Cornering the Two Higgs Doublet Model

Oliver Atkinson
o.atkinson.1@research.gla.ac.uk

YTF, December 2022

Based on arxiv:2107.05650, 2202.08807 and 2207.02789

Outline

- The Two Higgs Doublet Model (2HDM) as a solution for SM shortcomings
- 2HDM Background
- Methodology and packages
- Direct and indirect constraints
- Combining results and looking forward

Standard Model vs Reality

- The SM is great! Except when it’s not
- Tensions, anomalies and unexplained phenomena
  - $R_{K^{(*)}}$, $R(D^{(*)})$, a_μ, m_W, etc.
  - Dark matter
  - Neutrino masses
- Sakharov criteria for electroweak baryogenesis
  - Baryon number violation
  - CP Violation
  - Strong first order electroweak phase transition

Motivating the 2HDM

- Capable of solving problems in the SM
- New Higgs bosons give new contributions to observable processes
- Different electroweak symmetry breaking pattern possible

	Standard Model	Two Higgs Doublet Model
Baryon Number Violation	Sphalerons	Sphalerons
Parity and Charge-Parity Violation	Weak interactions	Additional violations possible
First Order Phase Transition	Higgs is too heavy	Yes

2HDM Theory

- The Standard Model has a single Higgs doublet φ
- $\mathcal{L}_m = -Y_{ij}^d \bar{Q}_L^i \phi d_R^j - Y_{ij}^u \bar{Q}_L^i \tilde{\phi} u_R^j + h.c.$
- Symmetry breaking gives rise to three massive vector bosons
- An additional massive scalar is produced – the Higgs boson
- In the 2HDM, there is a second doublet which also acquires a VEV
- Now 5 massive (pseudo)scalar bosons: h^0, H^0, A^0, $H^\pm$
- Take h^0 to be the observed 125 GeV scalar
- h^0 and H^0 undergo mixing with angle α
- Define $\tan\beta = v_2/v_1$

2HDM Theory

- 7 model parameters in the mass basis:
  - 4 masses, the softly $\mathbb{Z}_2$ breaking term m_{12}^2, $\tan\beta$ and $\cos(\beta - \alpha)$
- Focus on the masses and mixing angles for observable consequences
- 4 types of flavour conserving 2HDM, based on doublet-fermion couplings:

Model	u_R	d_R	e_R
Type I	2	2	2
Type II	2	1	1
Lepton specific (X)	2	2	1
Flipped (Y)	2	1	2

For a comprehensive review, see arxiv:1106.0034

Model Couplings

$$-\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right)$$
$$- \left[\frac{\sqrt{2} V_{ud}}{v} \bar{u} \left(m_d \, \xi_A^d P_R - m_u \, \xi_A^u P_L \right) d H^+ \right.$$
$$\left. + \frac{\sqrt{2}}{v} m_\ell \, \xi_A^l (\bar{\nu} P_R \ell) H^+ + \text{h.c.} \right], \qquad (2)$$

Model	I	II	X	Y
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
ξ_A^l	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

Methodology

- Theoretical considerations
- SM Higgs signal strengths
- 2HDecay and HiggsBounds for direct collider searches
  - Key $H^+ \to tb$ cross section x branching ratio through MadEvent
  - Scan 50k random points across the parameter space
- Extrapolate LHC results to HL-LHC performance of 13 TeV, 3/ab
  - SM Higgs searches matching SM predictions
  - 7-8 TeV search cross sections boosted using a MadEvent interpolation
- Flavio for 240 flavour observables
  - Calculate the Wilson Coefficients from 2HDM contributions and perform a global fit

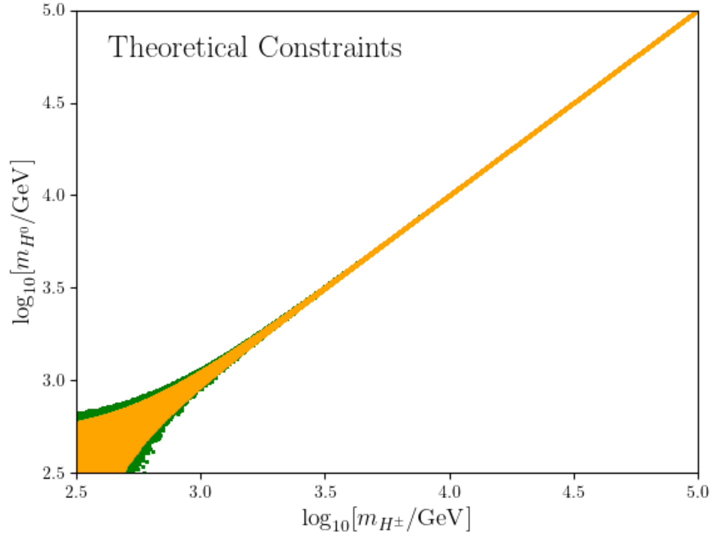
The 2HDecay homepage is at https://github.com/marcel-krause/2HDECAY, with a manual at arxiv:1810.00768
The HiggsBounds homepage is at https://gitlab.com/higgsbounds/higgsbounds, with a manual at arxiv:2006.06007
The Flavio homepage is at https://flav-io.github.io, with a manual at arxiv:1810.08132

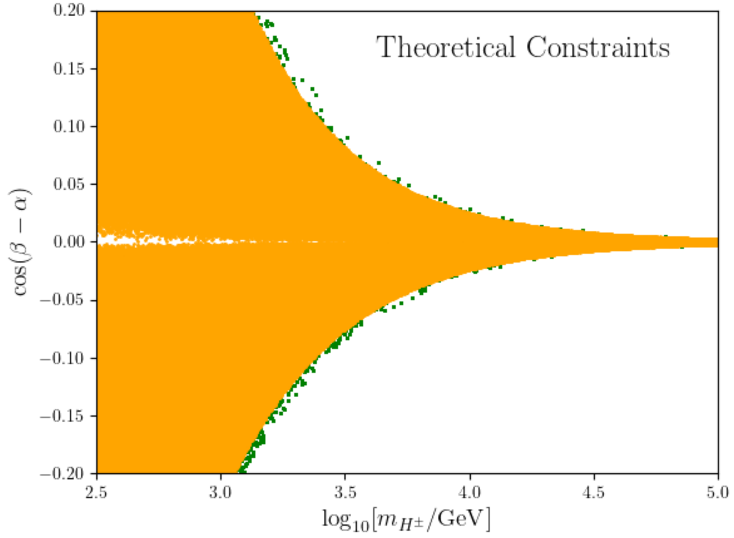
Theoretical Constraints

- 2HDM potential: $$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right].$$
- Enforce vacuum stability and unitarity
- For perturbativity we check limits of 4 and 4π, with minimal difference in the scan
- Perturbative limit of 4π in the type 2 charged Higgs couplings is used to inform the parameter space limits
- We perform Monte Carlo scans with 10^8 points in the lambda basis and convert results to the mass basis

Theoretical Constraints

- Only one of the mass plots shown – the other combinations look identical
- Type independent results
- Masses must be very nearly degenerate
- More freedom at lower masses
- $\cos(\beta - \alpha)$ constrained to be small at high $m_{H^\pm}$
- No constraints found on $\tan\beta$
- Minor differences between 4 and 4π
- Degeneracy a result we will return to often





Electroweak Precision Observables

- Electroweak precision observables: S, T, U
- By construction these are zero in the SM
- Involved calculation in the 2HDM
- New physics has no effect on U so we set it to zero
- Results show that $m_{H^\pm} = m_{H^0}$ or $m_{H^\pm} = m_{A^0}$ preferred, with full degeneracy allowed
- These results are also type independent
- Included in the global fit

Higgs Sector – Signal Strengths

- Focus on the measured properties of h^0
- The couplings differ in the 2HDM vs the SM, by factors:

$$\kappa_V = \sin(\beta-\alpha),$$
$$\kappa_u = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\kappa_{d,\ell} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

- $\cos(\beta-\alpha)=0$ recovers exactly the SM couplings – the alignment limit
- This is part of the reason we choose $\cos(\beta-\alpha)$ as a model parameter over α
- In the type 2 model a wrong sign limit can be achieved; $\kappa_u = 1$, $\kappa_V = 1$, $\kappa_{d,\ell} = -1$
- We use the Higgs signal strengths as the observables here, defined as:

$$\mu_i^f = \frac{(\sigma_i \cdot \mathcal{B}_f)_{\text{Exp.}}}{(\sigma_i \cdot \mathcal{B}_f)_{\text{SM}}}$$

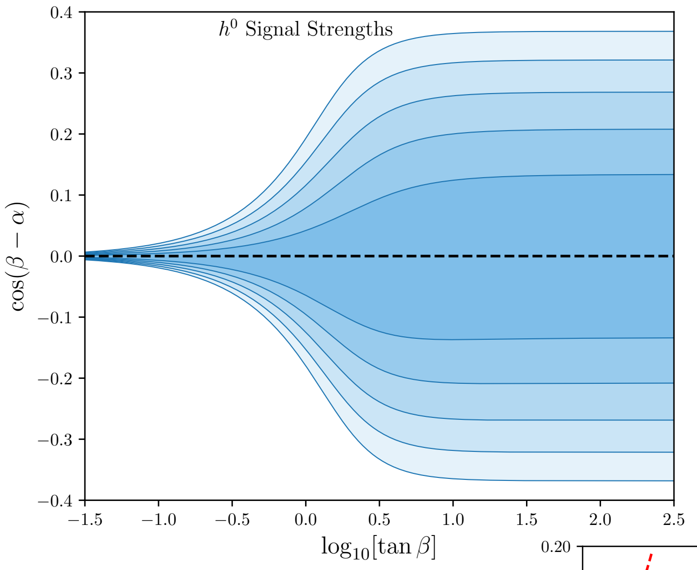
- 32 channels from CMS and ATLAS, with correlation matrices where appropriate
- All in these are in good agreement with the SM, lying within 2σ of 1

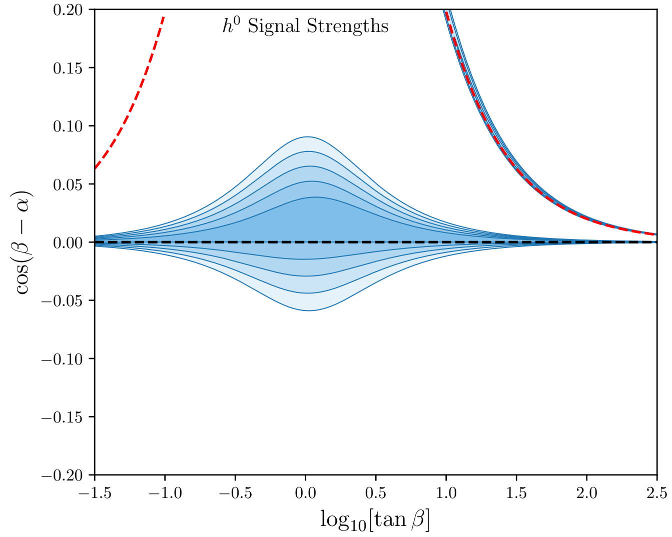
Higgs Sector – Signal Strengths

- Calculate the κ_i and use in analytic calculations
- Fairly unconstrained in T1, except at low $\tan\beta$
- $\cos(\beta-\alpha)$ must be small in T2:

$$|\cos(\beta-\alpha)| \leq 0.05$$

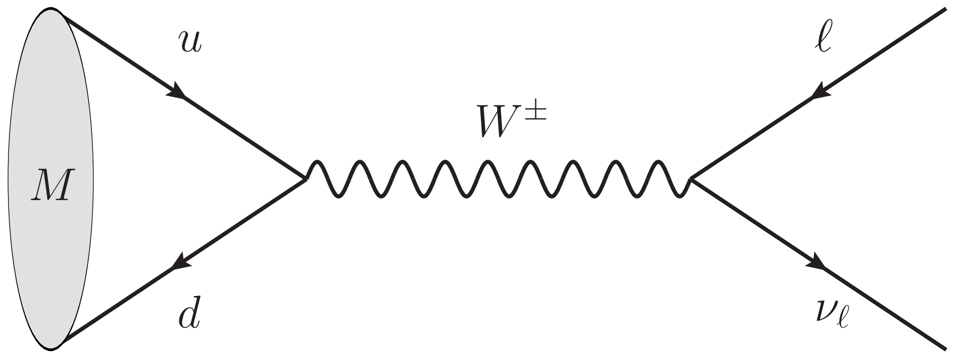
- Away from $\tan\beta \approx 1$, even smaller
- Alignment limit closely followed
- In good agreement with literature
- The wrong sign limit is excluded up to 2.7σ

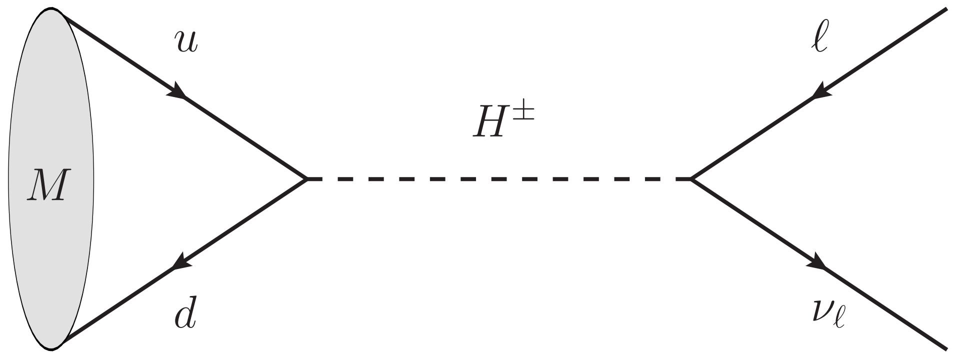




Flavour – Leptonic Decays

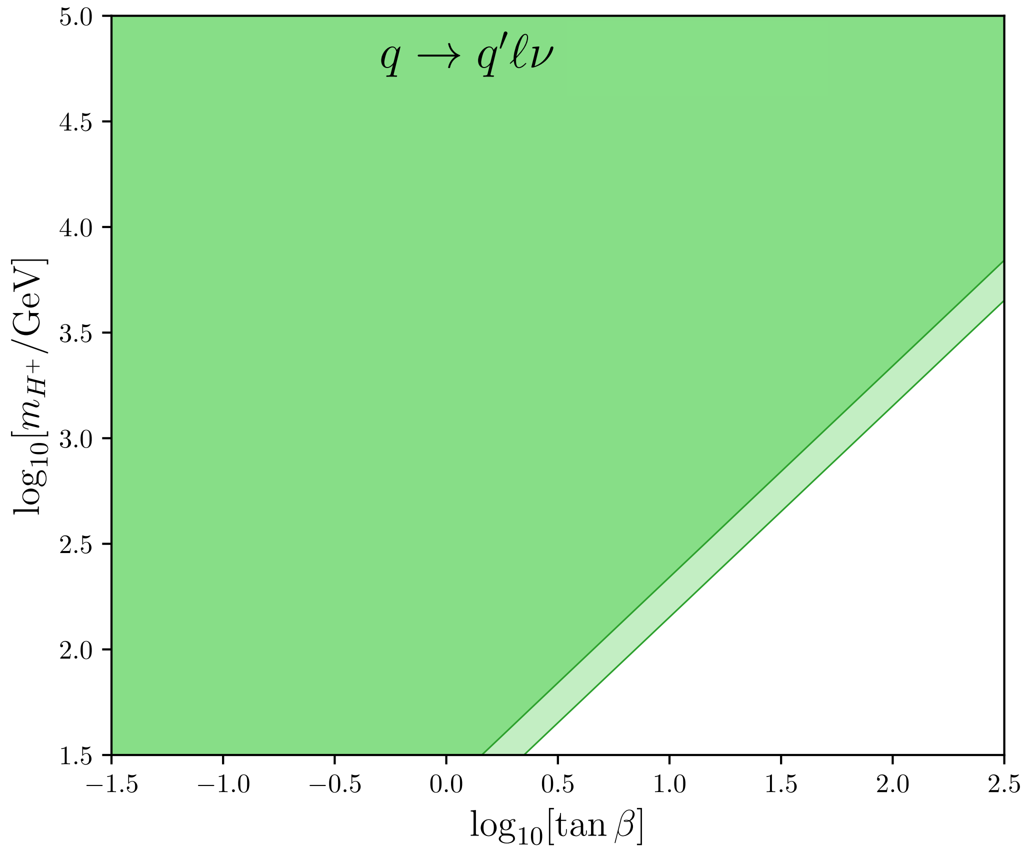
- A simple and constructive example of the project process
- Extra contributions when the decays are mediated by $H^\pm$
- Effective Hamiltonian: $\mathcal{H}_{H^+}^{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ud} (C_{S-P}\, \mathcal{O}_{S-P} + C_{S+P}\, \mathcal{O}_{S+P}) + \text{h.c.}$
- Operators: $\mathcal{O}_{S-P} = (\bar{u} P_L\, d)(\ell P_L \nu_\ell)$, $\mathcal{O}_{S+P} = (\bar{u} P_R\, d)(\ell P_L \nu_\ell)$
- Expressions: $C_{S-P} = \frac{m_u\, m_\ell}{m_{H^+}^2}$, $C_{S+P} = \frac{m_d\, m_\ell \tan^2 \beta}{m_{H^+}^2}$



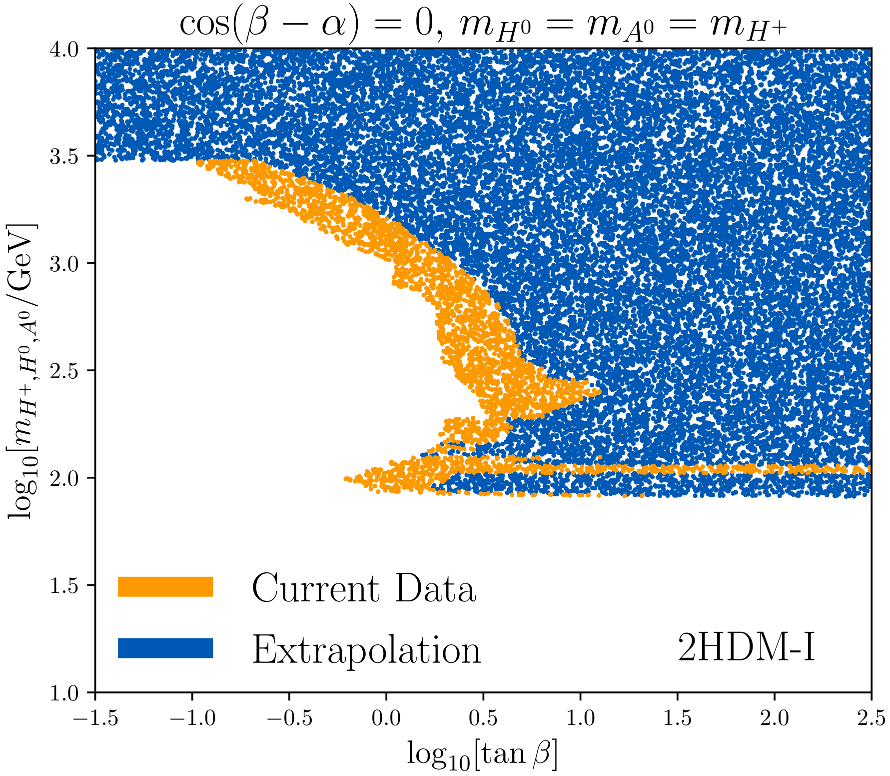


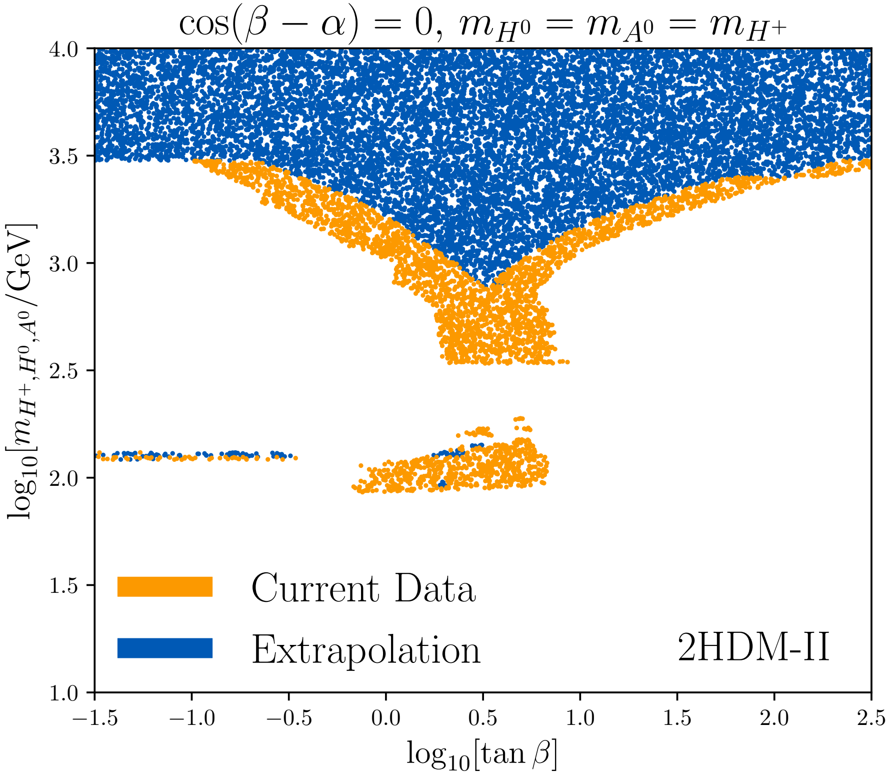
Flavour – Leptonic Decays

- 10 tree level leptonic decay BRs
- 24 tree level semi-leptonic decay BRs
- First inclusion of $B_s \to D_s^{(*)} \mu \bar{\nu}_\mu$
- Perform the fit in flavio
- Only a small exclusion region



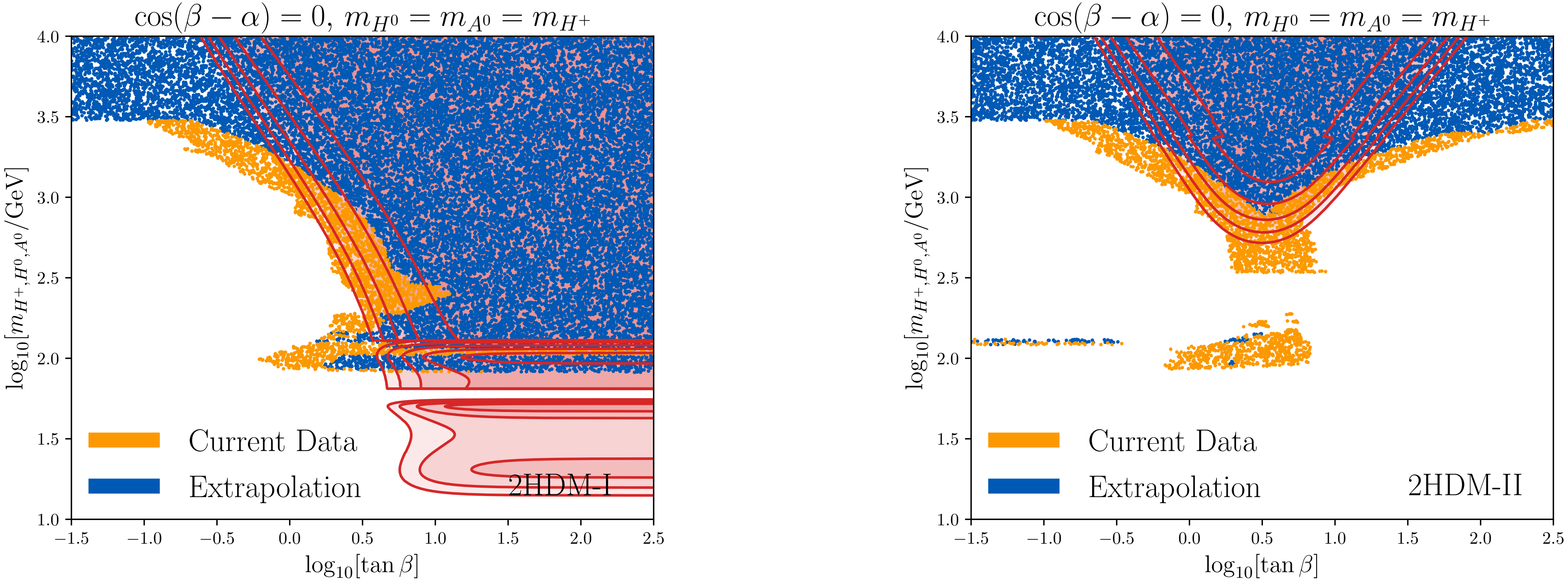
Collider Searches





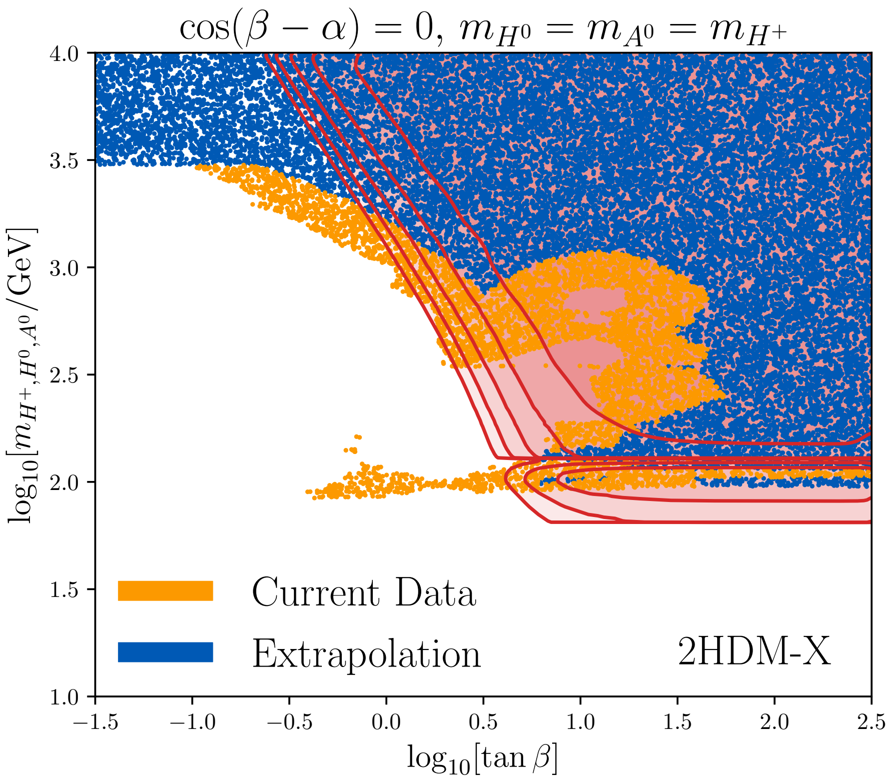
- LEP searches rule out the lowest masses
- $H^+ \longrightarrow tb$ provides exclusion zones above m_t for low tanβ
- $H^0 \rightarrow \tau^+\tau^-$ does so for large tanβ in Type II; Type I has minimal couplings here

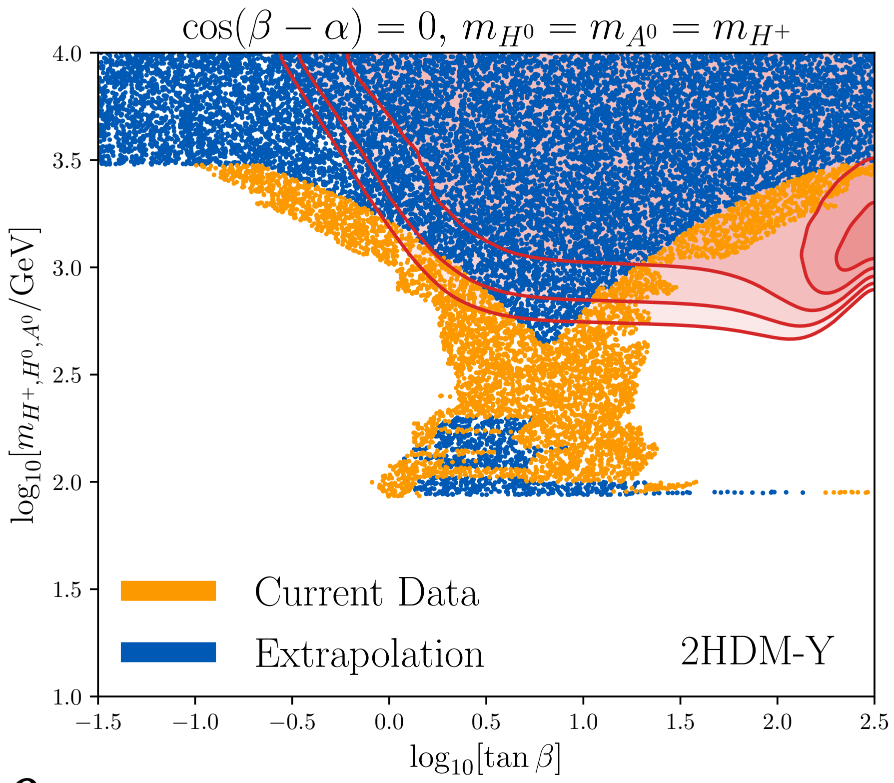
Collider and Flavour Complementarity



- Flavour results particularly helpful for low $\tan\beta$
- Collider searches provide low mass cut off in Type I
- In Type II, flavour gives a lower mass bound of 860 GeV, mainly from $b \to s\gamma$
- The extrapolation makes collider data competitive

Collider and Flavour Complementarity





- Flavour results still more potent for low $\tan\beta$
- Direct searches eat into more of the 1σ region from flavour in both cases
- Entire 1σ region excluded in current collider data for Type Y, and very nearly all the 2σ region in the extrapolation

Electroweak Phase Transition

- A strong first order EWPT (SFOEWPT) is required
- We use the BSMPT package to calculate the strength of the EWPT
- In BSMPT, calculations are done in the lambda basis, so we convert
- The strength of the EWPT is characterised by $\xi_c = \omega_c/T_c$
- We test individual benchmark points for $\xi_c > 1$
- For a SFOEWPT the new Higgs masses cannot be larger than around 860 GeV
- This is at the 2σ limit from the global fit
- Best fit points do not allow for a SFOEWPT by some distance
- Allowed points require at least one $\lambda_i > 4$, conflicting with perturbativity
- These results are consistent with other studies of the 2HDM

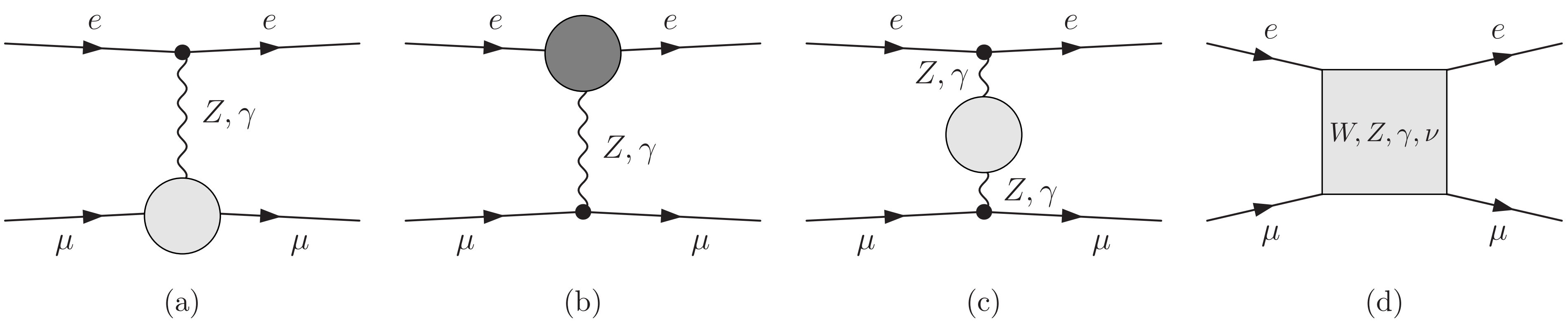
The BSMPT homepage is at https://github.com/phbasler/BSMPT
The main paper is arxiv:2007.01725

Type I EWPT

$\tan\beta$	Mass Basis (GeV)			Lambda Basis			m_{12}^2	ω_c	T_c	ξ_c
	m_{H^+}	m_{H^0}	m_{A^0}	λ_3	λ_4	λ_5	(GeV^2)	(GeV)	(GeV)	
11.4	50000	50000	50000	0.26	0	0	3.1×10^7	0.58	164	0.004
80	1750	1750	1750	0.26	0	0	3.8×10^4	23	162	0.14
50	1810	1750	1760	7.3	−6.5	−0.6	6.1×10^4	26	174	0.15
10	1810	1750	1760	7.3	−6.5	−0.6	3.0×10^5	26	174	0.15
150	1810	1750	1760	7.3	−6.5	−0.6	2.0×10^4	26	174	0.15
35	1020	960	970	4.2	−3.6	−0.3	2.6×10^4	24	169	0.14
80	860	710	860	8.0	−3.9	−3.9	6.3×10^3	142	174	0.82
80	860	690	860	9.0	−4.3	−4.3	6.0×10^3	177	174	1.02
80	680	470	680	8.2	−4.0	−4.0	2.8×10^3	211	147	1.43
80	570	320	570	7.6	−3.7	−3.7	1.3×10^3	226	125	1.81
80	490	250	490	6.1	−2.9	−2.9	7.8×10^2	207	126	1.65
80	490	490	490	0.26	0	0	3.0×10^3	23	161	0.14

MUonE

- ➢Also expect interactions in the muon-electron scatting to be tested at the upcoming MUonE experiment
- ➢Very little sensitivity to 2HDM of any type, apart from some extreme scenarios
- ➢Good news for the experiment, which is not aiming for new physics discovery



Conclusions

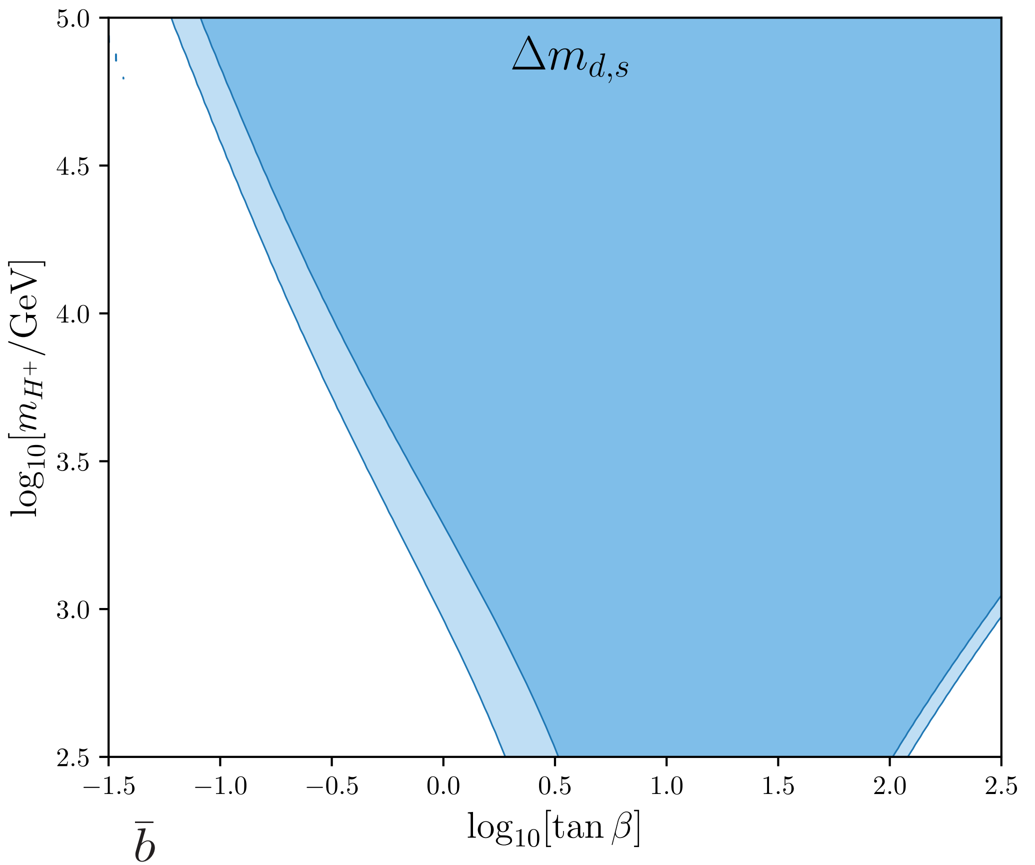
- Thorough analysis of the 2HDM, taking into account 275 indirect channels and a wealth of collider data, including an extrapolation to LHC potential
- Good interplay of the different sectors, particularly in the extrapolation
- We can rule out large amounts of the parameter space, exceeding bounds from previous studies
- Additionally, we can consider a SFOEWPT and a_μ
- A series of comprehensive studies of the 2HDM of all types, going further than any previous studies and setting new bounds

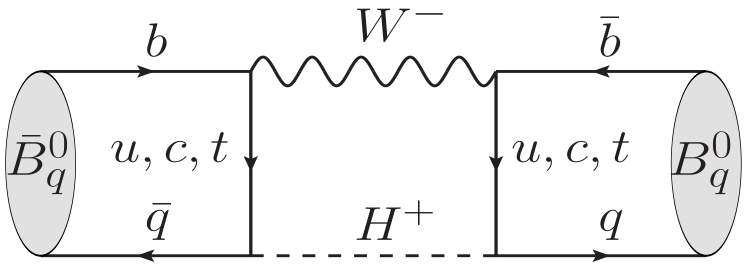
Questions

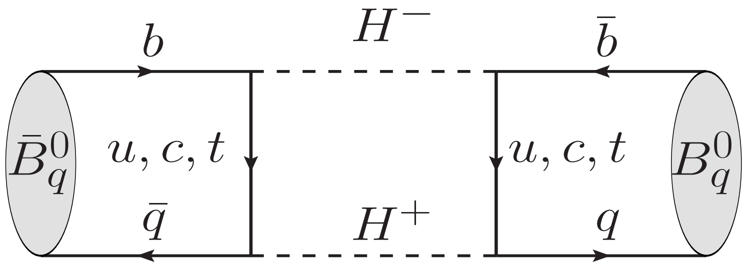
Backup Slides

Flavour – Neutral B Meson Mixing

- Mass difference in eigenstates of B_s and B_d
- Six operators to consider at LO in QCD
- Theory uncertainties from non-perturbative matrix elements in the operators
- Averages used based in HQET sum rules and lattice simulations
- Perturbative SM corrections implemented to NLO in QCD







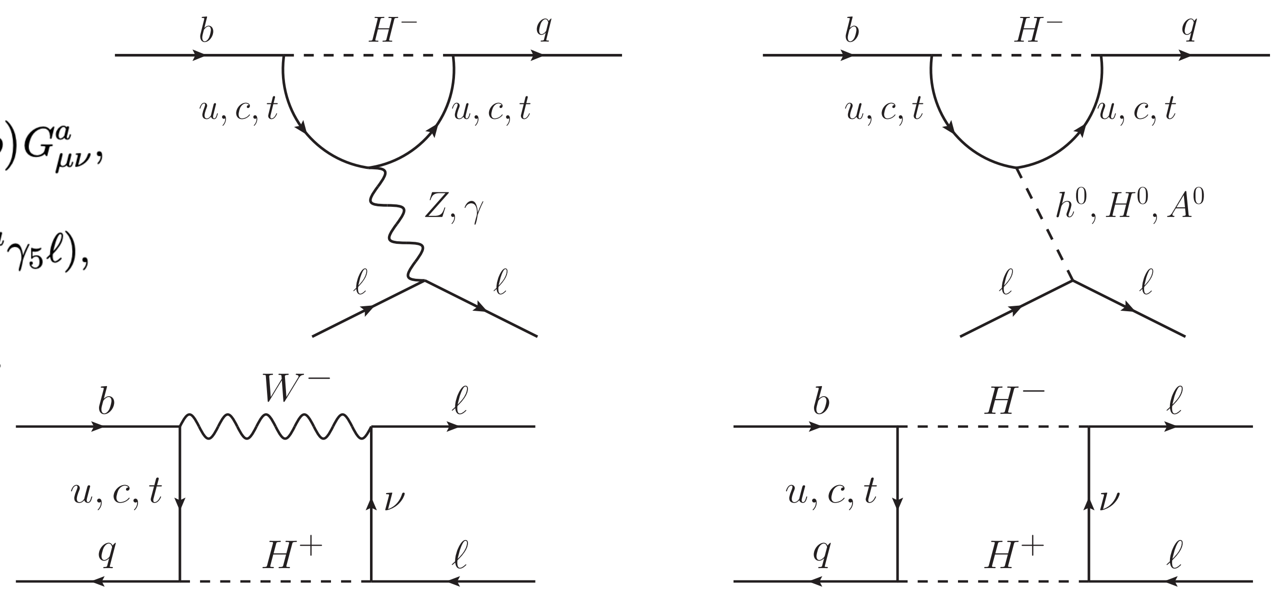
Flavour – Loop Level $b \to s,\, d$ Transitions

- Flavour changing neutral currents $b \to q\ell^+\ell^-$ $(q = s,\, d)$, $b \to s\gamma$
- We split these up into a few areas, following conventions
- Many observables, particularly in semi-leptonic $b \to q\ell^+\ell^-$
- Some deviations from the SM, up to 3.1σ
- Sensitive to 12 operators:

$$\mathcal{O}_7^{(\prime)} = \frac{e\, m_b}{16\pi^2}\left(\bar{q}\sigma^{\mu\nu}P_{R(L)}b\right)F_{\mu\nu}, \qquad \mathcal{O}_8^{(\prime)} = \frac{g_s\, m_b}{16\pi^2}\left(\bar{q}\sigma^{\mu\nu}P_{R(L)}T^a b\right)G^a_{\mu\nu},$$

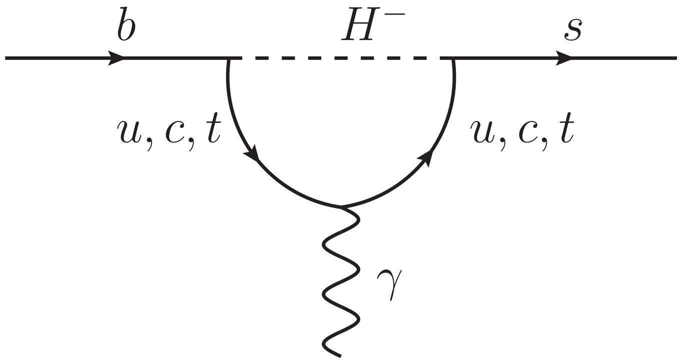
$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{q}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell), \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{q}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell),$$

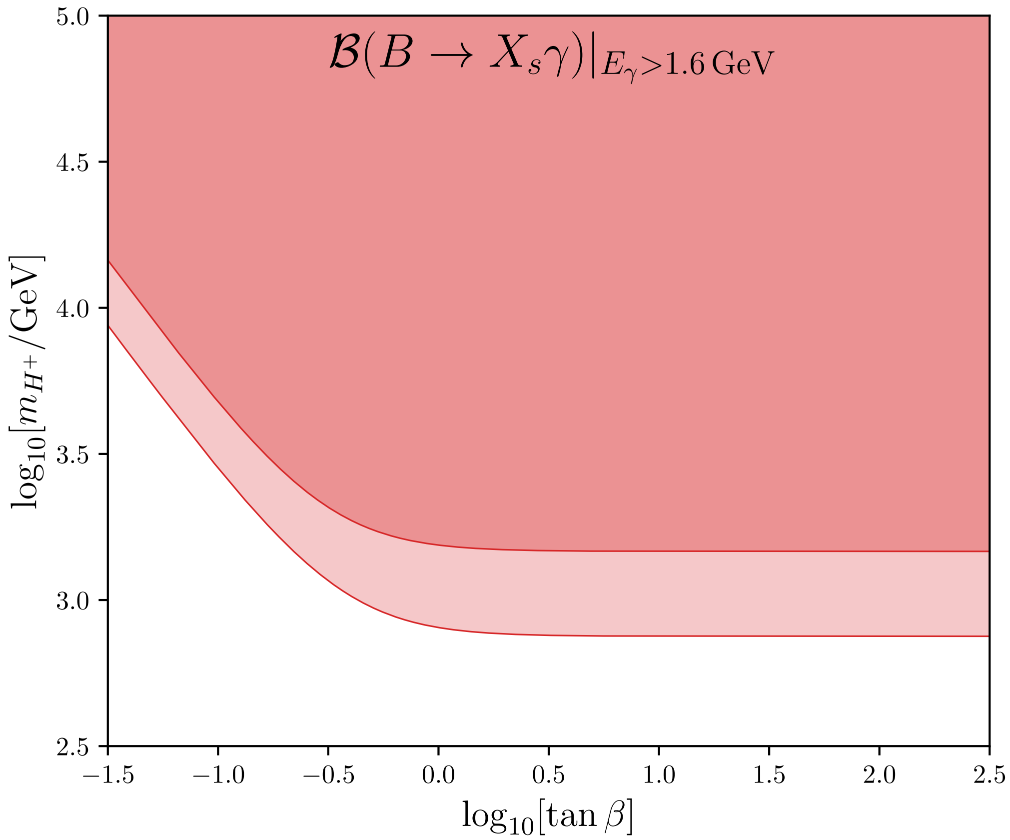
$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{q}P_{L(R)}b)(\bar{\ell}\ell), \qquad \mathcal{O}_P^{(\prime)} = \frac{e^2}{16\pi^2}(\bar{q}P_{L(R)}b)(\bar{\ell}\gamma_5\ell).$$



Flavour – $b \to s\gamma$

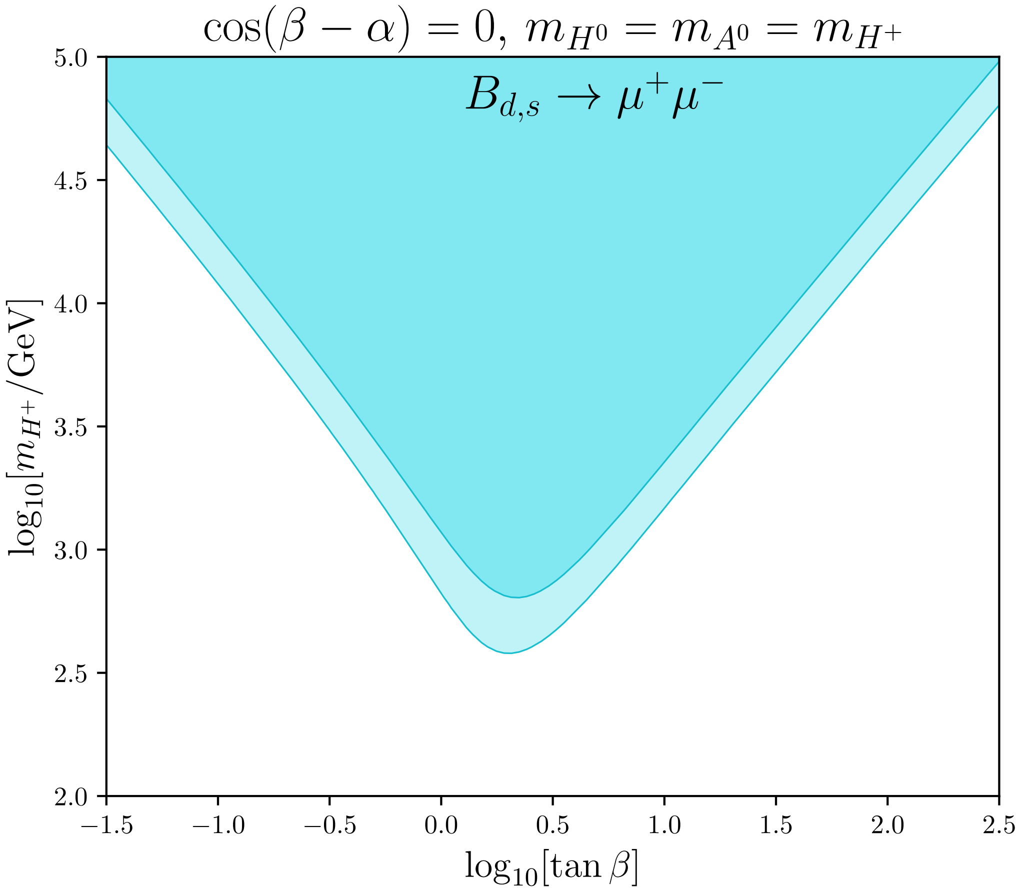
- Historically, a key constraint for enforcing a lower mass limit on $H^{\pm}$
- SM value calculated at NNLO in QCD:
  $\mathcal{B}^{\rm SM}(\bar{B} \to X_s\gamma)\big|_{E_\gamma>1.6\,\rm GeV} = (3.40 \pm 0.17) \times 10^{-4}$
- Our 2HDM contributions are at NLO
- We find $m_{H^+} \gtrsim 790\,(1510)\,\mathrm{GeV}$ at $2\sigma\,(1\sigma)$





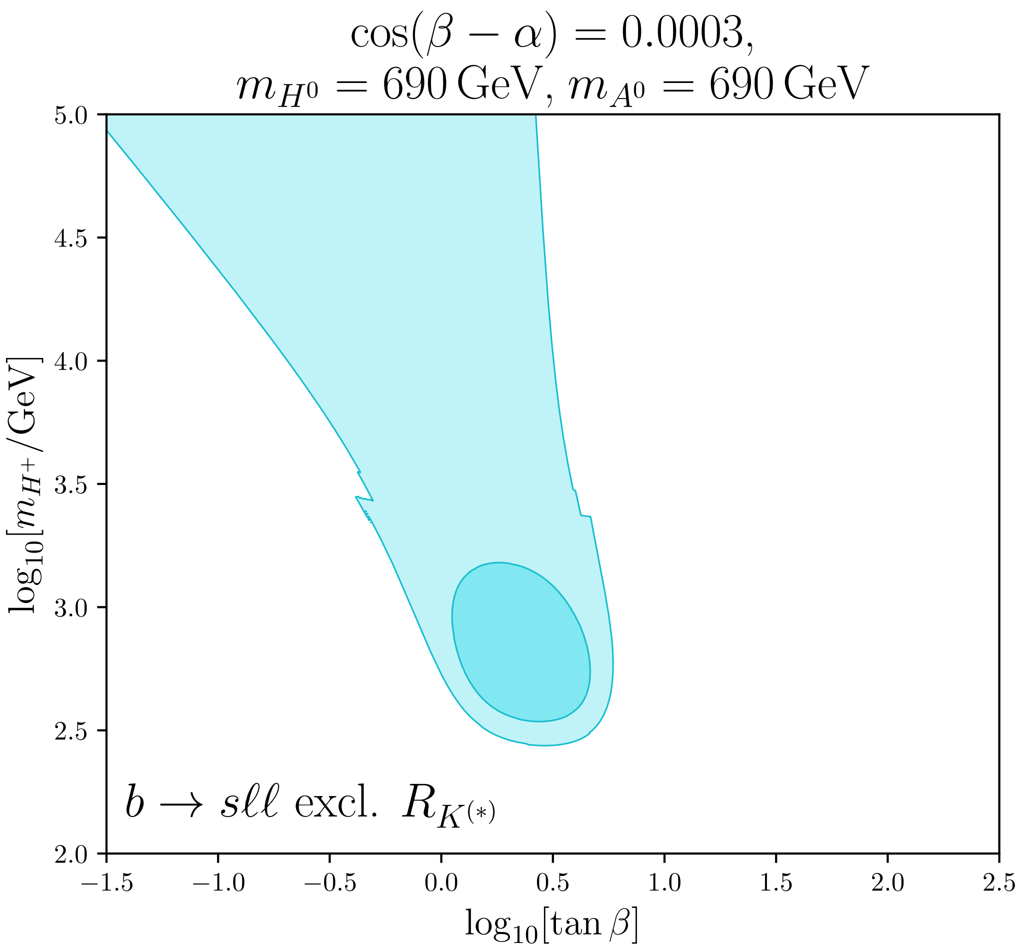
Flavour – Leptonic $B_{s,d} \longrightarrow \mu^+\mu^-$ Decays

- Fully general expressions for the WCs – no large $\tan\beta$ limit
- We now need the other model parameters
- Two approaches – degeneracy or best fit point fixing
- Lower mass bound of 300 GeV at 2σ
- Strong correlation of $m_{H^\pm}$ and $\tan\beta$



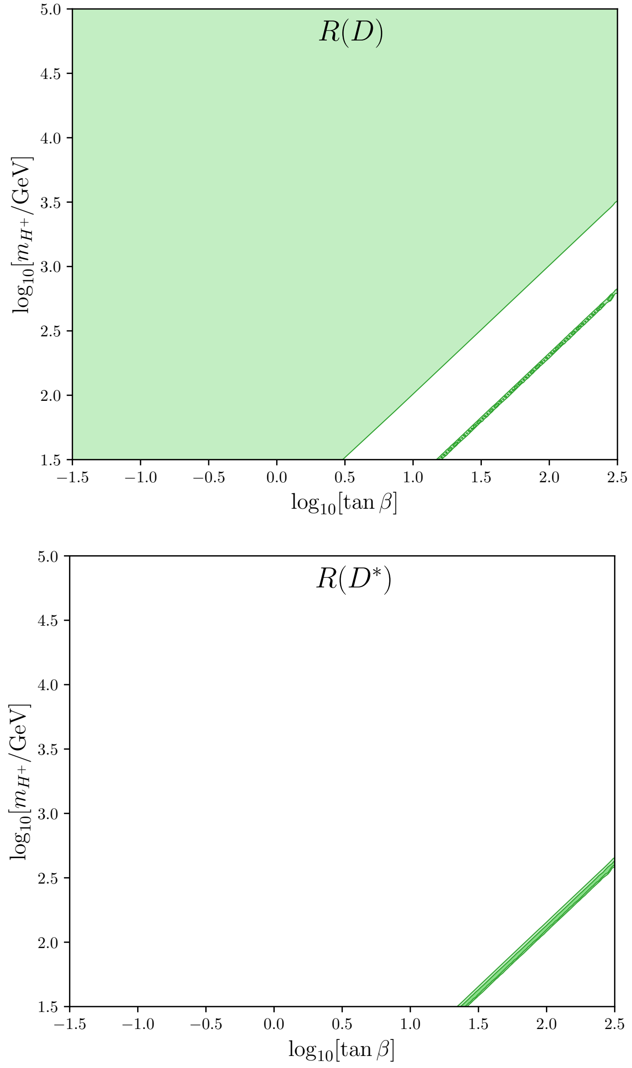
Flavour – Semi-leptonic $b \to s\ell^+\ell^-$ Transitions

- Ignore for now the LFU ratios $R_{K^{(*)}}$
- 192 total observables, including binned branching ratios, angular distributions, asymmetries
- There are some anomalies here
- We fix to the best fit point in this plot



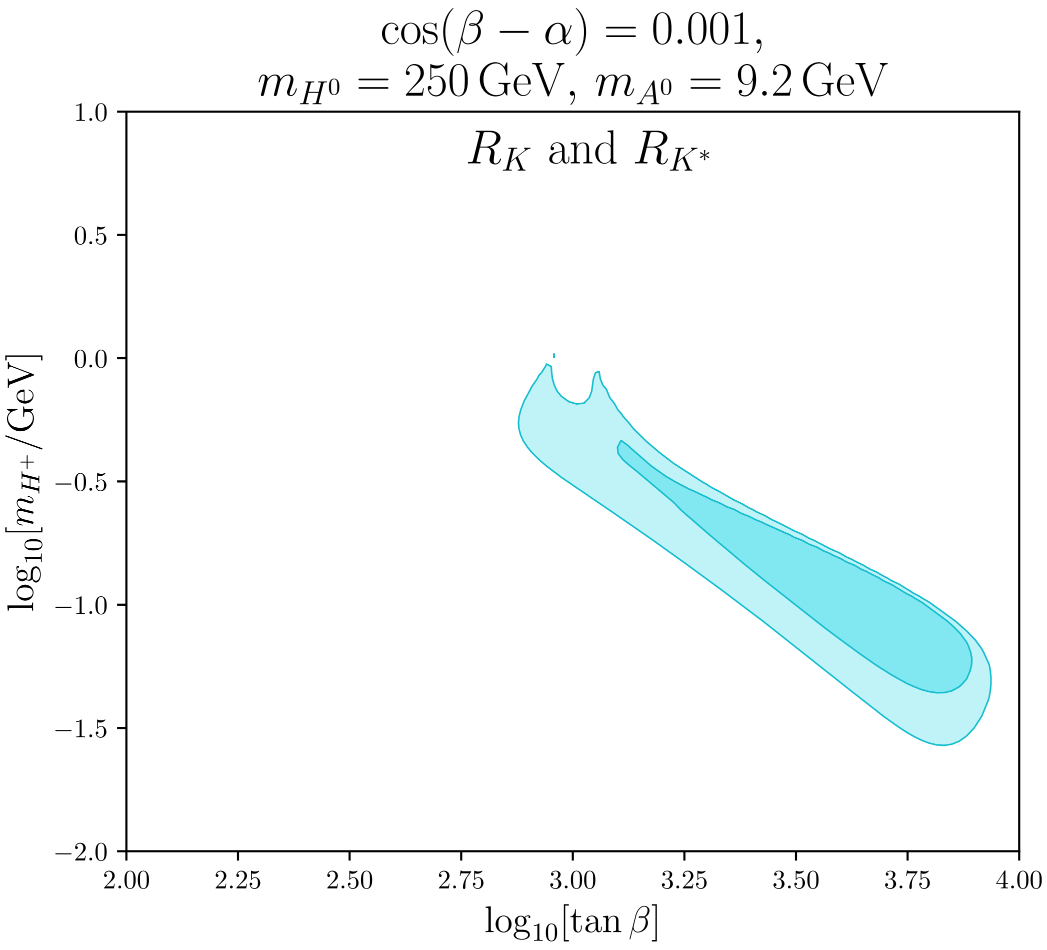
Flavour – Anomalies in Lepton Flavour Universalities

- Can we resolve these anomalies in the 2HDM? In short, no
- Negative contributions in the 2HDM and move further from the measured values
- Large allowed region for $R(D)$ as it is only 1.2σ from the SM, compared to 2.8σ for $R(D^*)$
- $R(D)$ and $R(D^*)$ cannot be consistently resolved in this 2HDM parameter space, up to 3.5σ, vs 3.2σ in the SM
- Included in the global fit



Flavour – Anomalies in Lepton Flavour Universalities

- We fix the parameters to the best fit values
- Allowed region only at very small $m_{H^\pm}$ and very large $\tan\beta$
- This is a non-physical region
- Additionally, the WC expressions assume heavier $m_{H^\pm}$
- Combined, the $R_{K^{(*)}}$ give a 4.2σ disagreement with the fit to all observables
- We take two approaches – fitting with and without the $R_{K^{(*)}}$



Global Fit

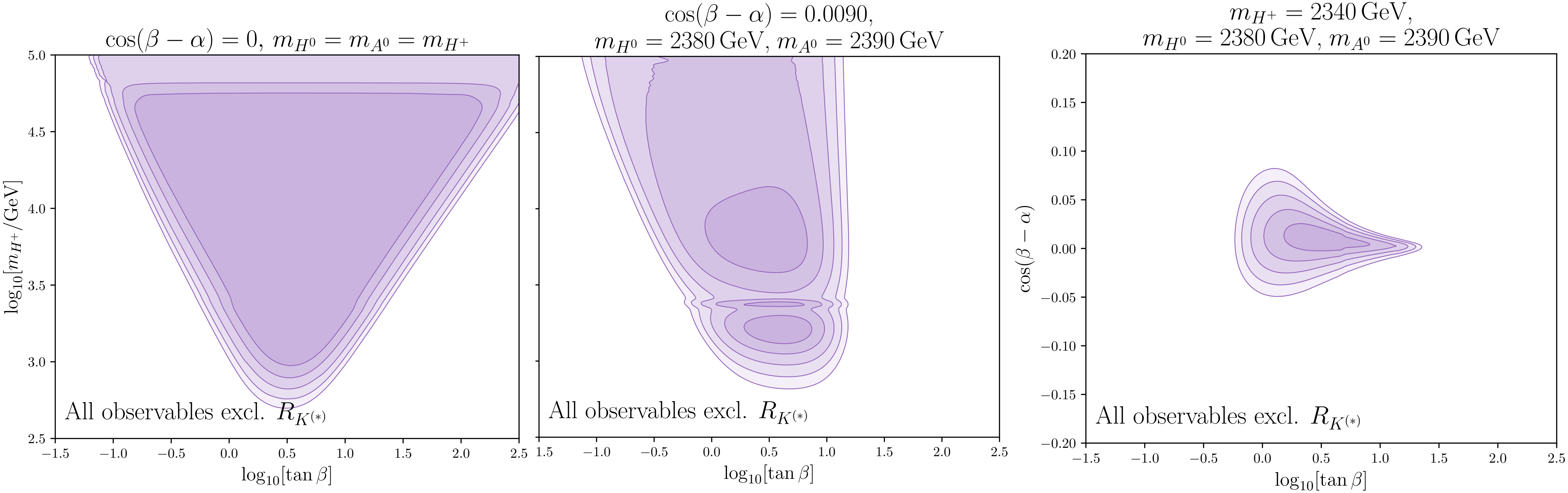
- A comprehensive 275 observable fit, including EWPOs, Higgs signals and the flavour observables
- We perform searches for the best fit points in various scenarios
- We find at 1σ (2σ):

$$\max\{|\cos(\beta-\alpha)|\} \leq 0.02\,(0.04)$$

$$m_{H^\pm} \geq 1.26\ (0.86)\ \text{TeV}$$

- The alignment limit is highly preferred
- $m_{H^\pm} \approx m_{H^0} \approx m_{A^0} \approx 2.3$ TeV, $\tan\beta \approx 4$
- Some variation between scenarios, with generally consistent results
- $b \to s\ell^+\ell^-$ is an exception, preferring masses around 700 GeV
- The p-values are 1.5% and 6.6%, including and excluding the $R_{K^{(*)}}$
- Nevertheless, 2HDM outperforms the SM, with pulls of 2.3σ and 1.8σ respectively

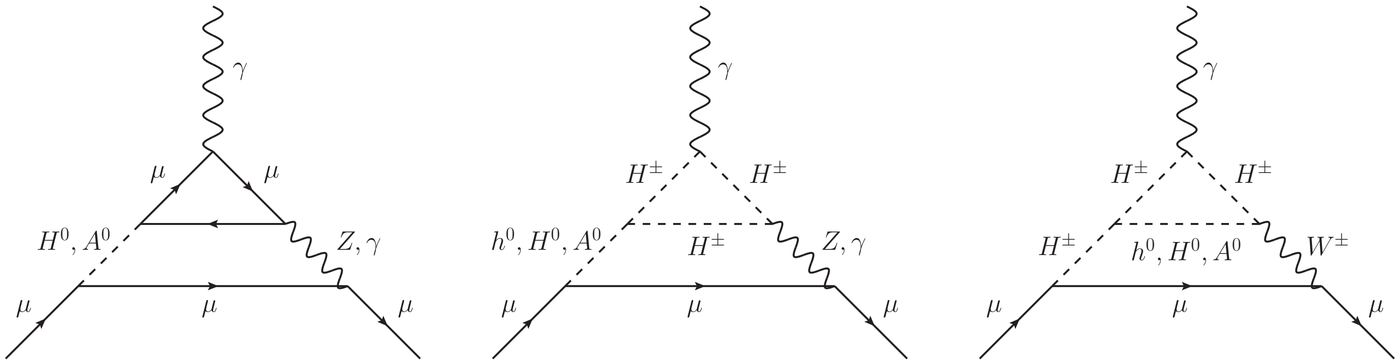
Global Fit

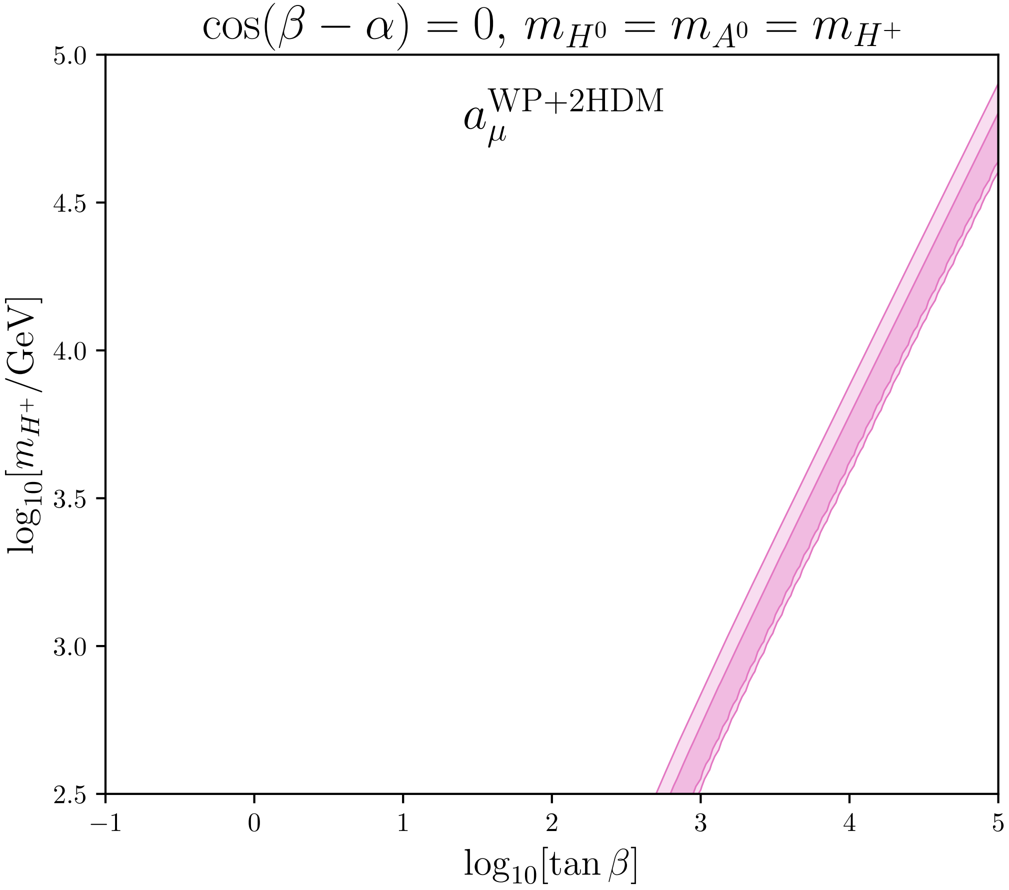


$\cos(\beta-\alpha)=0,\ m_{H^0}=m_{A^0}=m_{H^+}$
5.0
4.5
4.0
3.5
3.0
2.5
$\log_{10}[m_{H^+}/\mathrm{GeV}]$
All observables excl. $R_{K^{(*)}}$
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
$\log_{10}[\tan\beta]$
$\cos(\beta-\alpha)=0.0090,$
$m_{H^0}=2380\,\mathrm{GeV},\ m_{A^0}=2390\,\mathrm{GeV}$
All observables excl. $R_{K^{(*)}}$
$\log_{10}[\tan\beta]$
$m_{H^+}=2340\,\mathrm{GeV},$
$m_{H^0}=2380\,\mathrm{GeV},\ m_{A^0}=2390\,\mathrm{GeV}$
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
$\cos(\beta-\alpha)$
All observables excl. $R_{K^{(*)}}$
$\log_{10}[\tan\beta]$

Anomalous Magnetic Moment of the Muon, a_μ

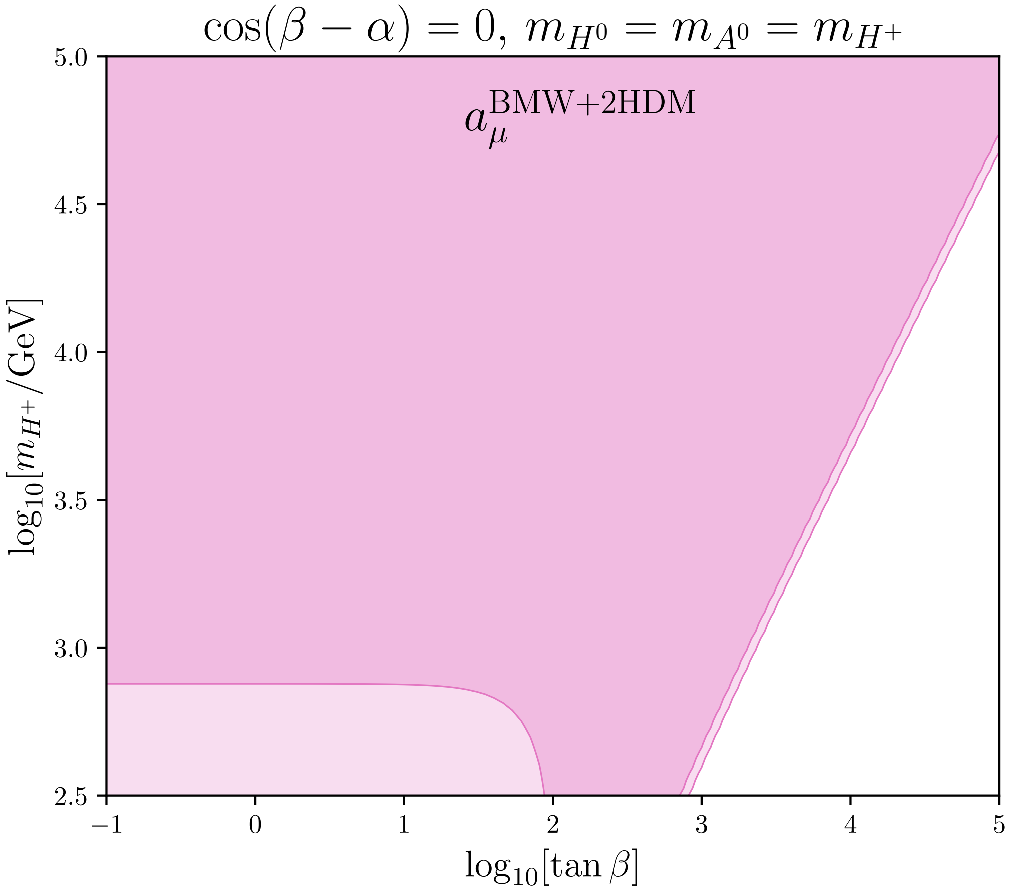
- One of the largest deviations from the SM, recently reported at 4.2σ
- We calculate two loop contributions of Bar-Zee diagrams, which depend on all model parameters
- We fix to the favored scenario of degeneracy and the alignment limit
- Flavio framework used to perform fits
- The only allowed regions are at non-perturbative values of $\tan\beta$





Anomalous Magnetic Moment of the Muon, a_μ

- A recent lattice QCD calculation by the BMW collaboration puts the disagreement with the SM at only 1.6σ
- Using this prediction for the SM value, we find that most of the parameter space is still allowed



Summary of Results

- Degenerate masses and alignment limit
- Type II:
  - 2σ limits of $\cos(\beta - \alpha) \leqslant 0.05$, $m_{H^\pm} \geqslant 860$ GeV
  - Best fit points at $m_{H^\pm} \approx m_{H^0} \approx m_{A^0} \approx 2.3$ TeV, $\tan\beta \approx 4$, $\cos(\beta - \alpha) \approx 0$
- Type I:
  - No mass limits from indirect searches, but a limit at around 100 GeV from direct searches
  - Best fit points at $m_{H^\pm} \approx m_{H^0} \approx m_{A^0} \approx 5.8$ TeV, $\tan\beta \approx 10$, $\cos(\beta - \alpha) \approx 0$
- Anomalies cannot be consistently resolved in either model
- SFOEWPT requires masses below 1 TeV – possible in Type I but not Type II
- Overall performance is comparable with the SM