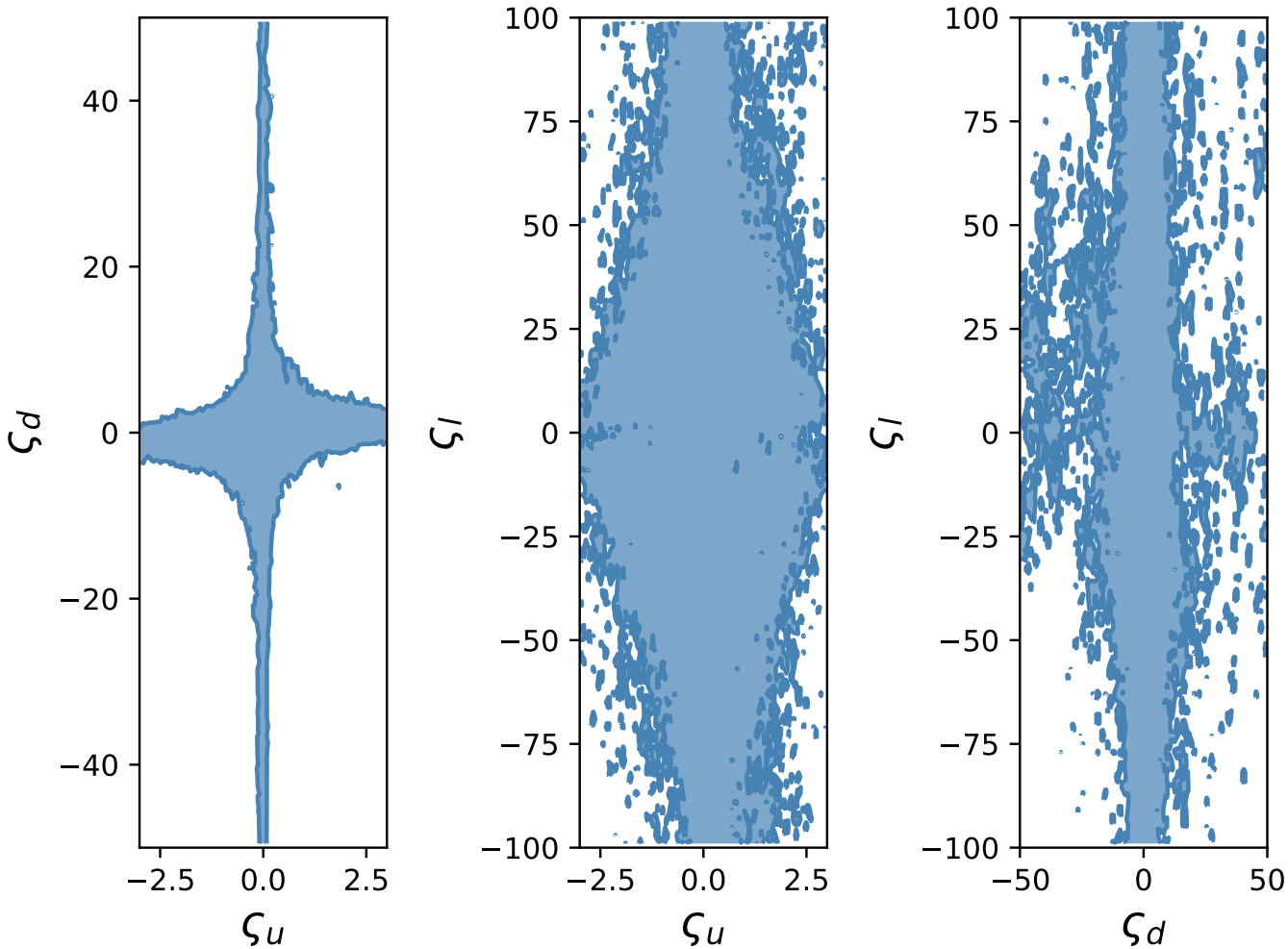
Higgs signal strengths observables. Allowed at 95%



Results-flavour

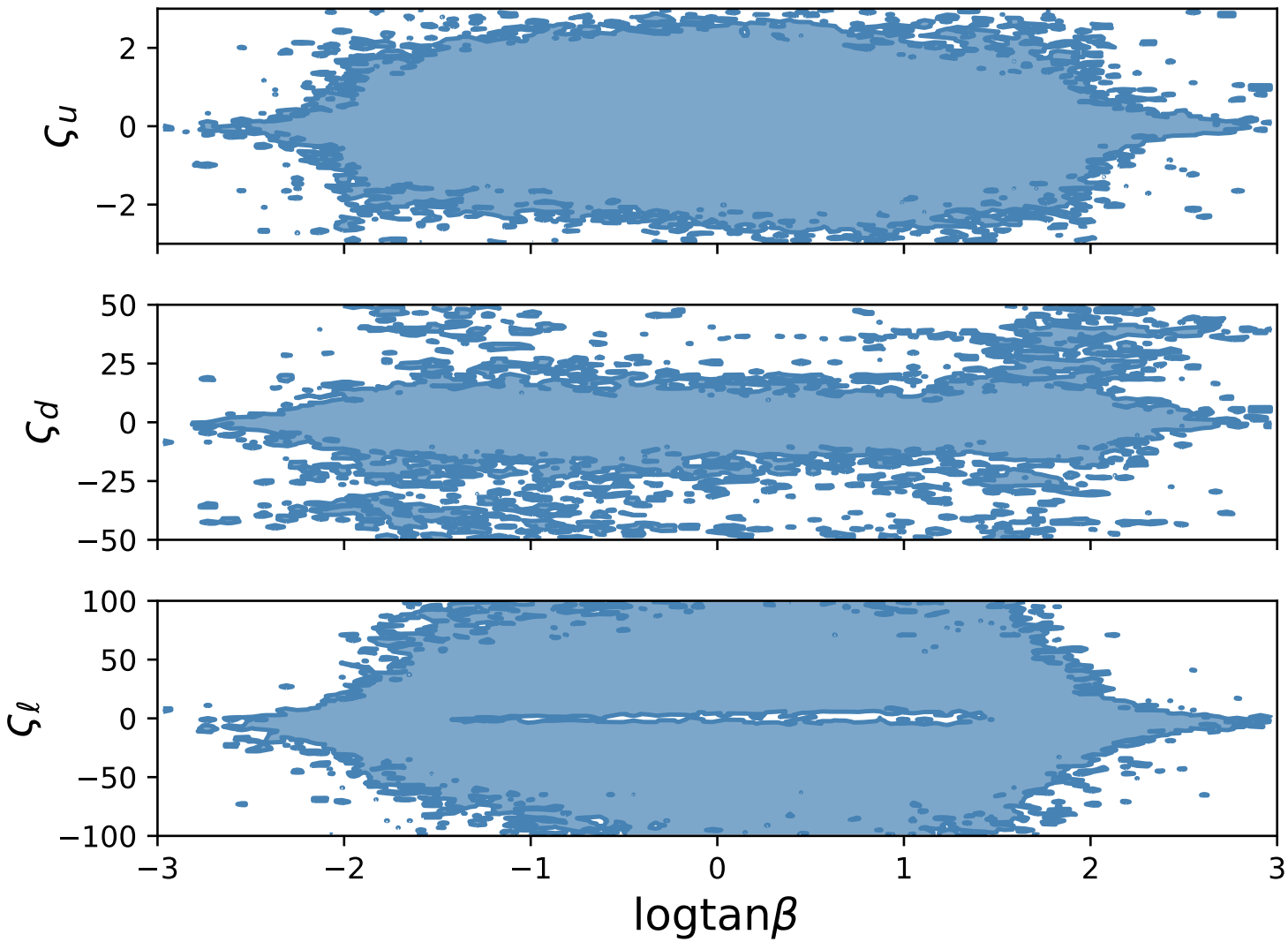
Flavour observables. Allowed at 95%

Vertex: $\varsigma_f m_f$



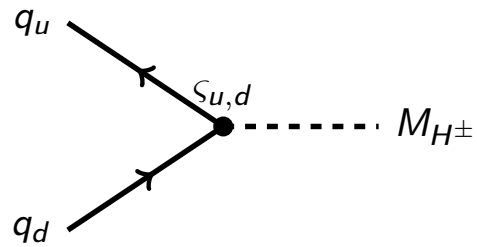
Results-flavour

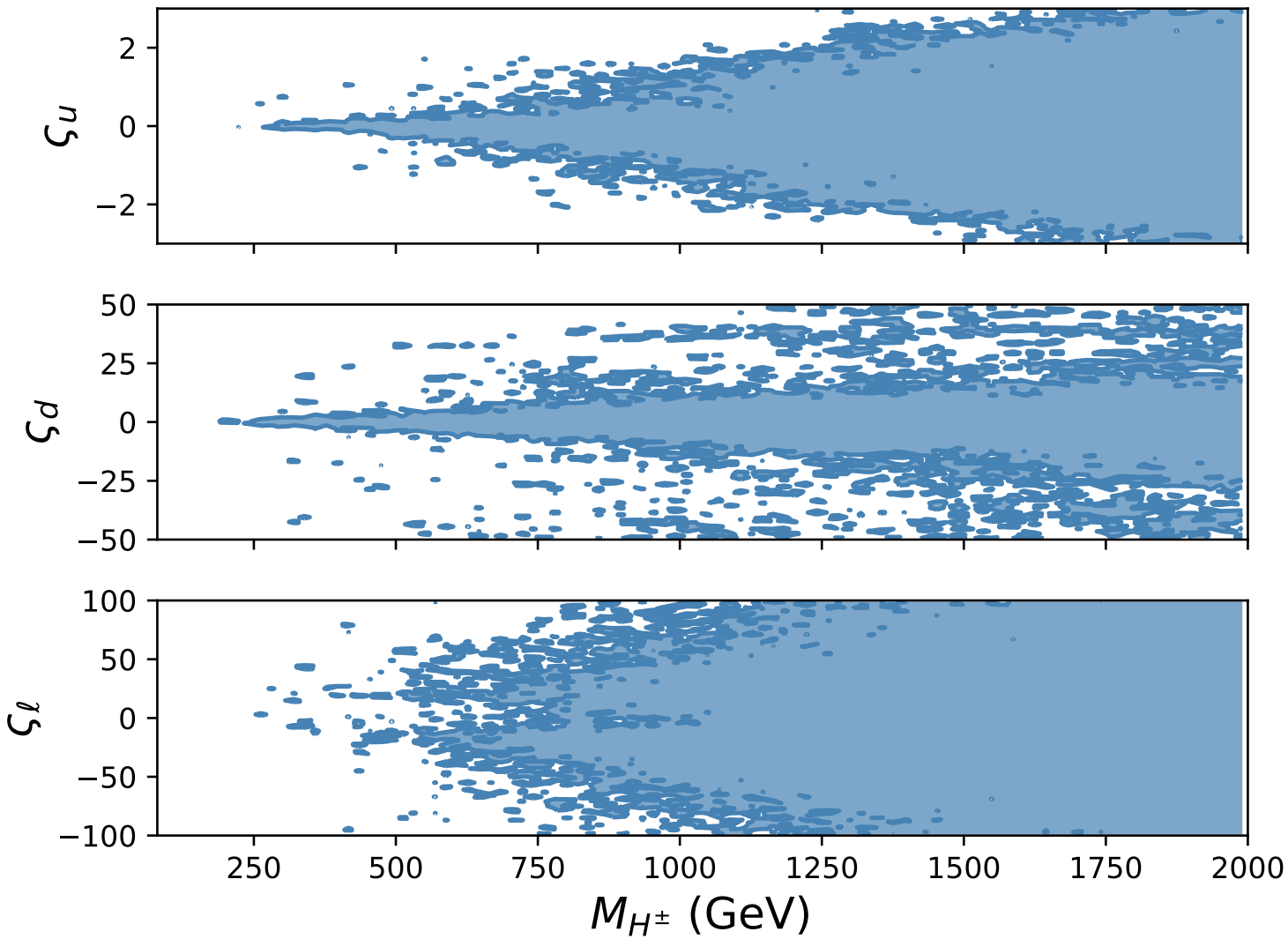
Flavour observables. Allowed at 95%



Results-flavour

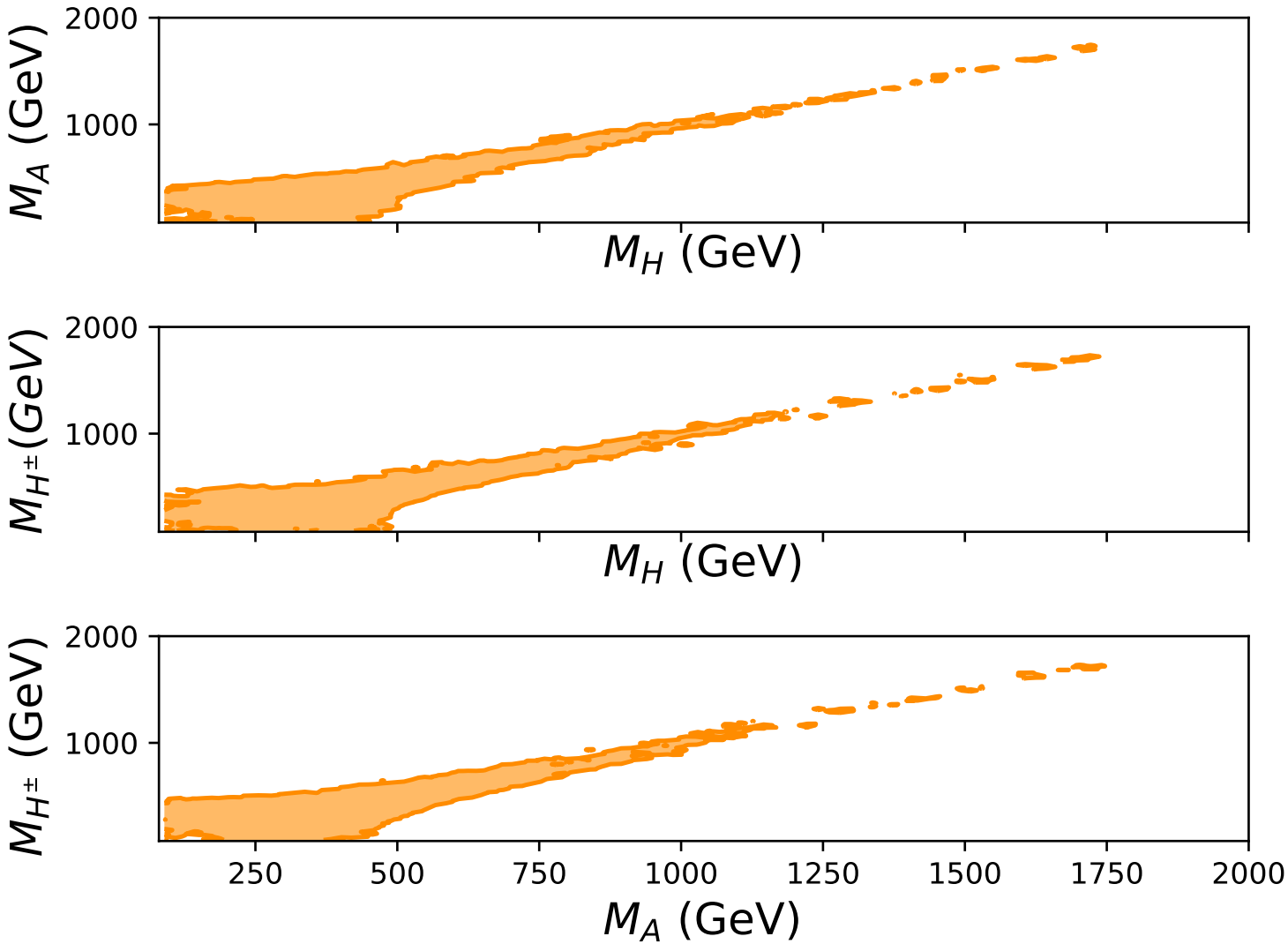
Flavour observables. Allowed at 95%





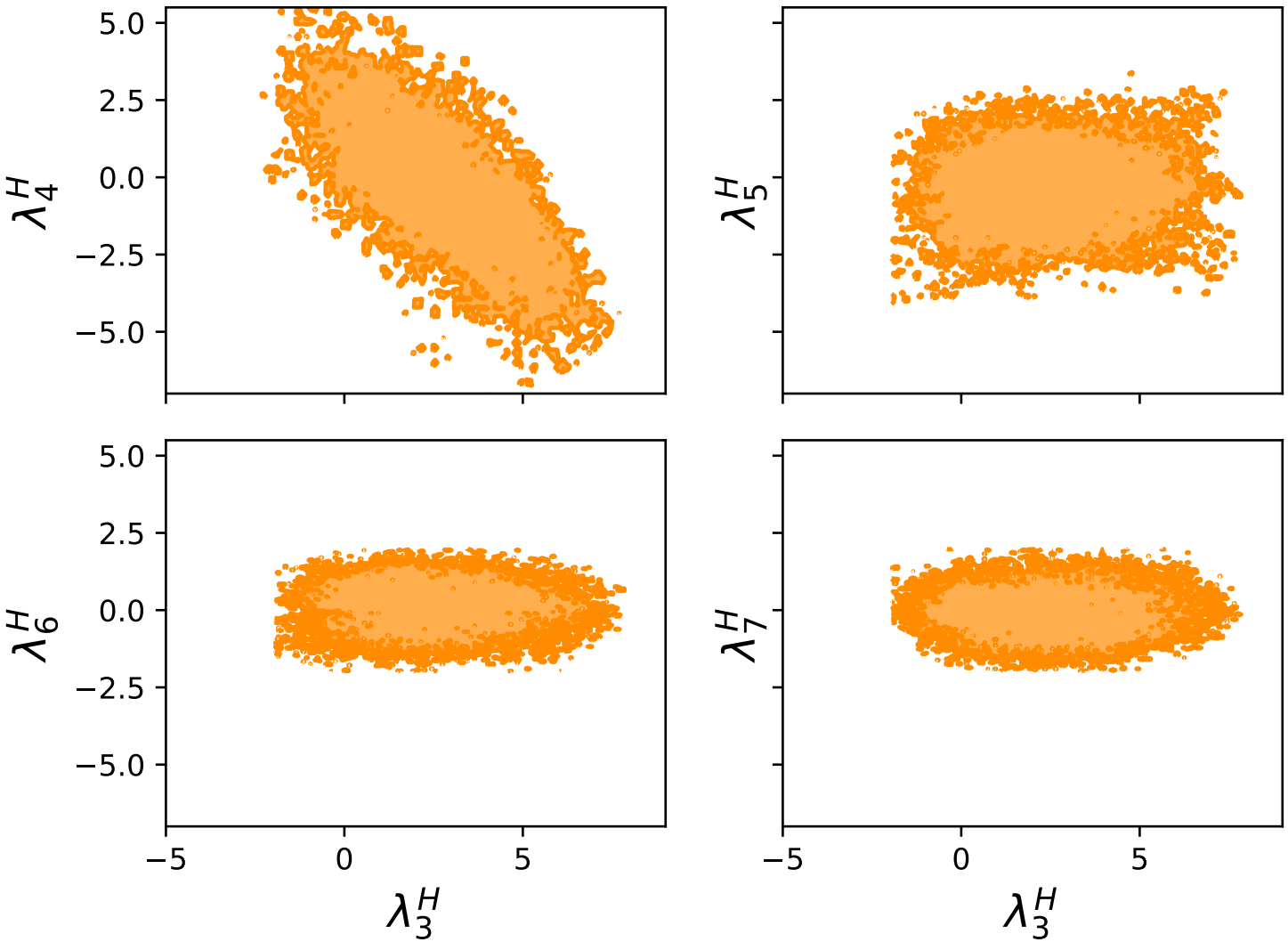
Results-theory + STU

Theory constraints + STU. Allowed at 95%

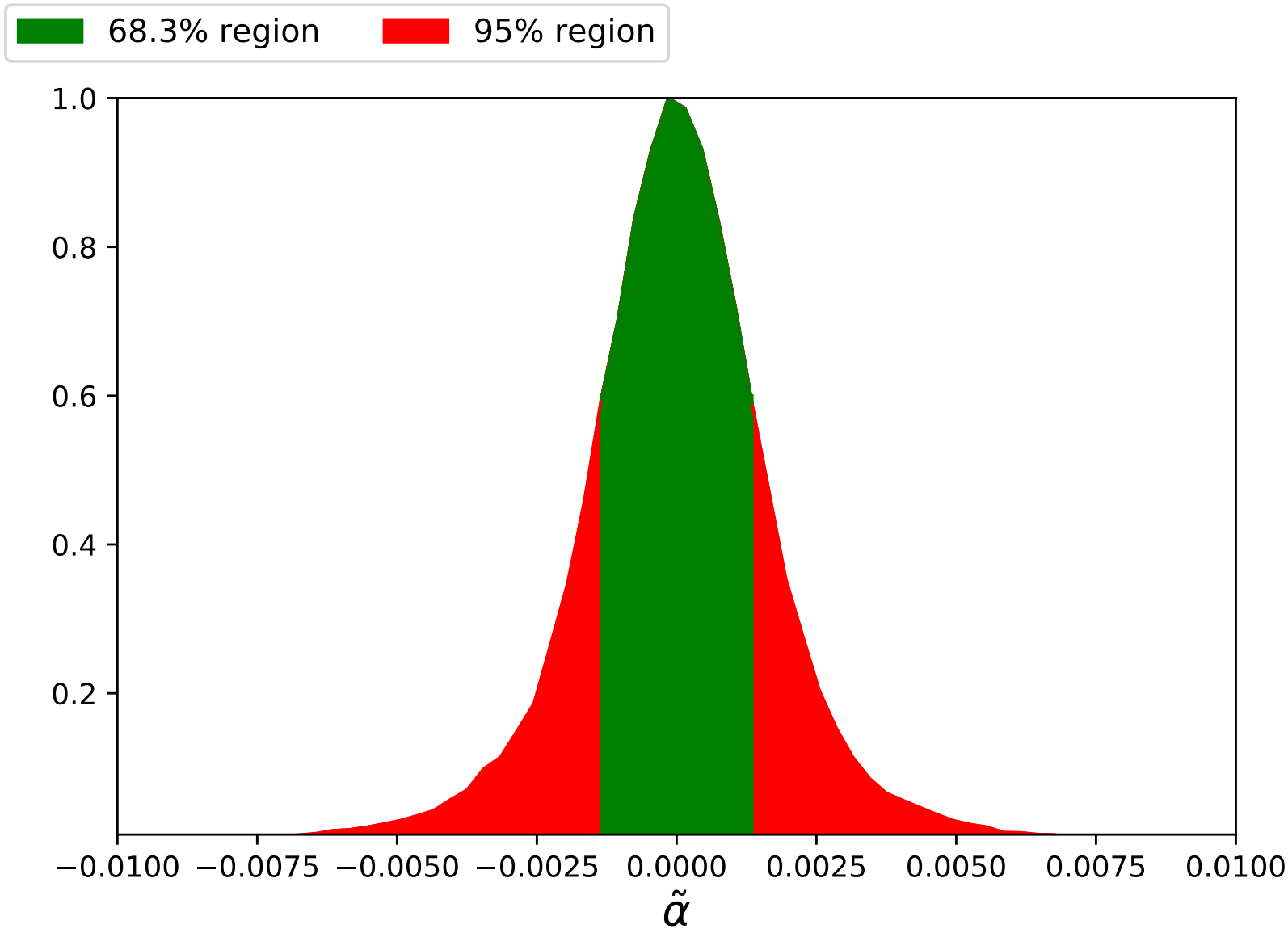


Results-theory + STU

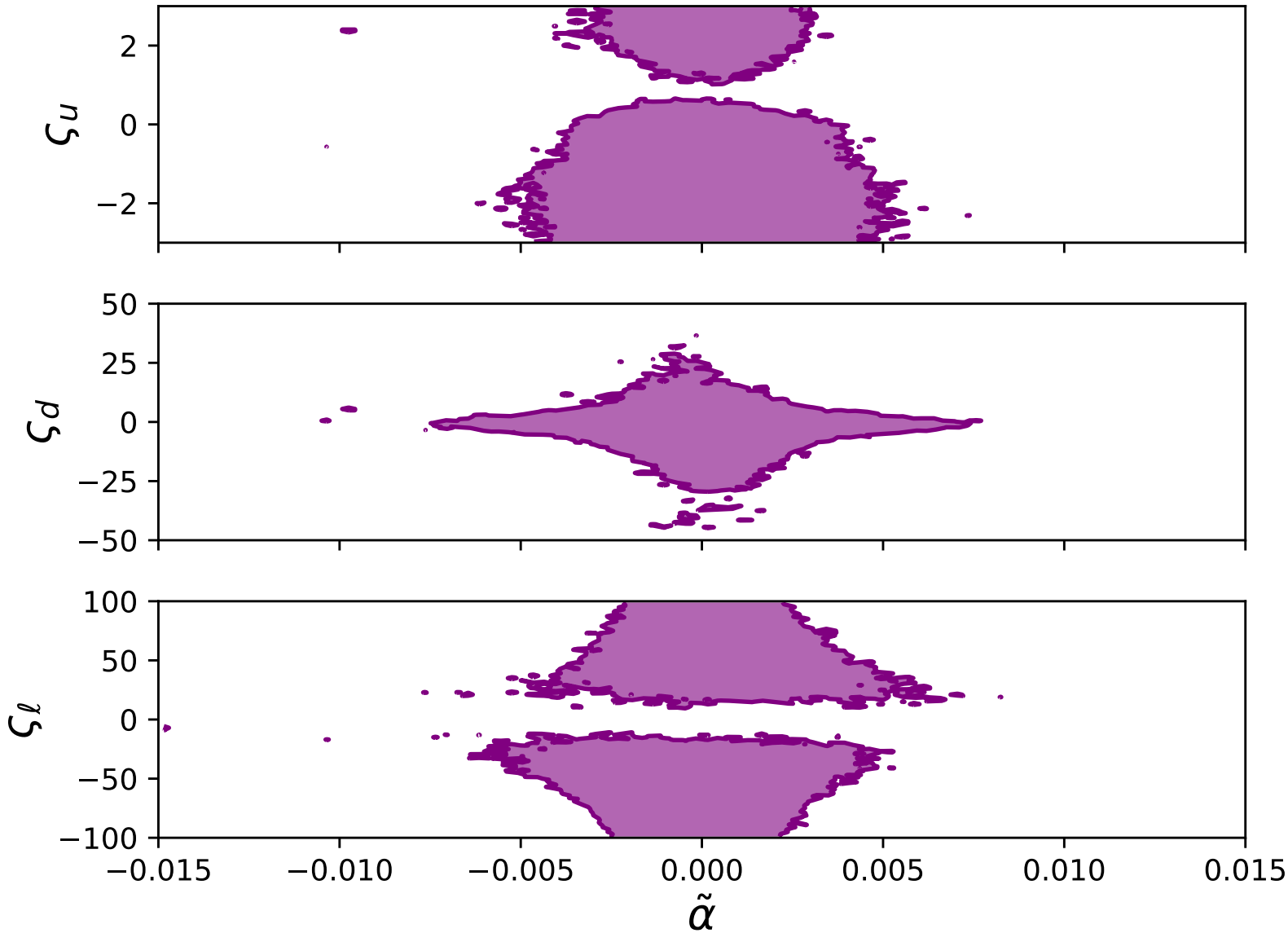
Theory constraints + STU. Allowed at 95%



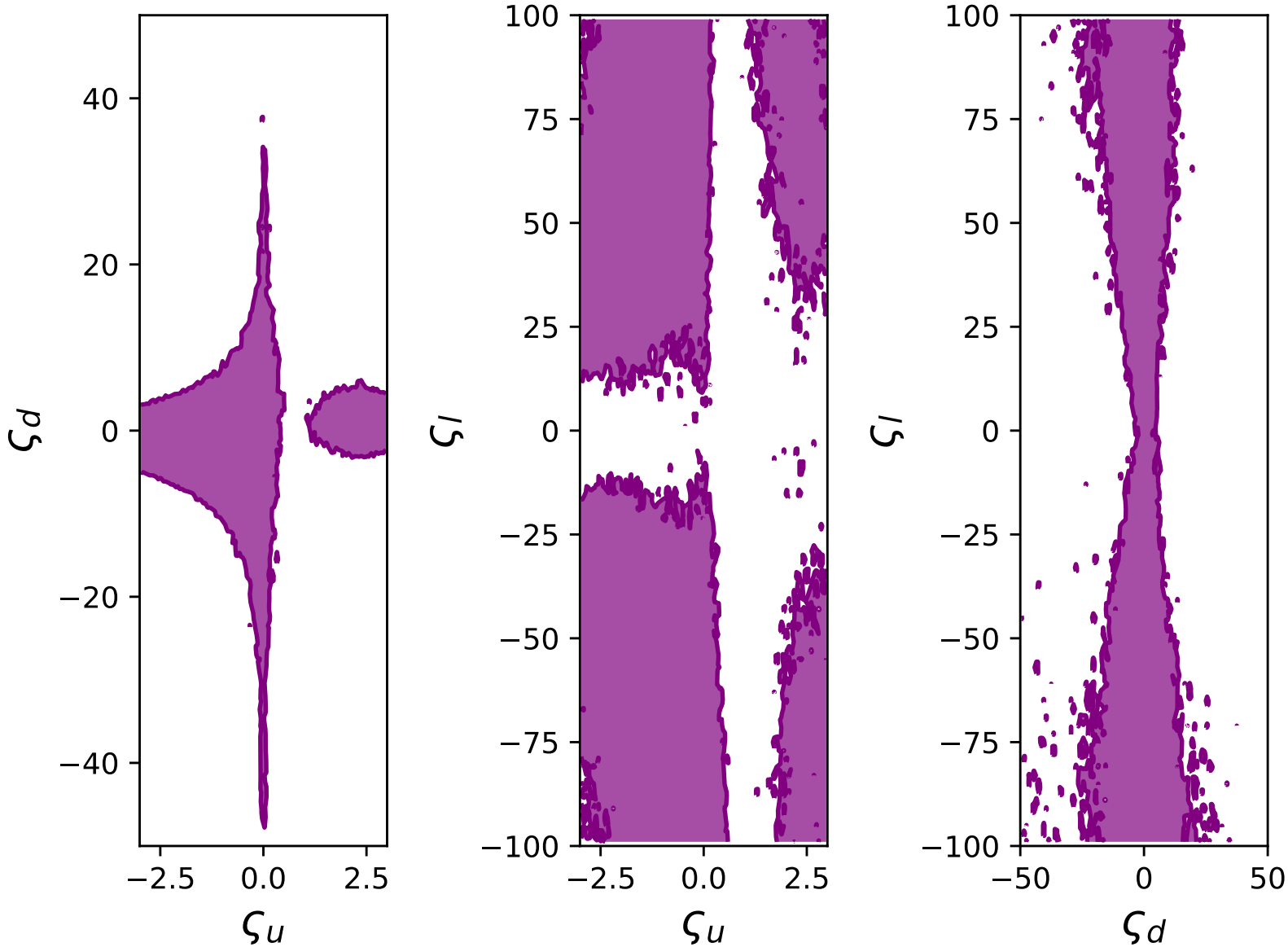
Results-combined



Results-combined



Results-combined



Summary

Bounds on:

- $|\tilde{\alpha}| < 0.015$ at 68.4 % and $|\tilde{\alpha}| < 0.075$ at 95 %
- $|\varsigma_u||\varsigma_d| \leq 6$ at 95 %
- Constraints on the planes
  - $\varsigma_i - \varsigma_j$
  - $\varsigma_i - M_{H^\pm}$
  - $\lambda_i - \lambda_j$

Future plans:

- Increase statistics
- Include direct searches
- Include more flavour observables
- Generalize to the non-CP conserving limit

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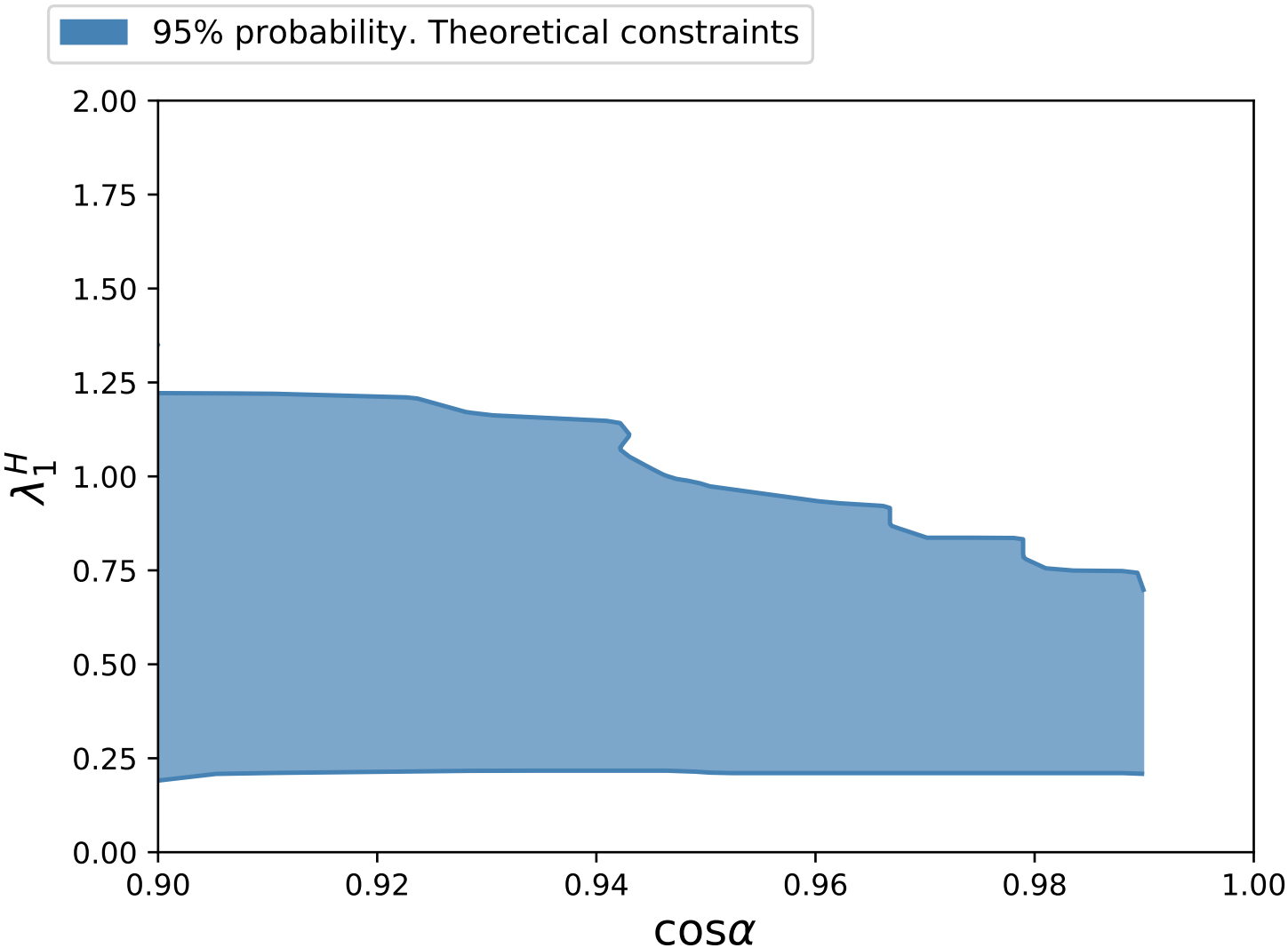
Higgs signal strengths-ratios

$$
\begin{aligned}
r_{ff} &= \cos\tilde{\alpha} + \varsigma_f \sin\tilde{\alpha}, \\
r_{VV} &= \cos\tilde{\alpha}, \\
r_{\gamma\gamma} &= \frac{\left|\sum_f r_{ff} N_C^f Q_f^2 \mathcal{F}(x_f) + \mathcal{G}(x_W) + \mathcal{C}_{H^\pm}\right|^2}{\left|\sum_f N_C^f Q_f^2 \mathcal{F}(x_f) + \mathcal{G}(x_W)\right|}, \\
r_{gg} &= \frac{\left|\sum_f r_{ff} \mathcal{F}(x_f)\right|}{\left|\sum_f \mathcal{F}(x_f)\right|}.
\end{aligned}
$$

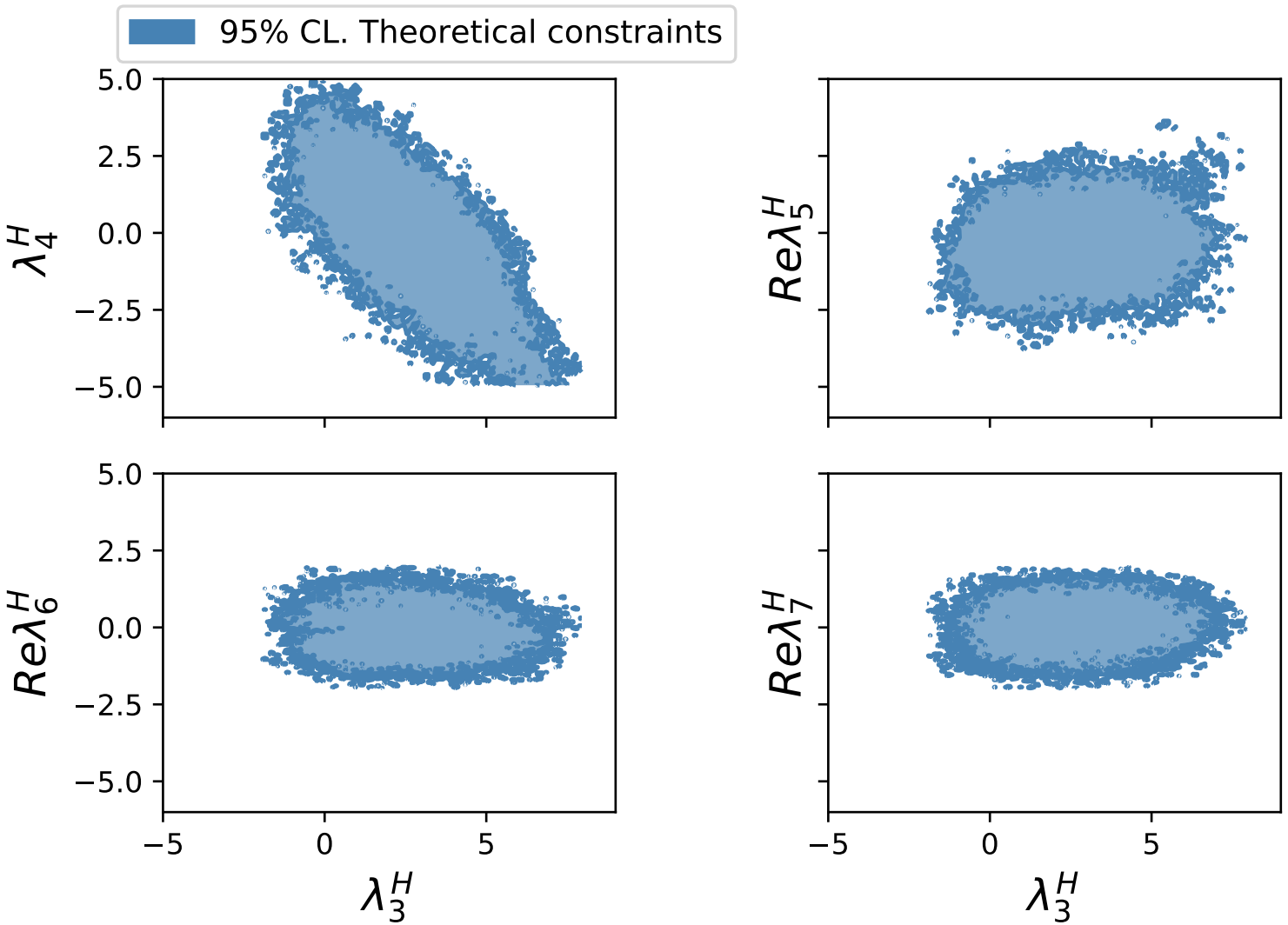
Results-theoretical

[Jurĉiukonis, Lavoura, 2018]



Results-theoretical

Only flavour observables. Allowed at 95%



Results-flavour

[Jurĉiukonis, Lavoura, 2018]