Global fits in the Aligned Two-Higgs-Doublet model

Non-Minimal Higgs workshop

Helsinki, 28th May 2019

Ana Peñuelas (Instituto de Física Corpuscular, València)
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
  - (...)

The Two-Higgs-Doublet Model

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + S_1 + iG^0) \end{bmatrix}, \quad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + iS_3) \end{bmatrix}$$

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

The Two-Higgs-Doublet Model

$$Q'_L(M'_d\Phi_1 + Y'_d\Phi_2)d'_R \rightarrow (d_L M_d d_R + d_L X_d^{\text{non-diag}} d_R)\varphi_a^0$$

FCNC at tree level (very constrained phenomenologically)

The Two-Higgs-Doublet Model

$$Q'_L(M'_d\Phi_1 + Y'_d\Phi_2)d'_R \to d_L(M_d + \varsigma_d M_d)d_R\varphi_a^0$$

Alignment in flavour space (A2HDM)

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

The Two-Higgs-Doublet Model

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

$$m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_1, \lambda_2, \lambda_3, \lambda_4 \rightarrow M_H^2,\ M_A^2,\ M_{H^\pm}^2,$$

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

The Two-Higgs-Doublet Model

Parameters of the fit

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

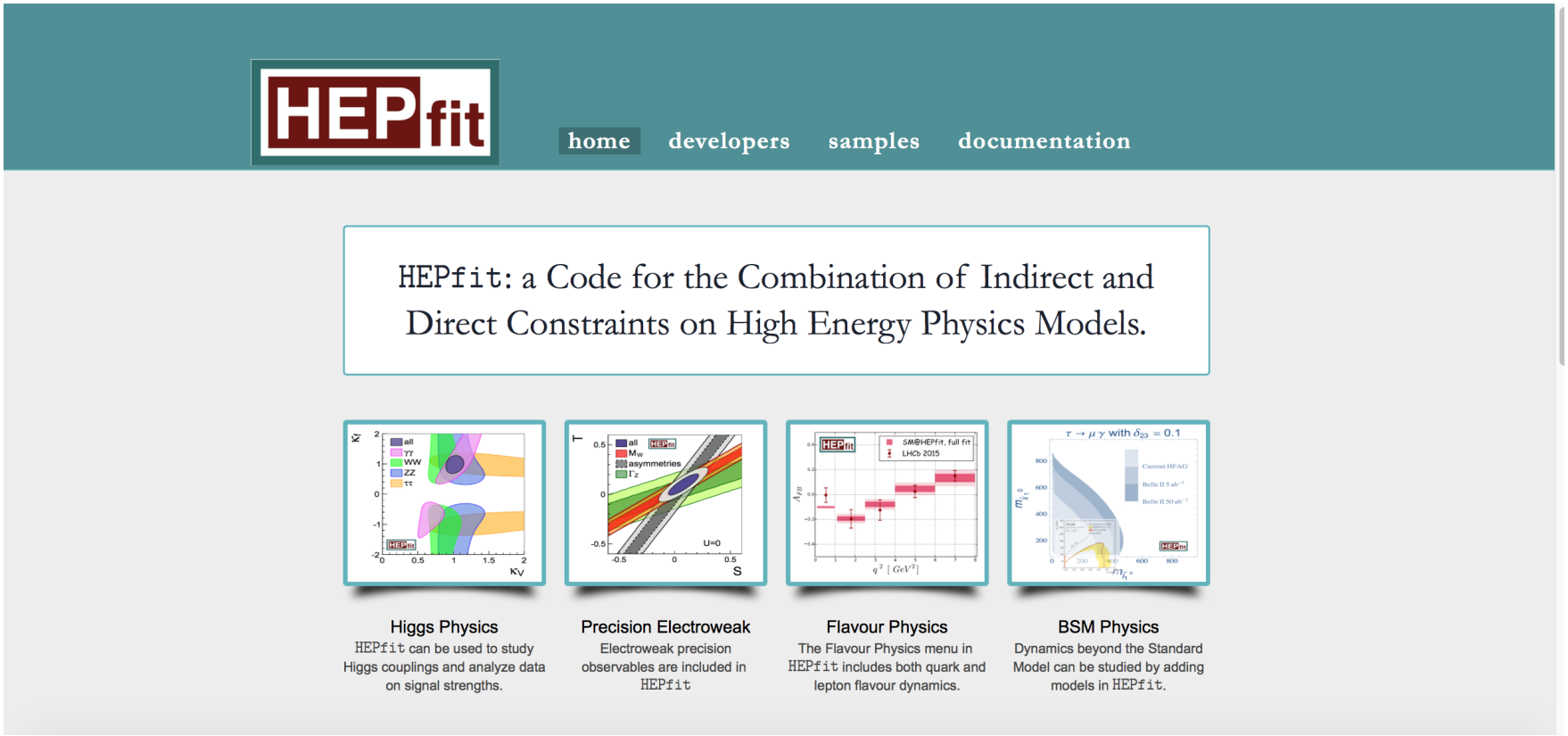
$|\lambda_i| < 10,\ i = 5, 6, 7,$ $\tilde{\alpha} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$,

$\varsigma_u \in [-1.5,\ 1.5]$, $\varsigma_d \in [-50,\ 50]$, $\varsigma_\ell \in [-100,\ 100]$,

$M_H^2, M_A^2, M_{H^\pm}^2 \in [80^2,\ 1500^2]\ \text{GeV}^2$.

$\longrightarrow$ 10 parameters

HEPfit



http://hepfit.roma1.infn.it

→ See Victor Miralles talk today @ 17:30

The Two-Higgs-Doublet Model – constraints

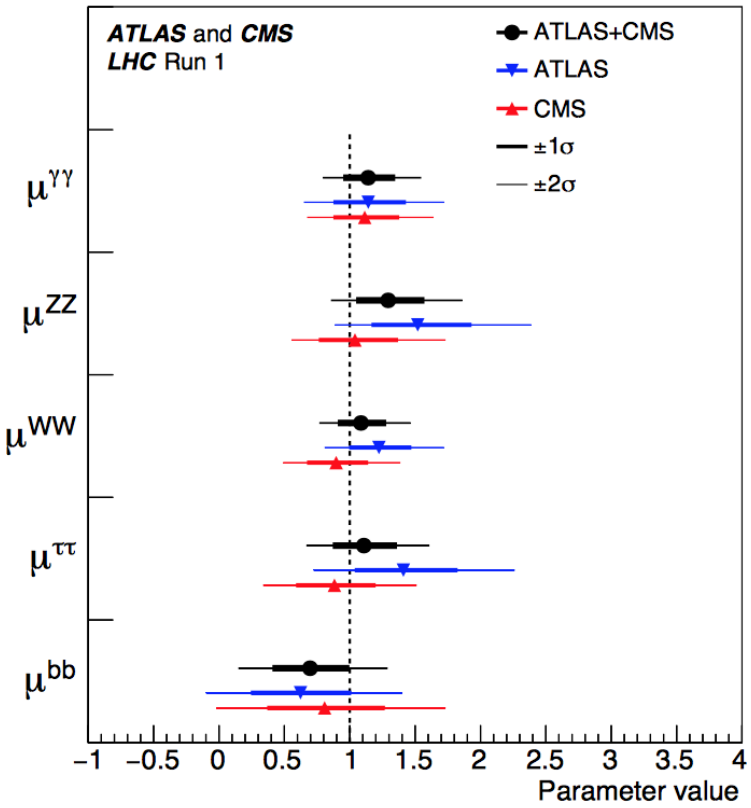
- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

The Two-Higgs-Doublet Model – constraints

- h signal strengths

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

- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches



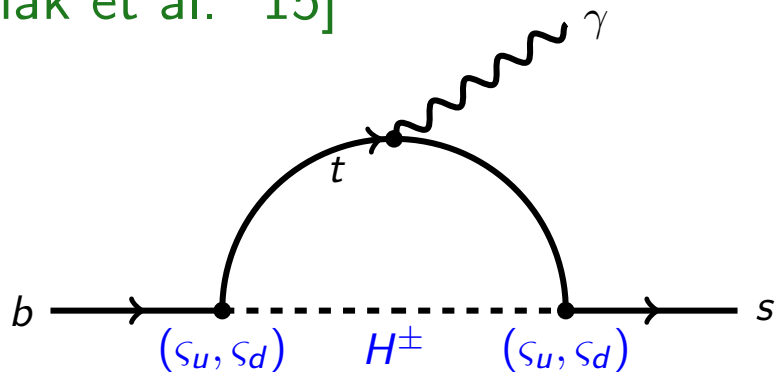
The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables $\longrightarrow$ $\begin{cases} b \to s\gamma \\ (g-2)_\mu \\ B_s \to \mu^+\mu^- \\ \Delta M_{B_s} \end{cases}$
- Unitarity and stability
- Electroweak precision observables
- Direct searches

The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

$b \to s\gamma$
[Misiak et al. '15]



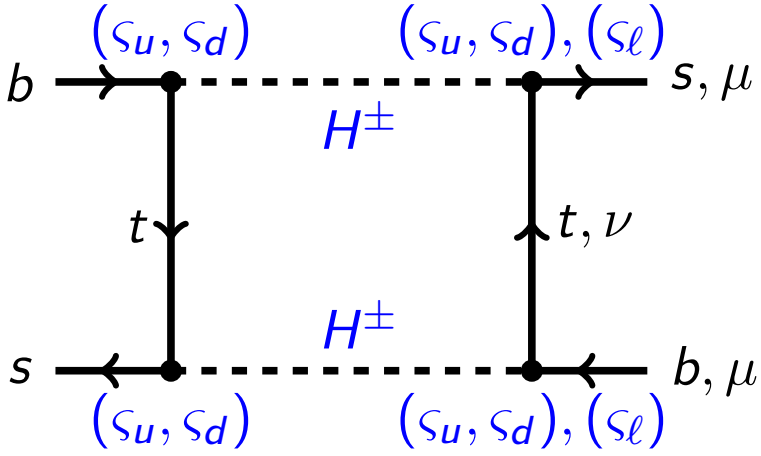
$(g-2)_\mu \to$ 2-loop computation
[Cherchiglia, Stöckinger, Stöckinger-Kim, '17] $\to \varsigma_\ell$

The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

$B_s \to \mu^+\mu^-$
[Li, Lu, Pich, '14]

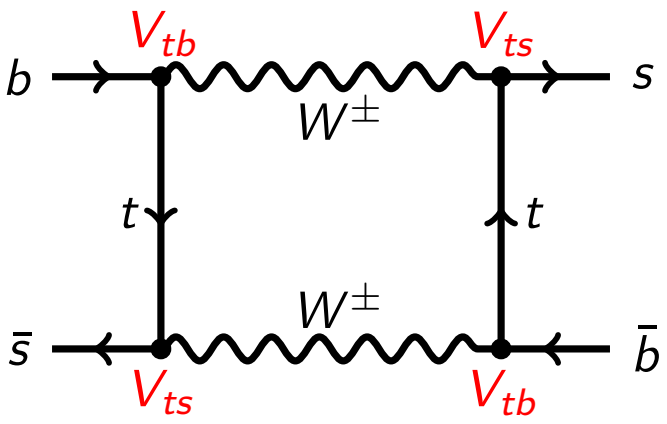
ΔM_{B_s}
[Jung, Pich, Tuzón, '06]



The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

CKM fits: $K_0^L \to \pi\ell\nu, D_s \to \mu\nu, B^0 - \bar{B}^0 ...$ **assume SM**



Pre-fit to CKM parameters

V_{ud} : $0^+ \to 0^+$ transitions [Hardy, Towner, '14]

$V_{ub}, V_{cb} : b \to q\ell\nu, q = u, c$ exclusive + inclusive + UTfit [HFLAV, '16], [UTfit]

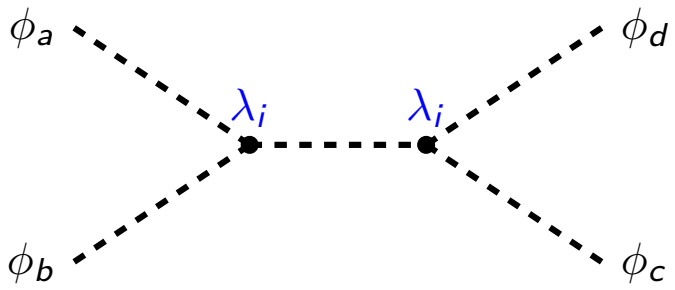
The Two-Higgs-Doublet Model – constraints

- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

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

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

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



[Ginzburg, I. P. Ivanov, '05]

Stability = potential bounded from below

$\downarrow$

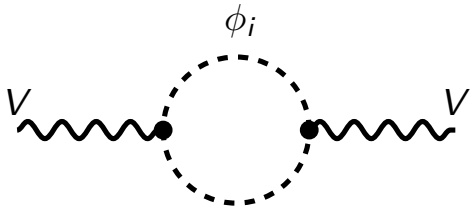
bounds on λ_i

[Barroso, Ferreira, Ivanov, Santos '13]

The Two-Higgs-Doublet Model – constraints

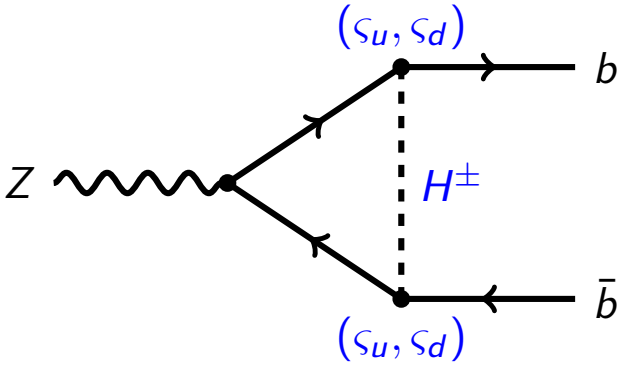
- h signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches

S, T, U: Oblique parameters



[Haber, O'Neil, '10]

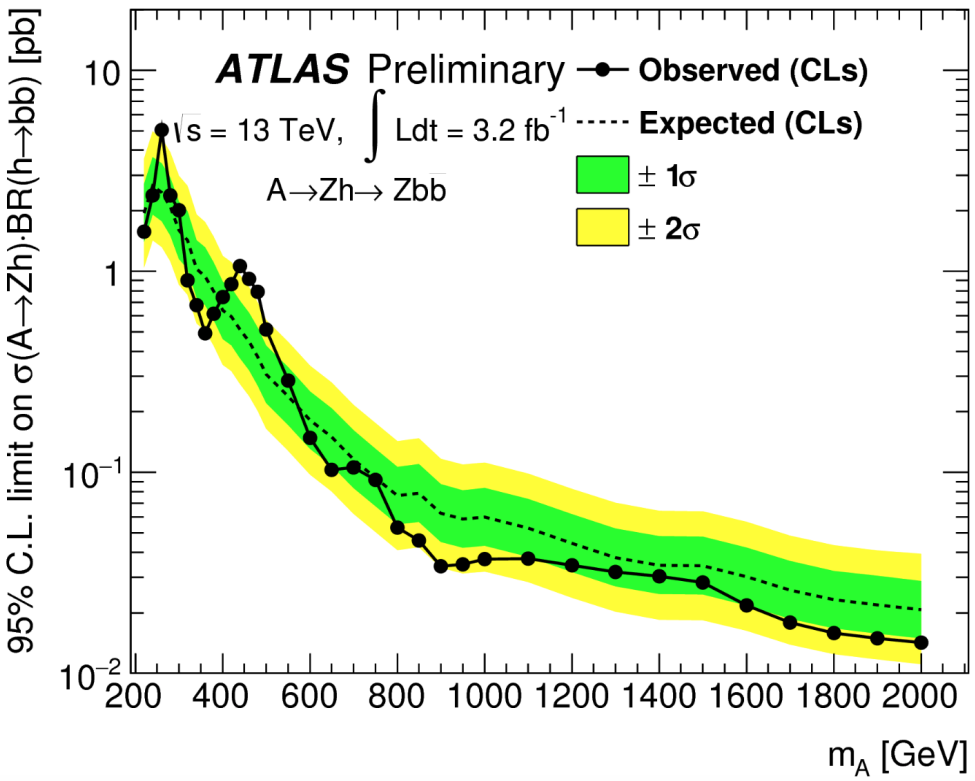
$$\mathbf{R_b} \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$



[Haber, Logan, '00]

The Two-Higgs-Doublet Model – constraints

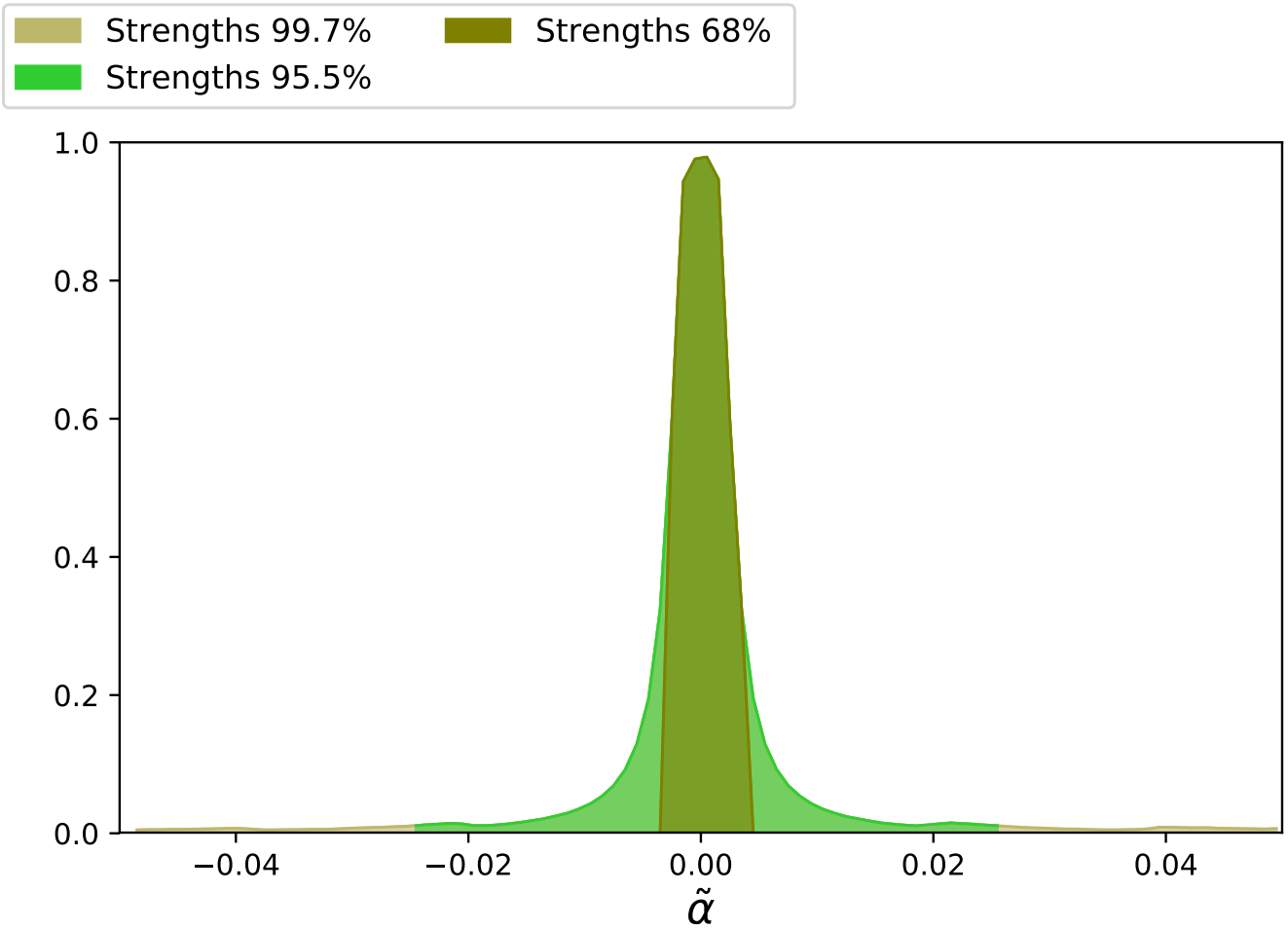
- *h* signal strengths
- Flavour observables
- Unitarity and stability
- Electroweak precision observables
- Direct searches



Results-h signal strengths

$$|\tilde{\alpha}| \leq 0.003 \quad 68\% \text{ probability}$$
$$|\tilde{\alpha}| \leq 0.024 \quad 95.5\% \text{ probability}$$

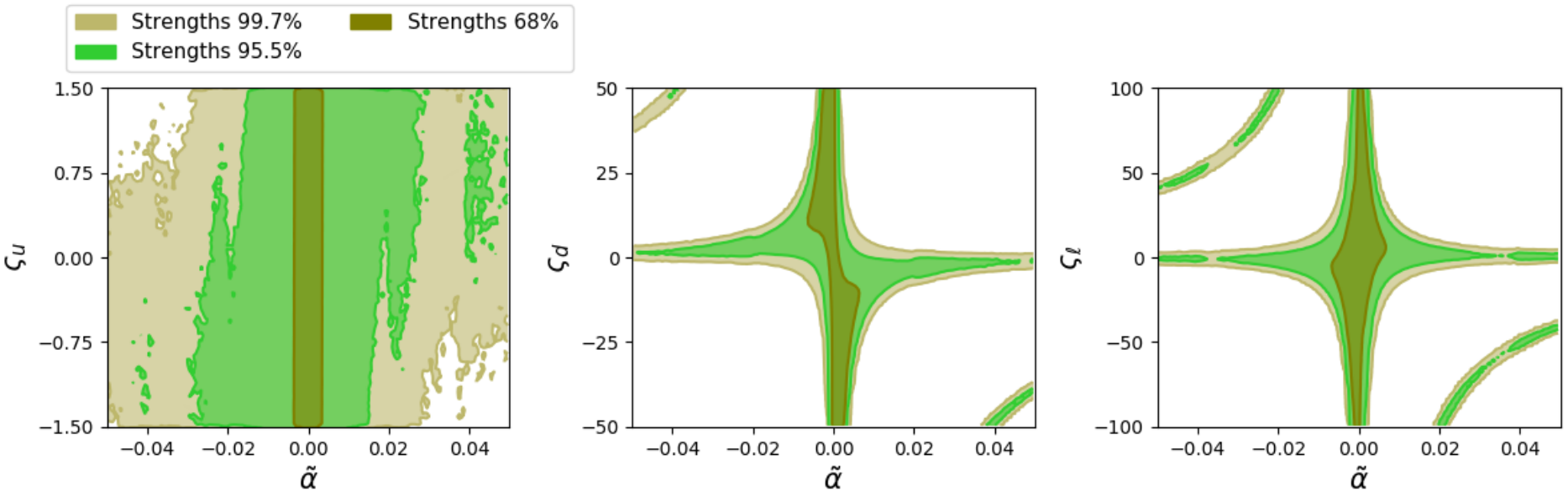
$$h = \cos\tilde{\alpha}\, S_1 + \sin\tilde{\alpha}\, S_2$$
$$H = -\sin\tilde{\alpha}\, S_1 + \cos\tilde{\alpha}\, S_2$$



Results-h signal strengths

Vertex: $\frac{\sqrt{2}\varsigma_i m_i}{v}$

$$y_f = 1 + \tilde{\alpha}\,\varsigma_f + \mathcal{O}(\tilde{\alpha}^2)$$

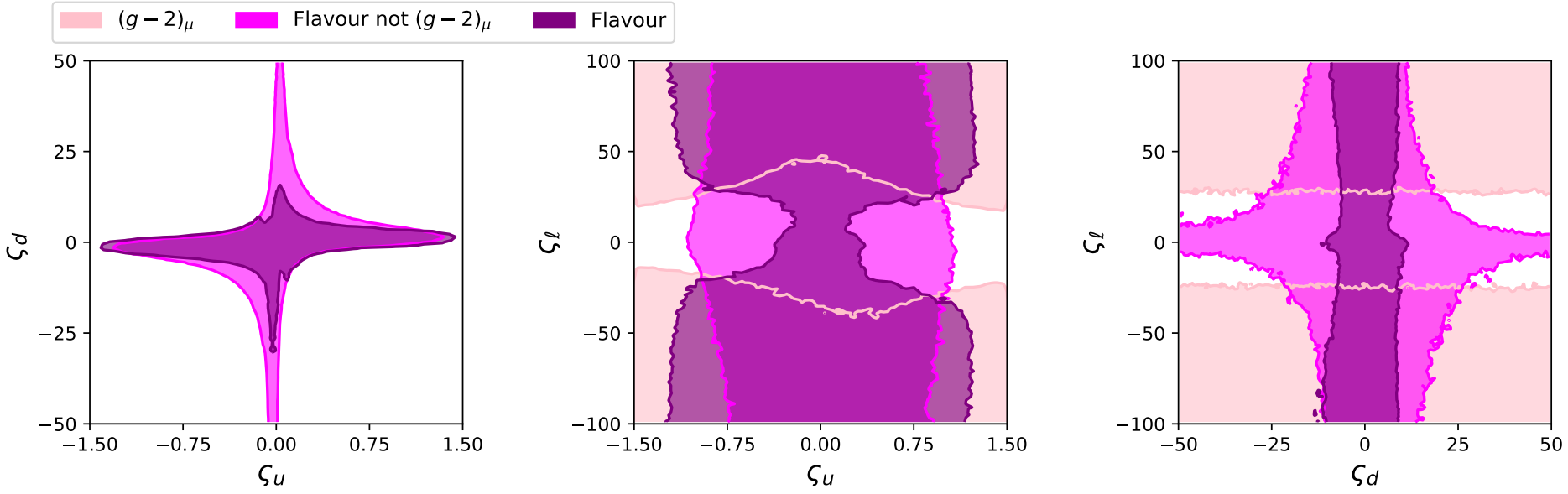


Results-flavour

Allowed at 95.5%

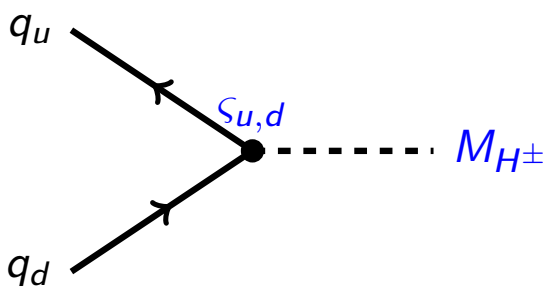
$|\varsigma_u||\varsigma_d| \lesssim 12$ 95.5% probability

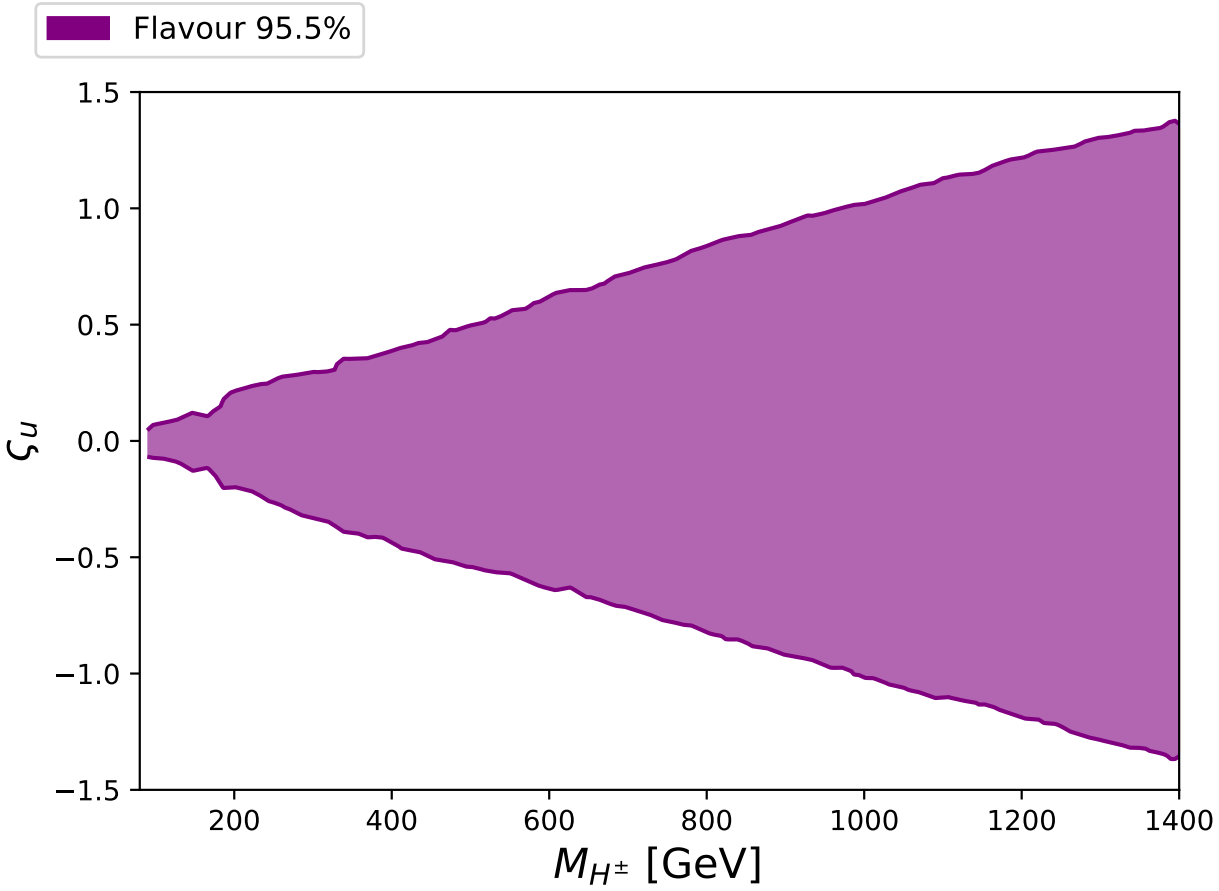
$|\varsigma_d| \lesssim 9$ 95.5% probability



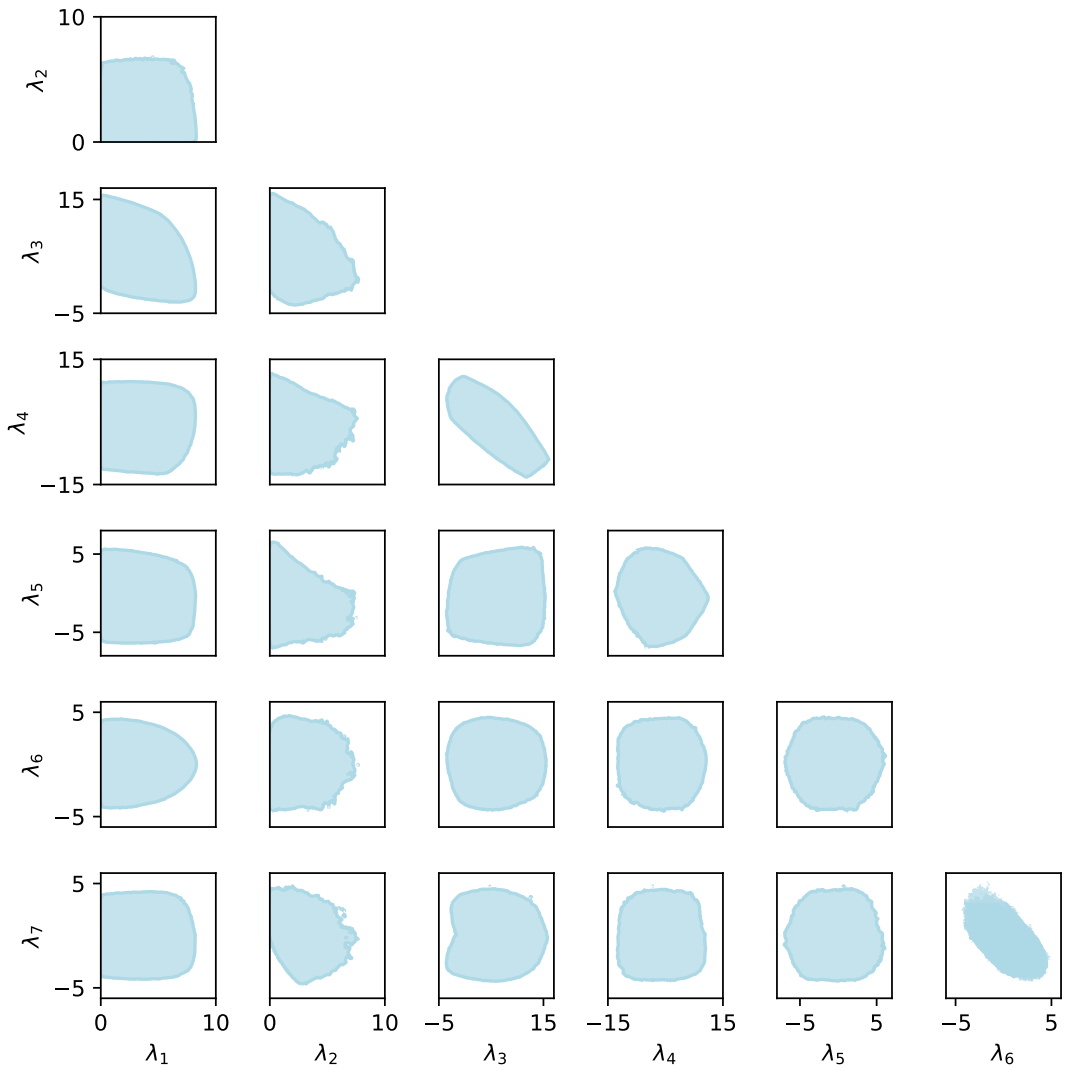
Results-flavour

$$\frac{|\varsigma_u|}{M_{H^\pm}} \leq 0.001 - \frac{0.102}{M_{H^\pm}}$$



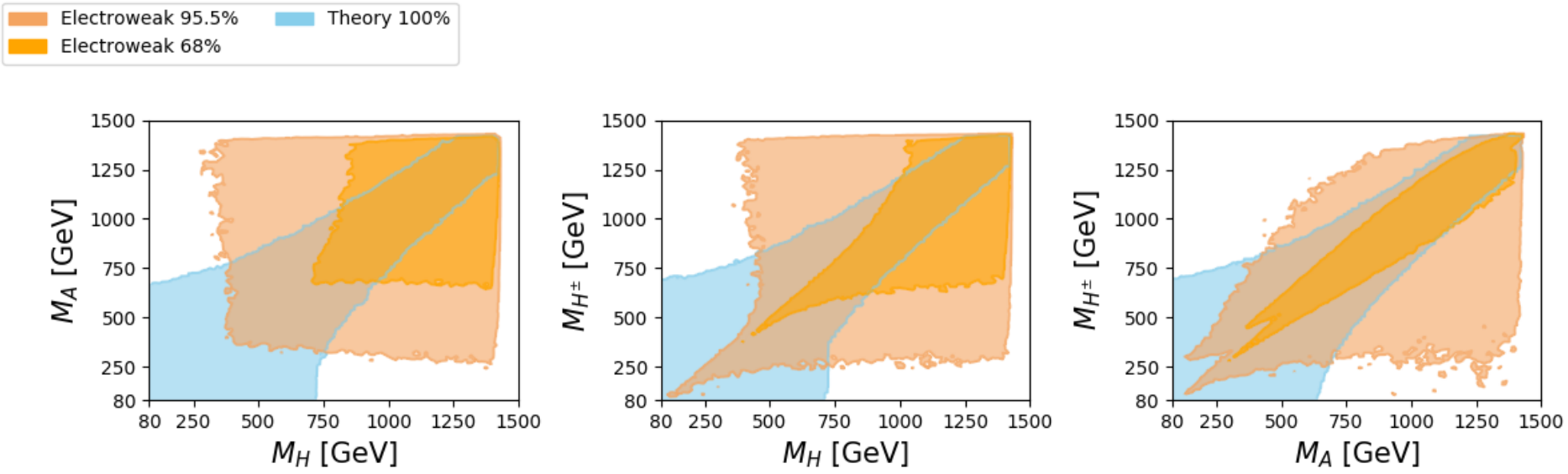


Results-theory

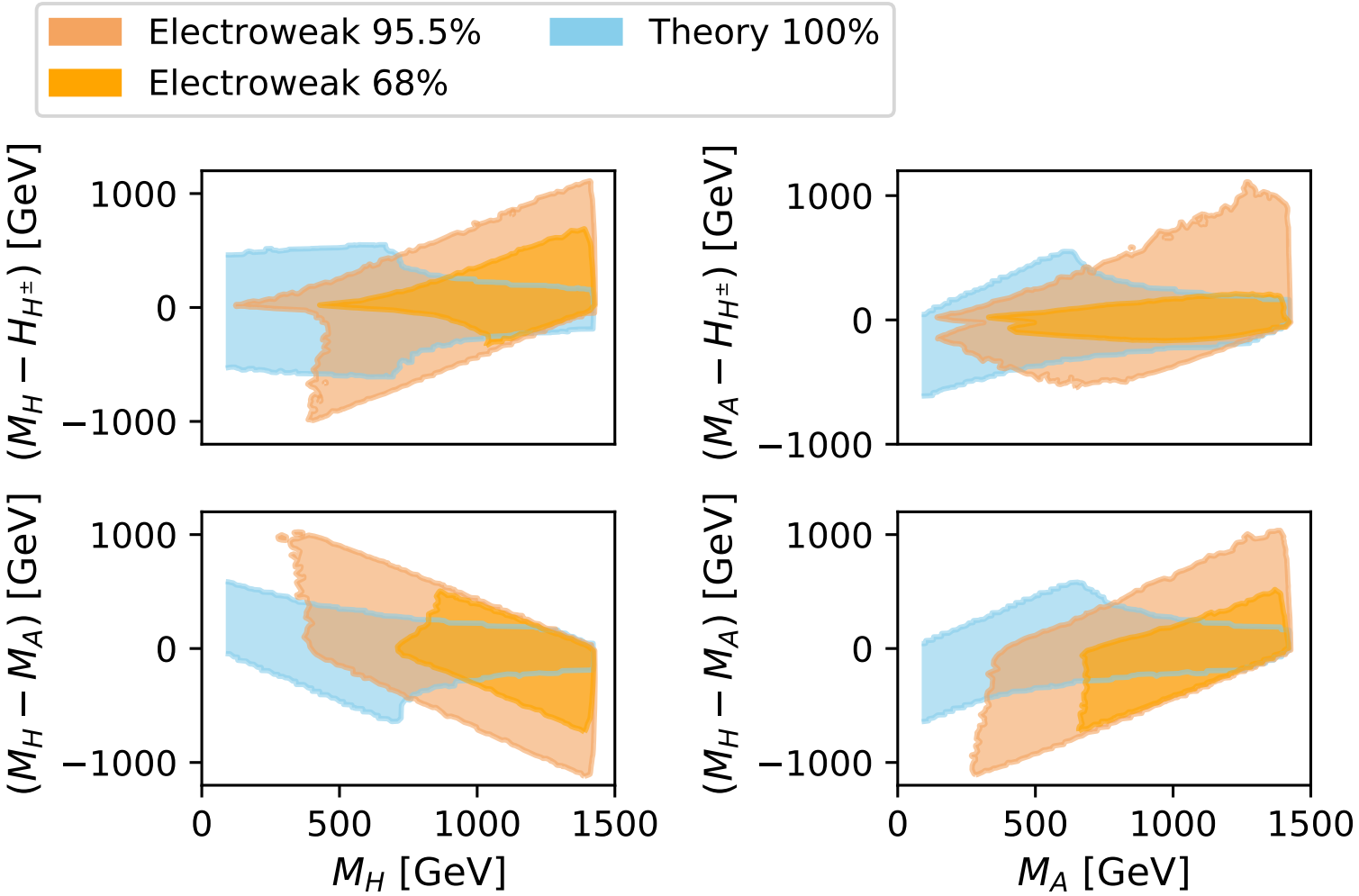


Results-Theory and EWPO

Theory: $|M_i - M_j| \leq 500$ GeV $\quad i, j = H, A, H^{\pm}$

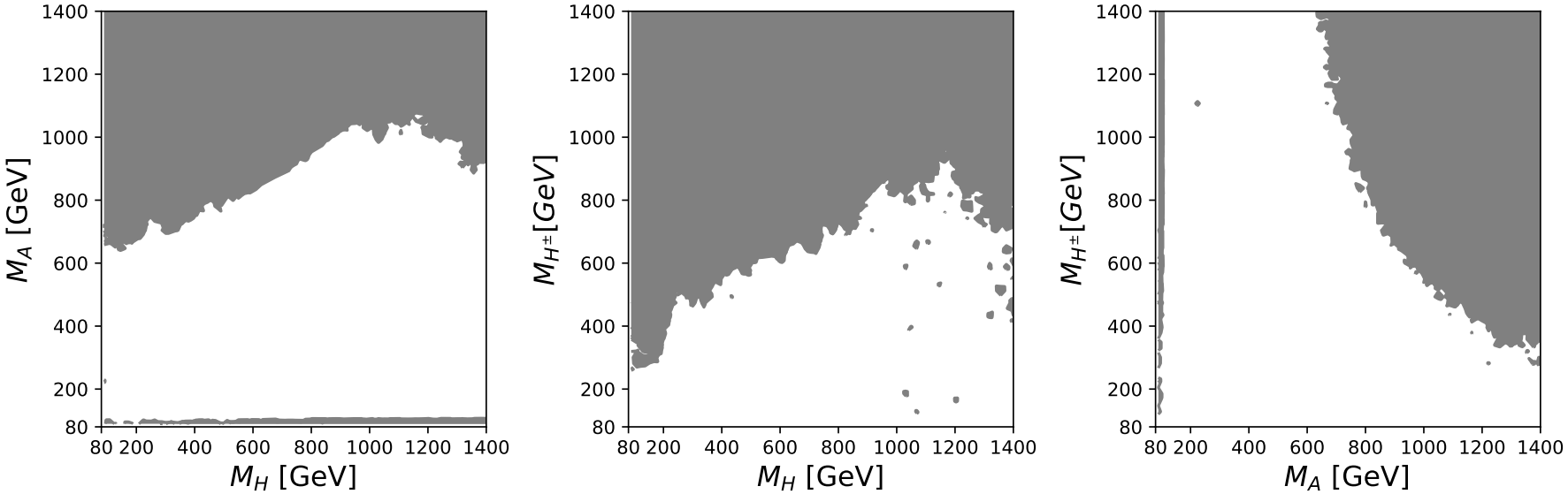


Results- Theory and EWPO



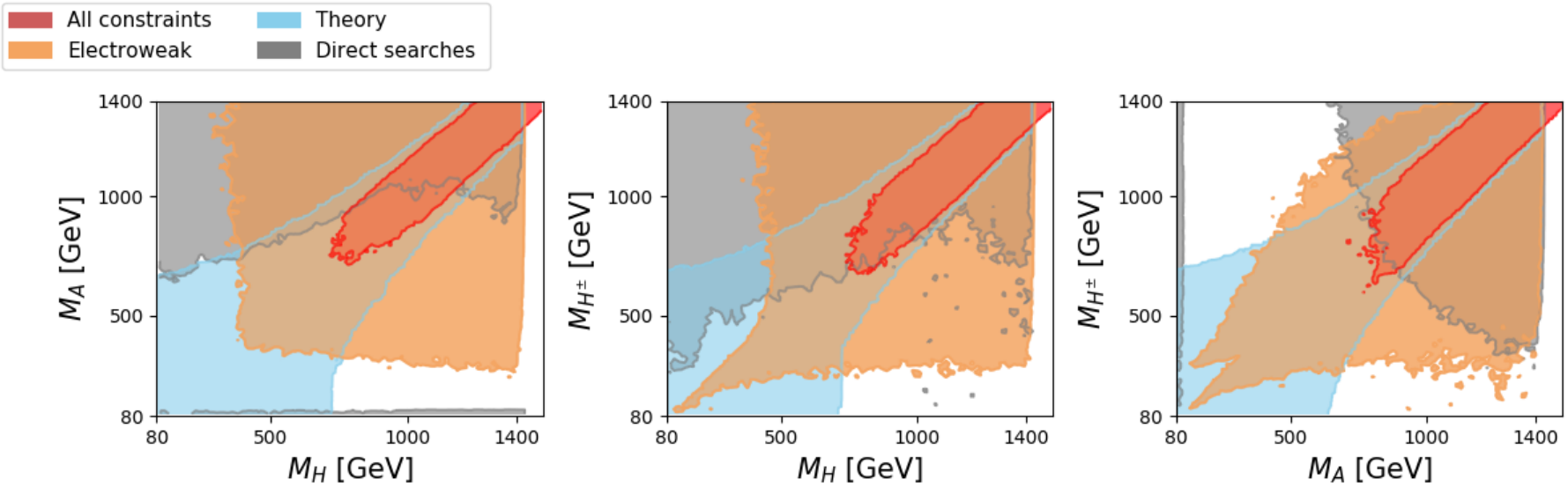
Results-Direct searches

Allowed at 95.5%



Results-Global fit

Allowed at 95.5%



Summary

Bounds on:

- $|\tilde{\alpha}|$
- $|\varsigma_u||\varsigma_d|$
- $|\varsigma_d|$
- $|M_i - M_j|$
- Constraints on the planes
  - $\varsigma_i - \varsigma_j$
  - $\varsigma_i - M_{H^\pm}$
  - $\lambda_i - \lambda_j$
- Model fulfilling all experimental+theoretical bounds
- Different constraints $\rightarrow$ constrain different planes/directions

Iterations/time

Fit	Iterations	Chains	Time
Strengths	10^8	12	97min
Flavour	10^7	8	140min
Theory	3×10^7	8	22h
Global fit	3×10^6	12	80h

HEPfit

- C++ open source
- Bayesian statistical analysis: Bayesian Analysis Toolkit (BAT)

Yukawa couplings

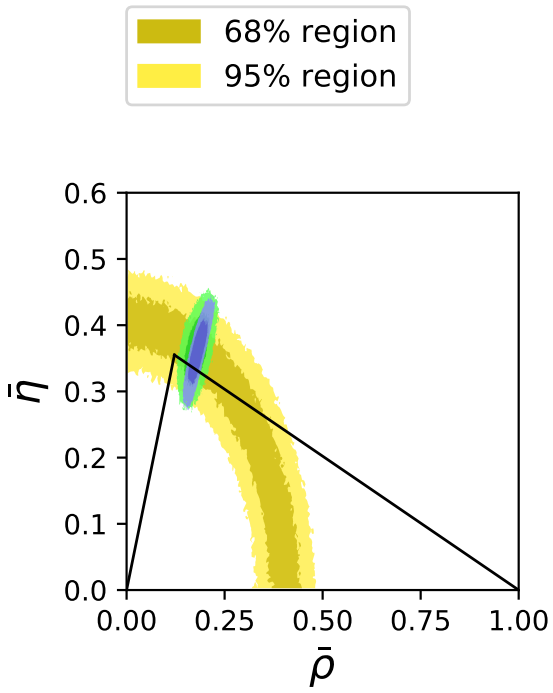
$$\frac{\sqrt{2}\varsigma_f m_f}{v} \leq 1$$

$$m_t \approx 170 \text{ GeV} \rightarrow |\varsigma_t| \lesssim 1.2 \tag{1}$$

$$m_b \approx 4 \text{ GeV} \rightarrow |\varsigma_b| \lesssim 43 \tag{2}$$

$$m_\tau \approx 2 \text{ GeV} \rightarrow |\varsigma_\tau| \lesssim 90 \tag{3}$$

CKM fit



Parameter	Value	Parameter	Value
λ	0.22564 ± 0.00090	$\bar{\rho}$	0.182 ± 0.016
A	0.829 ± 0.017	$\bar{\eta}$	0.360 ± 0.035
$\rho_{\lambda,A}$	-0.39	$\rho_{\bar{\rho},\bar{\eta}}$	0.82

Higgs signal strengths-ratios

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

The Two-Higgs-Doublet Model

FCNC at tree level (very constrained phenomenologically)

Yukawa Lagrangian

$$\mathcal{L}_Y = -\frac{1}{v}\left\{\bar{d}_L M_d d_R + \bar{u}_L M_u u_R + \bar{\ell}_L M_l \ell_R\right\}$$
$$- \sum_{a=2}^{N} \frac{1}{v}\left\{\sum_{i}^{2N-1} \mathcal{R}_{ia}\varphi_a^0 \left(\bar{d}_L Y_d^{(a)} d_R + \bar{u}_R Y_u^{(a)\dagger} u_L + \bar{\ell}_L Y_\ell^{(a)} \ell_R\right)\right.$$
$$\left. + \frac{\sqrt{2}}{v} H_a^+ \left(\bar{u}_L V_{\rm CKM} Y_d^{(a)} d_R - \bar{u}_R Y_u^{(a)\dagger} V_{\rm CKM} d_L + \bar{\nu}_L Y_\ell^{(a)} \ell_R\right)\right\} + \text{h.c.},$$

↓ **Natural flavour conservation**

↓ **Flavour alignment**