Flavour Physics in the Aligned Two-Higgs-Doublet Model

Martin Jung
in collaboration with Toni Pich and Paula Tuzón

Instituto de Física Corpuscular - IFIC, CSIC-UVEG, Valencia

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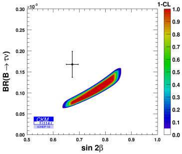
Outline

Tensions

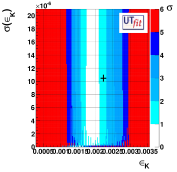
Present tensions in the global CKM fit:

- $\sin 2\beta_{B\to\tau\nu}$ vs. $\sin 2\beta|_{B\to J/\psi K^{(*)}}$
- (ϵ_K, depending on inputs and statistical treatment)



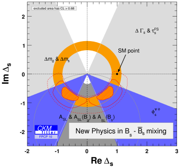
Tensions in the neutral B systems:

- Phase in $B_s \to J/\psi\phi$ (however: $2.x\sigma \to\sim 1\sigma$ recently)
- Like-sign dimuon charge asymmetry



Not discussed here:

- $|V_{ub}|$ exclusive vs. inclusive
- Pattern of $B \to \pi K$ CP asymmetries
- Neutrino physics
- Astrophysical constraints
- ...



Why 2HDM?

Model-independent analysis: Too many parameters in general

Electroweak symmetry breaking mechanism unknown yet:

- 1HDM minimal and elegant, but unlikely (SUSY,GUTs,...)
- 2HDM "next-to-minimal":
  - ρ-parameter "implies" doublets
  - low-energy limit of more complete NP models
    ➥Model-independent element
  - simple structure, but interesting phenomenology
  - affects the aforementioned tensions (with new CPV present)

Lots of 2HDMs. . .

General 2HDM:

$$-\mathcal{L}_Y^q \;=\; \bar{Q}_L'(\Gamma_1\phi_1 + \Gamma_2\phi_2)\, d_R' + \bar{Q}_L'(\Delta_1\widetilde{\phi}_1 + \Delta_2\widetilde{\phi}_2)\, u_R' \,+\, \mathrm{h.c.}$$

Γ_i, Δ_i: Independent 3×3 coupling matrices

Flavour problem: generic couplings imply huge NP scale

Most common solution: Applying a discrete $\mathcal{Z}_2$ symmetry:

- Eliminates two couplings, hence tree-level FCNCs
- Different charge assignments lead to "Type I,II,X,Y"
- Only one new parameter in the flavour sector: $\tan\beta$
- Type II SUSY-motivated: Bulk of analyses (Recently: El Kaffas et al. '07, GFitter '08, CKMfitter '09, UTfit '09)
- However: no new source of CP violation

Beyond $\mathcal{Z}_2$

Models/frameworks without $\mathcal{Z}_2$ symmetry:

- Type III: $Y'_{ij} \sim \sqrt{\frac{m_i m_j}{v^2}}$, e.g. Mahmoudi/Stål '09
- 2HDM with MFV (D'Ambrosio et al. '02):
  - EFT framework, unknown couplings
  - Yukawa matrices remain only source of flavour and *CP* violation
  - Spurion formalism with flavour-blind phases: can be used to arrive at the A2HDM (1st term in series)
  - Recently: Expansion around Type II (as '02 as well) with phases and decoupling (Buras et al. '10). See also Paradisi/Straub, Kagan et al., Botella et al., Feldmann/MJ/Mannel, Colangelo et al., all '09.
- BGL models (Branco et al. '96), Ferreira/Silva '10, ...

The Aligned two-Higgs-doublet model

Alignment condition: $\Gamma_2 = \xi_d \, e^{-i\theta} \, \Gamma_1 \, , \; \Delta_2 = \xi_u^* \, e^{i\theta} \Delta_1$

leads to [Pich/Tuzón '09]

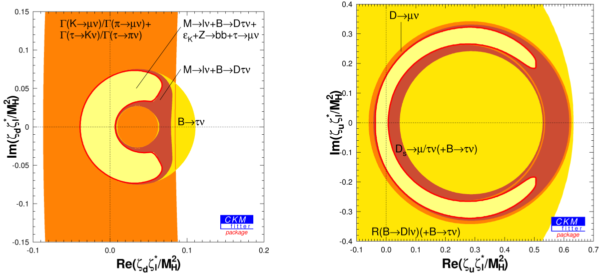
$$-\mathcal{L}_{Y,H^\pm}^{q} = \frac{\sqrt{2}}{v} \, H^+(x) \bar{u}(x) \left[\varsigma_d \, V M_d \mathcal{P}_R - \varsigma_u \, M_u^\dagger V \mathcal{P}_L \right] d(x) + \mathrm{h.c.}$$

with complex, observable parameters $\varsigma_{u,d,l}$, implying:

- No FCNCs at tree-level
- New sources for CP violation
- Only three complex new parameters (unlike Type III)
- $\mathcal{Z}_2$ models recovered for special values of $\varsigma_i^\prime s$
- Radiative corrections symmetry-protected, of MFV-type (Cvetic et al. '98, Braeuninger et al. '10, MJ/Pich/Tuzón '10)
- Recently: Proposals towards UV-completion (Medeiros Varzielas '11, Serôdio '11)

Combination of (semi-)leptonic constraints

Joining these constraints with semi-leptonic decays:



- Only combinations $\delta_{u/dl} = \varsigma_{u,d}\varsigma_l^* / M_{H^\pm}^2$ constrained
- Resulting "bananas" exclude the second real solution (with δ_{dl} help needed)
- $\delta_{dl} \lesssim 0.1$, δ_{ul} constraint weaker (but see later)
- Projection on Type II: δ_{dl} translates to $\tan\beta \lesssim 0.1 \frac{M_{H\pm}}{GeV}$

Loop-induced processes

High sensitivity for NP in general:

- SM-process suppressed by loop and CKM-factors
- Internal heavy particles can contribute

➥ Large Higgs-couplings

➥ Sensitivity to UV-completion as well

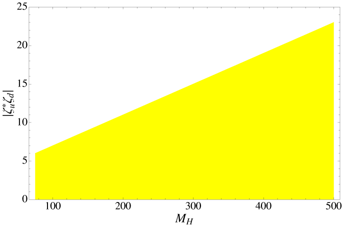
Here only examples, for full analyses see
[JM/Pich/Tuzón '10,'11,'11 (in prep.)]

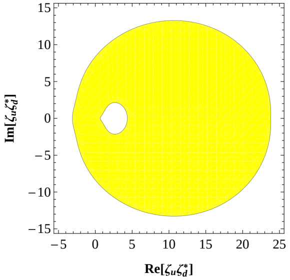
$b \to s\gamma$

Famous example for this NP-sensitivity:

- Inclusive process, theoretically well under control
  (but affected by non-local effects, see Benzke et al. '10)
- *BR* @ ∼NNLO (NLO) in the SM (2HDM)(community effort)
- Experimental accuracy $\sim 7\%$, thanks to B-factories
- Type II: $\varsigma_u \varsigma_d^* = -1$: mainly limit on M_H
- A2HDM: $\zeta_{u,d}$ independent → more freedom

Correlations are extremely important:





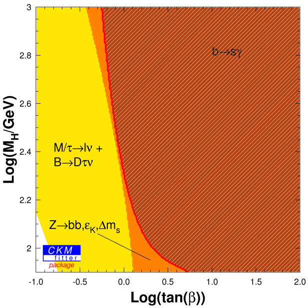
Projections

Models with $\mathcal{Z}_2$ symmetry are limits of the A2HDM:

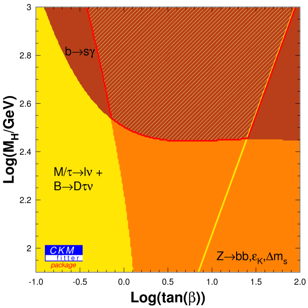
- Additional correlations
- All models: $\tan\beta \gtrsim 1$
- Type II/Y: $M_{H^\pm} \gtrsim 277$ GeV
- Type II: Upper limit on $\tan\beta$

Type	ς_d	ς_u	ς_l
I	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Type I

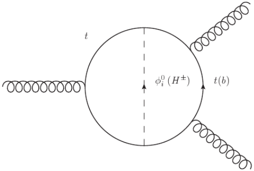


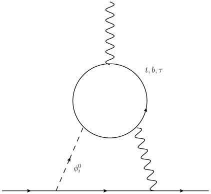
Type II



Electric dipole moments

- Highly sensitive to new CPV sources (SM tiny)
- In the A2HDM:
  - One-loop (C)EDMs: not tiny, but under control
  - 4-fermion operators: small, no $\tan\beta^3$-enhancement
  - ➥ Two-loop graphs dominant (Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90)
  - ➥ Again sensitivity to UV-completion





- Largest charged Higgs contribution from Weinberg diagram
- Barr-Zee(-like) diagrams dominate neutral Higgs exchange
- For neutrals: sum includes cancellations in general

Charged Higgs in the neutron EDM

- Two-step matching (Boyd et al. '90): b-CEDM at $\mu_{EW} \to \mathcal{O}_W$ at μ_b
- QCD sum rule estimate for matrix element

$$d_n \sim d_n^{exp} \frac{500 \text{ GeV}}{M_{H^\pm}} \, Im[\zeta_d \zeta_u^*]$$

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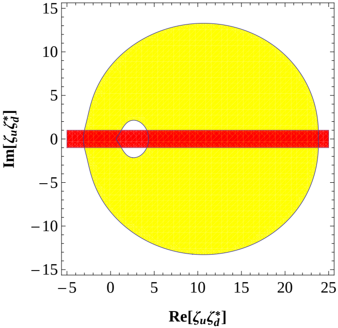
Constraint from neutron EDM on charged Higgs contribution:



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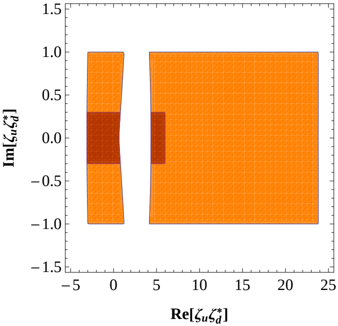
Combination of $BR(b \to s\gamma)$ and neutron EDM:



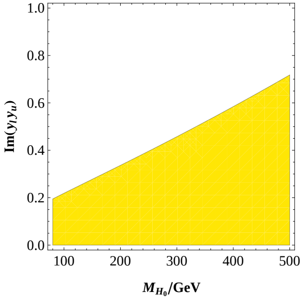
orange: $M_{H^\pm} = 500$ GeV
brown: $M_{H^\pm} = 80$ GeV

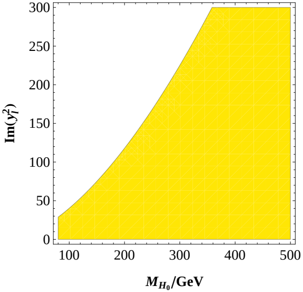
➡ $Im(\zeta_d \zeta_u^*)$ strongly constrained, but not tiny

Neutral Higgs in EDMs

- Effect dominated by Barr-Zee(-like) diagrams
- Non-trivial constraints for all combinations apart from $\mathrm{Im}(y_u^2)$
- Here: only results for Thallium, one neutral Higgs

➡ Paramagnetic atom, EDM dominated by d_e: $d_{\mathrm{Tl}} \approx -585\, d_e$





➡ Again $\mathcal{O}(1)$ imaginary parts remain allowed

➡ The A2HDM passes the EDM-test ✔

Conclusions and outlook

Conclusions:

- 2HDMs active field, new developments
- Type II: best constrained, but no effect on present tensions
- A2HDM:
  - New CPV possible with sufficient FCNC suppression(!)
  - Rich phenomenology, only three new flavour-parameters
  - Strong (but not "killing") constraints from EDMs

Outlook:

- A2HDM: Additional analyses in progress:
  - neutral Higgs effects
  - combined electroweak and radiative decays
  - EDMs continued
- Interesting times! Measurements to come from LHC, SuperB/BelleII, BES-III, NA-62,. . .

➥ Shortly we might see limits changing to determinations

Public protests about to change the picture?

Backupslides

- Radiative corrections in the A2HDM
- Neutron EDM in the A2HDM
- Experimental data used
- Hadronic inputs

Radiative corrections in the A2HDM

Symmetry structure forces the (one-loop) corrections to be of the form [MJ/Pich/Tuzón '10, Cvetic et al. '98]

$$\begin{aligned} \mathcal{L}_{\rm FCNC} \quad &= \quad \frac{C(\mu)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\;\times \\ &\times \sum_i \varphi_i^0(x)\;\Big\{(\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\;\Big[\bar{d}_L\,V^\dagger M_u M_u^\dagger\,V M_d\,d_R\Big] - \\ &-(\mathcal{R}_{i2}-i\,\mathcal{R}_{i3})\,(\varsigma_d^*-\varsigma_u^*)\;\Big[\bar{u}_L\,V M_d M_d^\dagger\,V^\dagger M_u\,u_R\Big]\Big\}\;+\;\mathrm{h.c.} \end{aligned}$$

- Vanish for $\mathcal{Z}_2$ symmetry
- FCNCs still strongly suppressed
- See also Braeuninger et al. '10, Ferreira et al. '10

Observables

Observable	Value
$\|g^S_{RR}\|_{\tau\to\mu}$	< 0.72 (95% CL)
$\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)$	$(17.36 \pm 0.05) \times 10^{-2}$
$\mathrm{Br}(\tau \to e\nu_\tau\bar{\nu}_e)$	$(17.85 \pm 0.05) \times 10^{-2}$
$\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)/\mathrm{Br}(\tau \to e\nu_\tau\bar{\nu}_e)$	0.9796 ± 0.0039
$\mathrm{Br}(B \to \tau\nu)$	$(1.73 \pm 0.35) \times 10^{-4}$
$\mathrm{Br}(D \to \mu\nu)$	$(3.82 \pm 0.33) \times 10^{-4}$
$\mathrm{Br}(D \to \tau\nu)$	$\leq 1.3 \times 10^{-3}$ (95% CL)
$\mathrm{Br}(D_s \to \tau\nu)$	$(5.58 \pm 0.35) \times 10^{-2}$
$\mathrm{Br}(D_s \to \mu\nu)$	$(5.80 \pm 0.43) \times 10^{-3}$
$\Gamma(K \to \mu\nu)/\Gamma(\pi \to \mu\nu)$	1.334 ± 0.004
$\Gamma(\tau \to K\nu)/\Gamma(\tau \to \pi\nu)$	$(6.50 \pm 0.10) \times 10^{-2}$
$\log C$	0.194 ± 0.011
$\mathrm{Br}(B \to D\tau\nu)/BR(B \to D\ell\nu)$	0.392 ± 0.079
$\Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$	0.21629 ± 0.00066
$\mathrm{Br}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\mathrm{GeV}}$	$(3.55 \pm 0.26) \times 10^{-4}$
$\mathrm{Br}(\bar{B} \to X_c e\bar{\nu}_e)$	$(10.74 \pm 0.16) \times 10^{-2}$
$\Delta m_{B^0_d}$	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$
$\Delta m_{B^0_s}$	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$
$\|\epsilon_K\|$	$(2.228 \pm 0.011) \times 10^{-3}$

Hadronic Inputs I

Parameter	Value	Comment
f_{B_s}	$(0.242 \pm 0.003 \pm 0.022)$ GeV	Our average
f_{B_s}/f_{B_d}	$1.232 \pm 0.016 \pm 0.033$	Our average
f_{D_s}	$(0.2417 \pm 0.0012 \pm 0.0053)$ GeV	Our average
f_{D_s}/f_{D_d}	$1.171 \pm 0.005 \pm 0.02$	Our average
f_K/f_π	$1.192 \pm 0.002 \pm 0.013$	Our average
$f_{B_s}\sqrt{\hat{B}_{B_s^0}}$	$(0.266 \pm 0.007 \pm 0.032)$ GeV	
$f_{B_d}\sqrt{\hat{B}_{B_s^0}}/(f_{B_s}\sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	
λ	0.2255 ± 0.0010	$\left(1 - \lvert V_{ud}\rvert^2\right)^{1/2}$
$\lvert V_{ub}\rvert$	$(3.8 \pm 0.1 \pm 0.4) \cdot 10^{-3}$	$b \to ul\nu$ (excl. + incl.)
A	$0.80 \pm 0.01 \pm 0.01$	$b \to cl\nu$ (excl. + incl.)
$\bar{\rho}$	$0.15 \pm 0.02 \pm 0.05$	Our fit
$\bar{\eta}$	$0.38 \pm 0.01 \pm 0.06$	Our fit

Table: *Input values for the hadronic parameters. The first error denotes statistical uncertainty, the second systematic/theoretical.*

Hadronic Inputs II

Parameter	Value	Comment
$\bar{m}_u(2\ \mathrm{GeV})$	$(0.00255\,^{+\,0.00075}_{-\,0.00105})$ GeV	
$\bar{m}_d(2\ \mathrm{GeV})$	$(0.00504\,^{+\,0.00096}_{-\,0.00154})$ GeV	
$\bar{m}_s(2\ \mathrm{GeV})$	$(0.105\,^{+\,0.025}_{-\,0.035})$ GeV	
$\bar{m}_c(2\ \mathrm{GeV})$	$(1.27\,^{+\,0.07}_{-\,0.11})$ GeV	
$\bar{m}_b(m_b)$	$(4.20\,^{+\,0.17}_{-\,0.07})$ GeV	
$\bar{m}_t(m_t)$	$(165.1 \pm 0.6 \pm 2.1)$ GeV	
$\delta_{\mathrm{em}}^{K\ell 2/\pi\ell 2}$	-0.0070 ± 0.0018	
$\delta_{\mathrm{em}}^{\tau K2/K\ell 2}$	0.0090 ± 0.0022	
$\delta_{\mathrm{em}}^{\tau\pi 2/\pi\ell 2}$	0.0016 ± 0.0014	
$\rho^2\|_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\|_{B\to Dl\nu}$	0.46 ± 0.02	
$f_+^{K\pi}(0)$	0.965 ± 0.010	
$\bar{g}_{b,SM}^L$	$-0.42112\,^{+\,0.00035}_{-\,0.00018}$	
κ_ϵ	0.94 ± 0.02	
$\bar{g}_{b,SM}^R$	$0.07744\,^{+\,0.00006}_{-\,0.00008}$	

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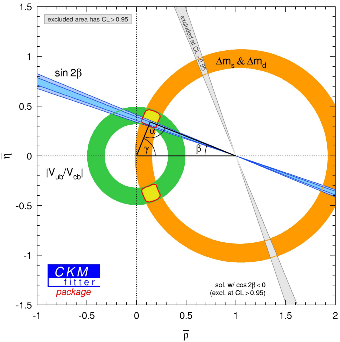
CKM-fit within the A2HDM

In the A2HDM, the CKM-parameters are determined as follows:



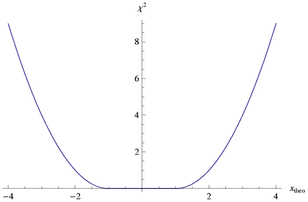
- Only the constraints from $|V_{ub}/V_{cb}|$ and $\Delta m_s/\Delta m_d$ survive.
- γ from tree-level decays not competitive yet, but excludes 2nd solution.
- $\Delta m_s/\Delta m_d = \Delta m_s/\Delta m_d|_{SM} + \mathcal{O}\left(\frac{m_s - m_d}{M_W}\varsigma_d\right)$

Statistical Treatment

In this work, the RFit-scheme is used: [Höcker et al., 2001]

- Philosophy: distance from central value has no statistical meaning for theory errors / large systematics
- This implies that the statistical problem is not well-defined

➥ Assumption: Within a range no contribution to χ^2, outside increase corresponding to statistical error
➥Choose range conservatively
➥Theory errors add linearly

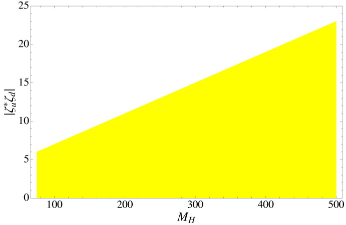


Averaging different theory-results even less well-defined...
➥Theory error at least that of best single result
➥Statistical errors treated “normally”
➥Here additionally: Criteria from FLAG (where available)

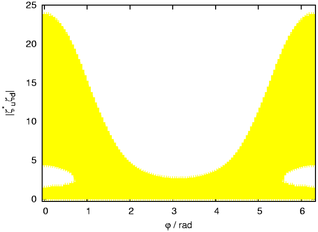
$b \to s\gamma$: Results

However: Correlations are extremely important:

$|\varsigma_u^* \varsigma_d|$ vs. M_H



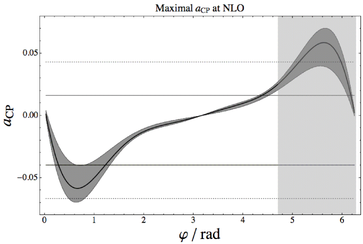
$|\varsigma_u^* \varsigma_d|$ vs. $\text{Arg}(\varsigma_u^* \varsigma_d)$



- Constraint much stronger for small Higgs masses
- For $\phi \sim \pi$ constructive, $\phi \sim 0$ destructive interference
- Implies small effect to LCDA from charged Higgs (neutral sector effects might be large: see Buras et al. '10)

Direct CP-asymmetry in $b \to s\gamma$

- Small in the SM (Ali et al.'98, Kagan/Neubert '98, Hurth et al.'05). See however again Benzke et al. '11.
- Potentially large in 2HDMs with new CPV (Borzumati/Greub '98)
- However, $BR(b \to s\gamma)$ constrains the asymmetry strongly:



➥ Compatible with measurement, but enhancement possible

➥ More precise measurement interesting ($\mapsto$ SuperB)

Constraints from mixing

Mixing in the SM induced by box-graphs:

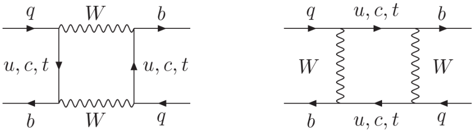


Figure taken from Fleischer, R: Phys. Rept.370,537-680,2002.

- B-system: internal top-quark dominant for $\Delta m_{d,s}$
- K-system: charm-loop dominant in Δm_K, but top in ϵ_K

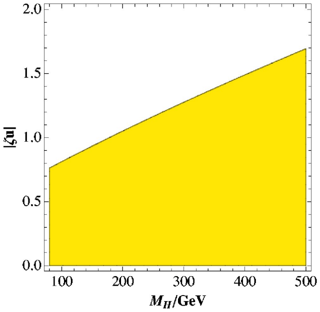
➥ Short-distance calculations possible

Large Higgs-effects expected in top loops: $m_t/M_H \sim 1$ possible
➥Effects in $\Delta m_{d,s}, \phi_{d,s}, \epsilon_K$

However: main effect real, $\sim |\varsigma_u|^2$, CPV suppressed as $\left(\varsigma_d \varsigma_u^* \frac{m_b m_t}{M_H^2}\right)^2$

Kaon mixing

- Two SM amplitudes relevant → no NP phase needed
- Recent updates: improved non-perturbative corrections [Buras et al. '08,'10] and NNLO in η_{ct} [Brod/Gorbahn '10]
- In $\mathcal{Z}_2$-models $\sim \tan^{-2}\beta$
- In the A2HDM: constraint on general parameter $|\varsigma_u|$
- At 68% preference for non-vanishing NP-contribution
  ➥ automatically right direction for mini-tension

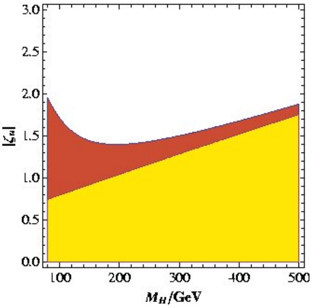


Mixing in the B system

- In the SM completely dominated by the top-loop
- ➥ Complex NP-contributions necessary to change the mixing-phase
- Below only charged Higgs discussed, but neutral Higgs effects can be sizable [Buras et al. '10]

A2HDM: large (sizable) effect in $\Delta m_{d,s}$ ($\phi_{d,s}$) possible:

- $\mathcal{O}(1)$ effect to SM-contribution w/o phase $\rightarrow \Delta_{d,s}$
- Up to $10-40\%$ effect for $\mathcal{O}_{SLL}$ with weak phase $\rightarrow \phi_{d,s}$
- Both contributions universal for $q = d, s:\ \Delta_d \simeq \Delta_s$
  ➥ $\Delta m_s/\Delta m_d$ still usable in UT fit



The Like-sign dimuon charge asymmetry

Difference of $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs from a $B - \bar{B}$-system

➡ Measure for CP-violation in mixing

- For B_d measured at the B-factories
- At D0: Measurement for sum B_d, B_s
  ➡ effect in B_s-mixing
- Characteristic measure: $\frac{a_{sl}^s|_{\rm full}}{a_{sl}^s|_{\rm SM}} = \frac{\sin\phi_s^{\rm full}}{\Delta_s \sin\phi_s^{\rm SM}}$
- Central value unphysical ($a_{sl}^s|_{\rm full} \sim 400 a_{sl}^s|_{\rm SM}$), but error still large
- Correlations from $b \to s\gamma$ important!
- Effect of $H^\pm$ too small
- Neutrals contribute