Phenomenology of Two-Higgs-Doublet Models at the LHC

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work in collab. with V. Ilisie and A. Pich [arXiv:1302.4022]

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Exploring Fundamental Interactions in the Higgs Era

Standard Model

$\bar{Q}'_L \equiv (\bar{u}'_L, \bar{d}'_L) \quad , \quad \tilde{\Phi} \equiv i\tau_2 \Phi^*$

One Higgs Doublet $\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \quad , \quad \langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$

$$\mathcal{L}_Y = -\bar{Q}'_{iL}\,\Gamma_{ij}\,\Phi\, d'_{jR} - \bar{Q}'_{iL}\,\Delta_{ij}\tilde{\Phi}\, u'_{jR} - \bar{L}'_{iL}\,\Pi_{ij}\Phi\, l'_{jR} + \text{h.c.}$$

↓ **SSB**

$$M'_d = \frac{v}{\sqrt{2}}\,\Gamma \quad , \quad M'_u = \frac{v}{\sqrt{2}}\,\Delta \quad , \quad M'_l = \frac{v}{\sqrt{2}}\,\Pi$$

Diagonalization → { **GIM Mechanism** (Unitarity) ; Yukawas proportional to masses }

No Flavour-Changing Neutral Currents

The CKM description, tested so far in many corners with an incredible precision, remains successful

The Two-Higgs-Doublet Model (2HDM)

A simple extension of the SM scalar sector $\quad \phi_a \quad (a = 1, 2)$

$$\langle 0|\, \phi_a^T(x) |0\rangle = \frac{1}{\sqrt{2}}\,(0\,, v_a\, e^{i\theta_a}) \quad , \quad \theta_1 = 0 \quad , \quad \theta \equiv \theta_2 - \theta_1$$

Higgs basis: $\quad v \equiv \sqrt{v_1^2 + v_2^2} \quad , \quad \tan\beta \equiv v_2/v_1$

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta}\,\phi_2 \end{pmatrix}$$

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

Mass eigenstates: $\quad H^\pm \quad , \quad \varphi_i^0(x) \equiv \{h(x), H(x), A(x)\} = \mathcal{R}_{ij}\, S_j(x)$

Neutral Higgs bosons have not definite CP-quantum numbers in general

Yukawa Interactions in 2HDMs

$$\mathcal{L}_Y = -\bar{Q}_L'(\Gamma_1\phi_1 + \Gamma_2\phi_2)\, d_R' - \bar{Q}_L'(\Delta_1\tilde{\phi}_1 + \Delta_2\tilde{\phi}_2)\, u_R' - \bar{L}_L'(\Pi_1\phi_1 + \Pi_2\phi_2)\, l_R' + \text{h.c.}$$

↓ **SSB**

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left\{\bar{Q}_L'(M_d'\Phi_1 + Y_d'\Phi_2)\, d_R' + \bar{Q}_L'(M_u'\tilde{\Phi}_1 + Y_u'\tilde{\Phi}_2)\, u_R' + \bar{L}_L'(M_l'\Phi_1 + Y_l'\Phi_2)\, l_R' + \text{h.c.}\right\}$$

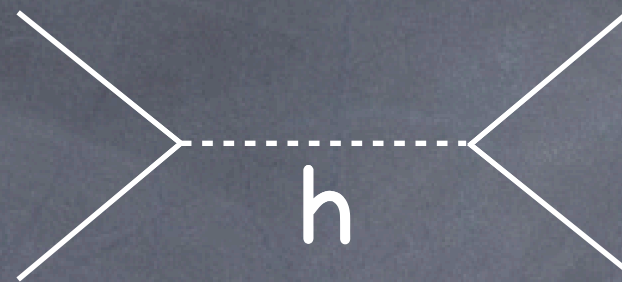
M_f' and Y_f' unrelated → **FCNCs**

$$\sqrt{2}\, M_d' = v_1\Gamma_1 + v_2\Gamma_2 e^{i\theta} \quad , \quad \sqrt{2}\, M_u' = v_1\Delta_1 + v_2\Delta_2 e^{-i\theta}$$

$$\sqrt{2}\, Y_d' = v_1\Gamma_2 e^{i\theta} - v_2\Gamma_1 \quad , \quad \sqrt{2}\, Y_u' = v_1\Delta_2 e^{-i\theta} - v_2\Delta_1$$

Adding a second Higgs doublet introduces tree-level FCNCs and new sources of CP-violation

Avoiding FCNCs



$\bar{K}^0 - K^0$

$\bar{B}^0 - B^0$

- Very large scalar masses ➡ THDM irrelevant at low energies
- Very small scalar couplings
- Type III model: $(Y_f)_{ij} \propto \sqrt{m_i m_j}$ Yukawa textures (Cheng - Sher '87)
- Discrete $\mathcal{Z}_2$ symmetries: only one $\phi_a(x)$ couples to a given $f_R(x)$ (Glashow - Weinberg '77)

$\mathcal{Z}_2$: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$, $Q_L \to Q_L$, $L_L \to L_L$, $f_R \to \pm f_R$

➡ **CP conserved in the scalar sector**

Aligned 2HDM

(Pich - Tuzón '09)

Require alignment in Flavour Space of Yukawa couplings:

$$\Gamma_2 = \xi_d \, e^{-i\theta} \, \Gamma_1 \quad , \quad \Delta_2 = \xi_u^* \, e^{i\theta} \, \Delta_1 \quad , \quad \Pi_2 = \xi_l \, e^{-i\theta} \, \Pi_1$$

$$\Downarrow$$

$$Y_{d,l} = \varsigma_{d,l} \, M_{d,l} \, , \qquad Y_u = \varsigma_u^* \, M_u \, , \qquad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1 + \xi_f \tan\beta}$$

new sources of CP violation

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d \, V_{\mathrm{CKM}} M_d \mathcal{P}_R - \varsigma_u \, M_u^\dagger V_{\mathrm{CKM}} \mathcal{P}_L \right] d + \varsigma_l \, (\bar{\nu} M_l \mathcal{P}_R l) \right\}$$
$$-\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \, \varphi_i^0 \, (\bar{f} M_f \mathcal{P}_R f) \quad + \quad \mathrm{h.c.}$$

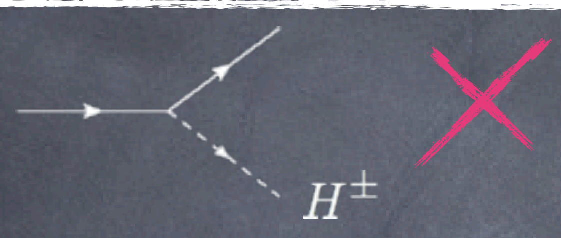
- Fermionic couplings proportional to fermion masses.
- Neutral Yukawas are diagonal in flavour

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3}) \, \varsigma_{d,l} \quad , \quad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3}) \, \varsigma_u^*$$

LHC bounds on the A2HDM

AC, V. Ilisie, A. Pich
[arXiv:1302.4022]

★ $\varsigma_f = 0$ fermiophobic charged Higgs scenario



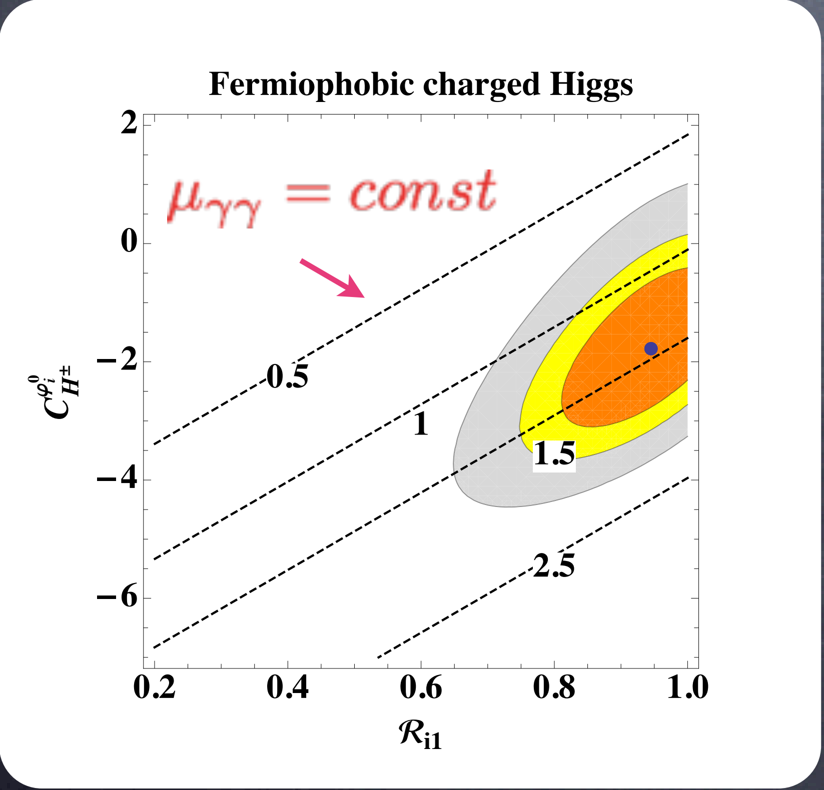
Flavor and collider constraints naturally avoided.

Contains the Inert 2HDM as a limit

Neutral Higgs bosons are not inert due to mixing and are not CP-eigenstates in general

$$y_f^{\varphi_i^0} = g_{\varphi_i^0 VV} / g_{\varphi_i^0 VV}^{\rm SM} = \mathcal{R}_{i1}$$

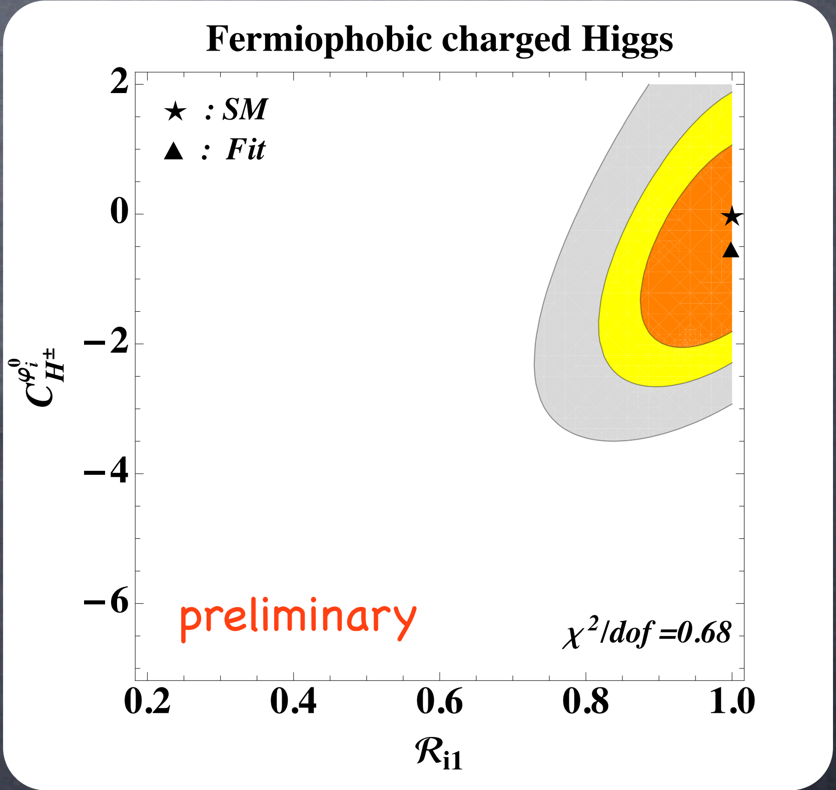
126 GeV Higgs phenomenology characterized by the Higgs couplings to vector bosons and the $H^\pm$ contribution to $\varphi_i^0 \to \gamma\gamma$



Before Moriond 2013

$$g_{\varphi_i^0 VV} = \mathcal{R}_{i1} \, (g_{hVV})^{\rm SM}$$

$$C_{H^\pm}^{\varphi_i^0} \propto \frac{v^2}{M_{H^\pm}^2} \lambda_{\varphi_i^0 H^+ H^-}$$



After Moriond 2013

LHC bounds on the A2HDM

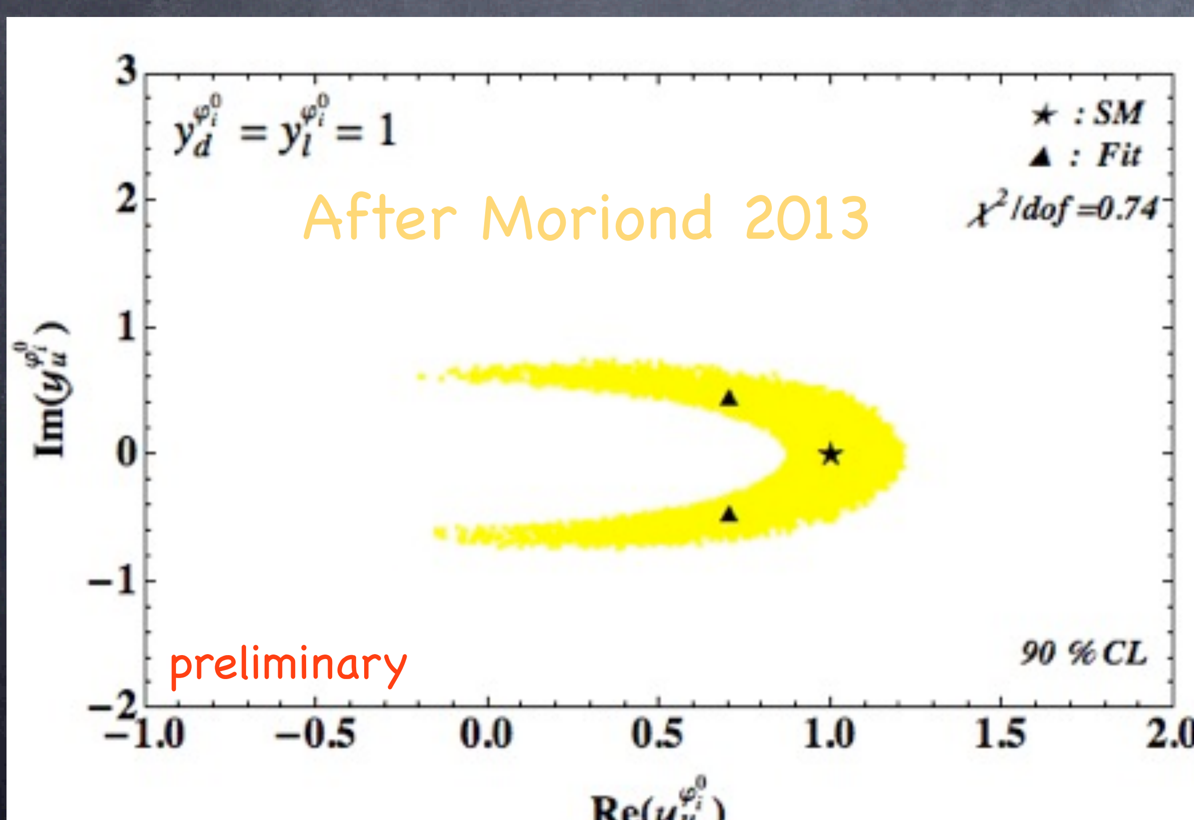
Models with a $\mathcal{Z}_2$ symmetry
are recovered as particular cases of the A2HDM

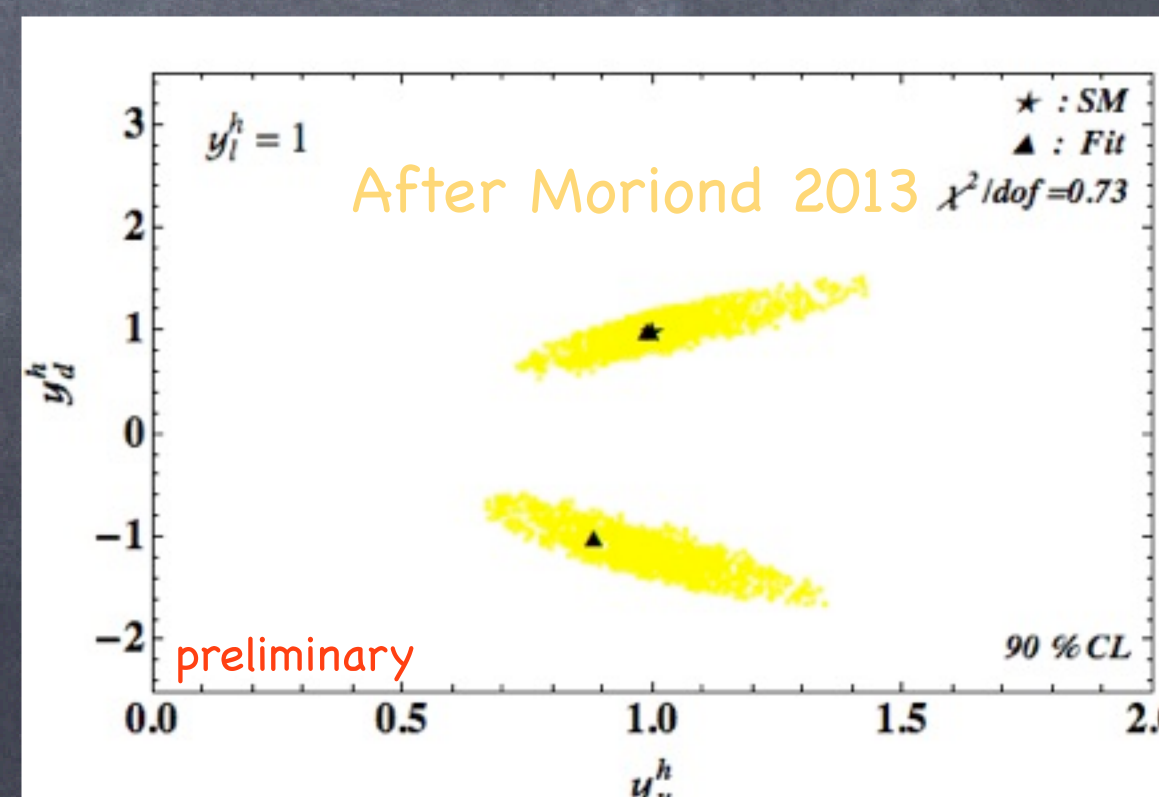
Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

An analysis of the experimental
data within the A2DHM
would reveal the presence of
any $\mathcal{Z}_2$ symmetry.
If it is there, data will tell...

See Chien-Yi Chen talk

In the A2HDM, $\tan\beta$ ⟶ three complex parameters: $\varsigma_u, \varsigma_d, \varsigma_l$





Conclusions:

Understanding the mechanism of electroweak symmetry breaking involves a rich interplay between flavor and collider physics (LHC, Tevatron,...)

This is just the beginning of a new era

- The Aligned 2HDM provides a general phenomenological setting,
  includes all $\mathcal{Z}_2$ models as particular limits

- Tree-level FCNCs are absent, rich scalar sector possible at accessible energy scales

- Provides new sources of CP-violation: $\varsigma_u, \varsigma_d, \varsigma_l$ BAU?

Interesting effects possible at the intensity, cosmic and energy frontiers

Back-up Slides

Higgs mediated Lepton Flavor Violation

work in progress with E. Passemar and V. Cirigliano

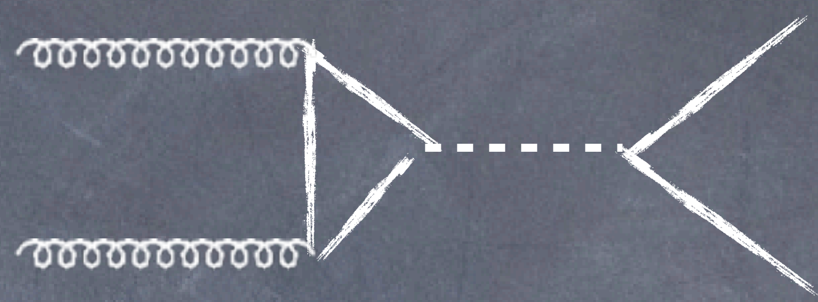
interesting sensitivity at LHC

Harnik, Zupan, Kopp (2012)
Davidson, Verdier (2012)

$H \to \tau\mu$

large BR are allowed by
low energy constraints

Ellis, Isidori, Blankenburg (2012)



Important to look
for other states in this channel

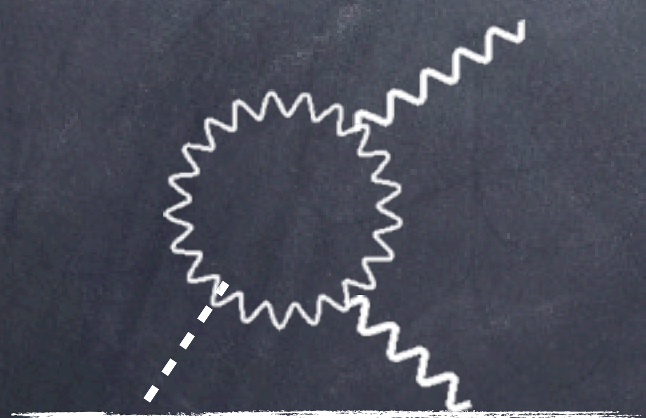
$A \to \tau\mu$ (CP-odd)

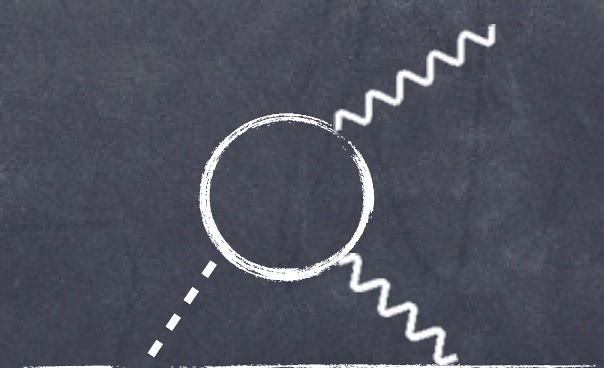
Intensity Frontier ? ⟷ Energy Frontier

Higgs mediated loop-contributions to LFV decays are very important Chang, Hou, Keung (1993)

$\tau \to \mu\mu\bar{\mu}$

$\tau \to \mu\gamma$





$\tau \to \mu\rho$

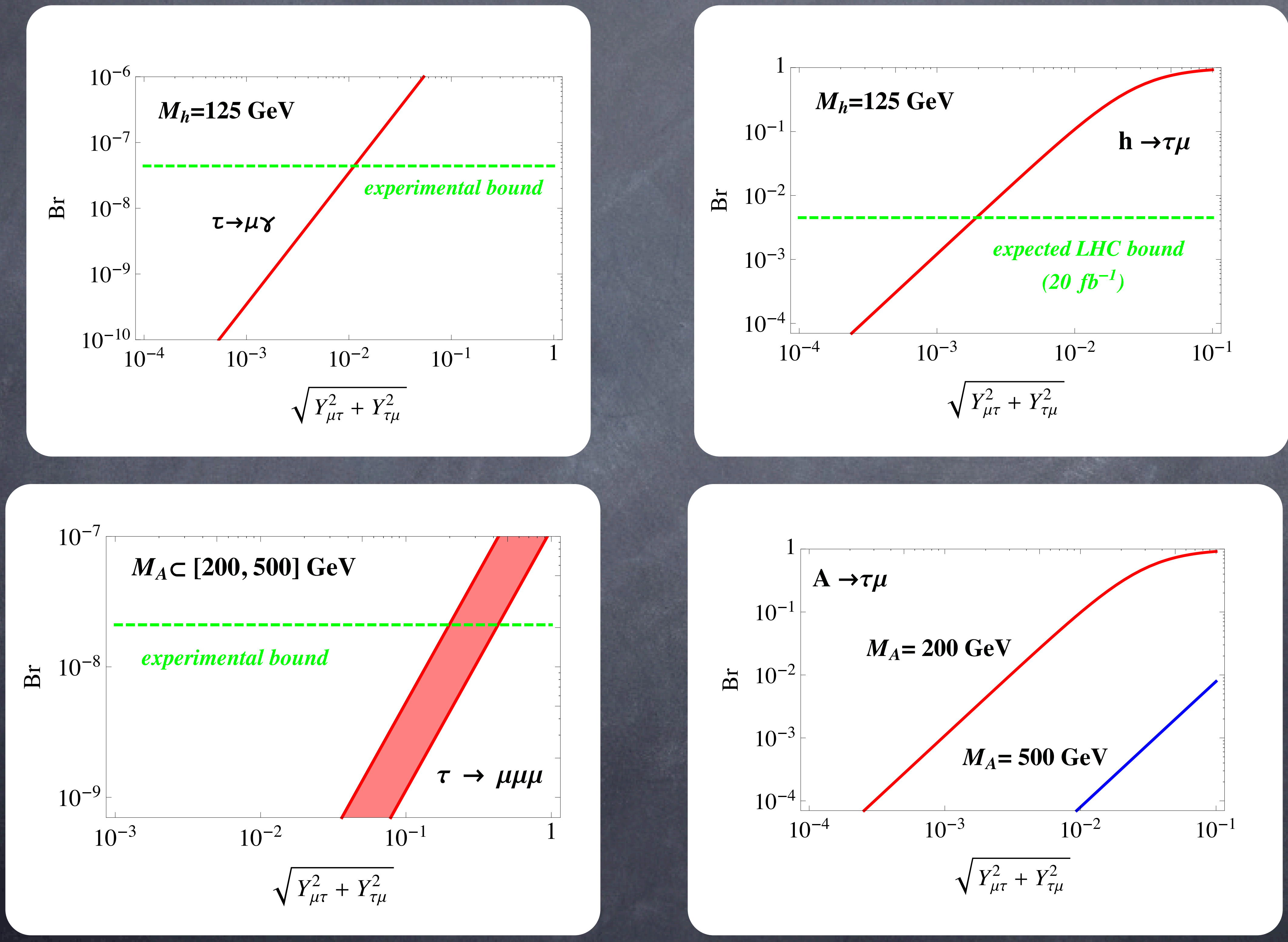
$\tau \to \mu\pi\pi$

$\tau \to \mu\eta^{(\prime)}$

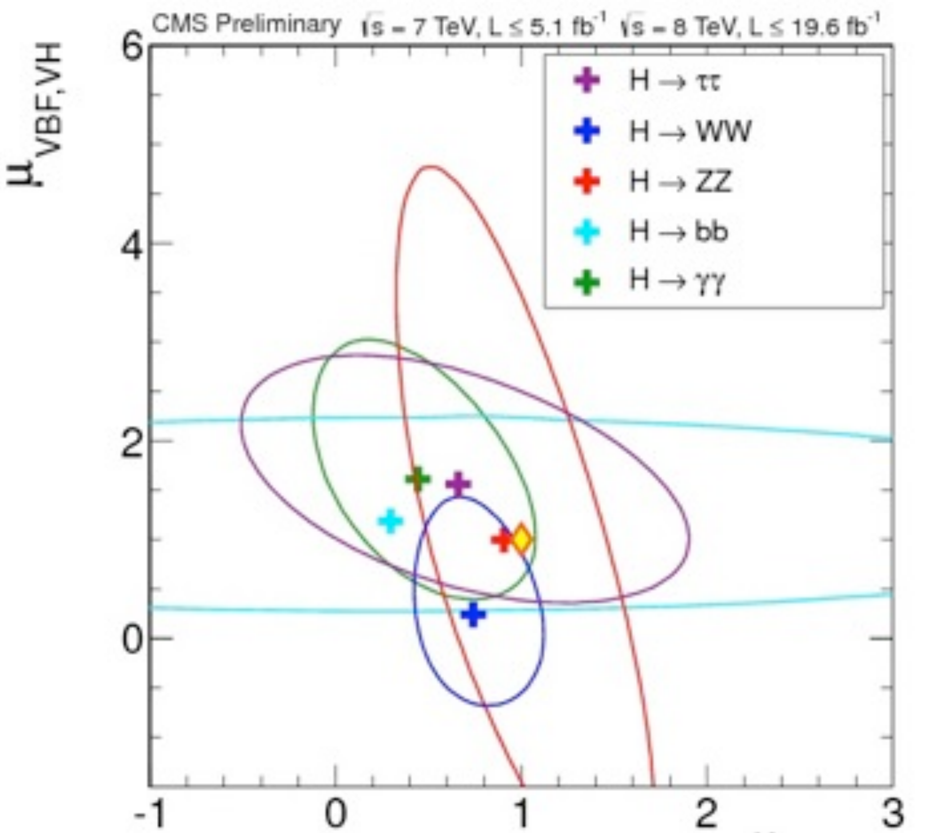
Higgs mediated Lepton Flavor Violation

work in progress with E. Passemar and V. Cirigliano

$$\mathcal{L} = -Y_{ij}\,\bar{f}_i\,P_R f_j\,\varphi + \text{h.c.}$$



Higgs data by April 2013



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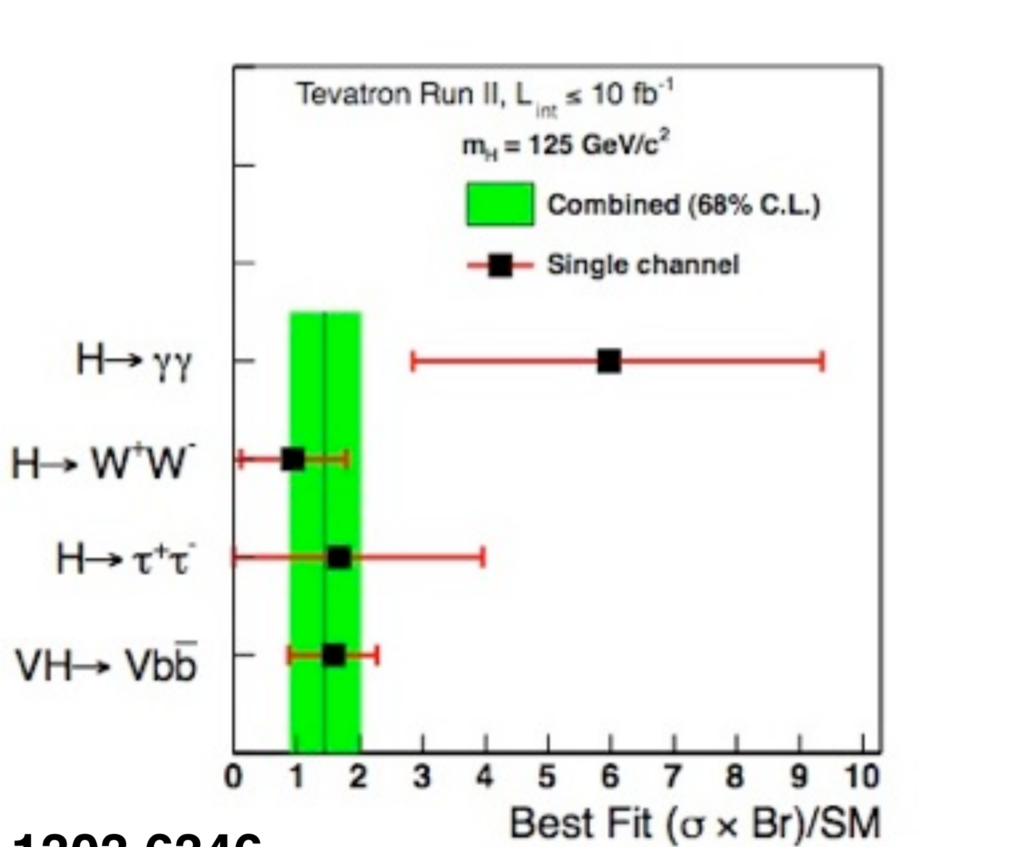

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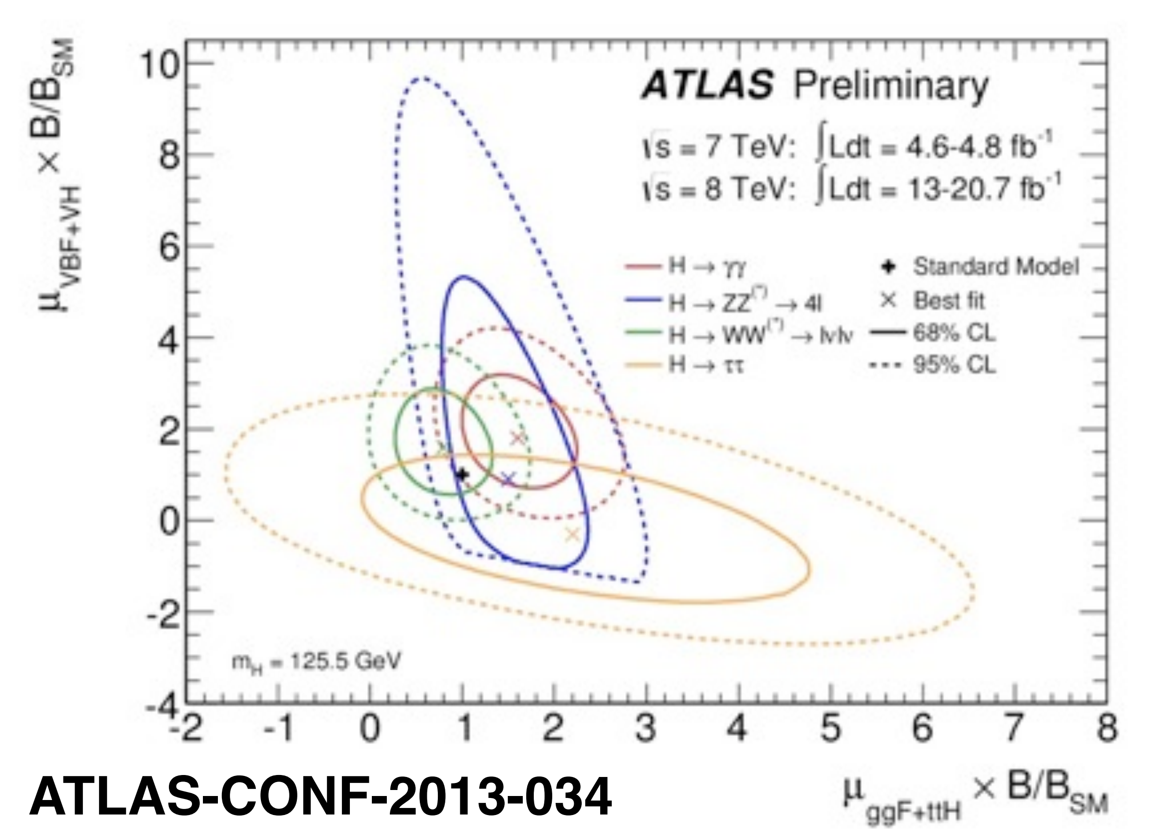
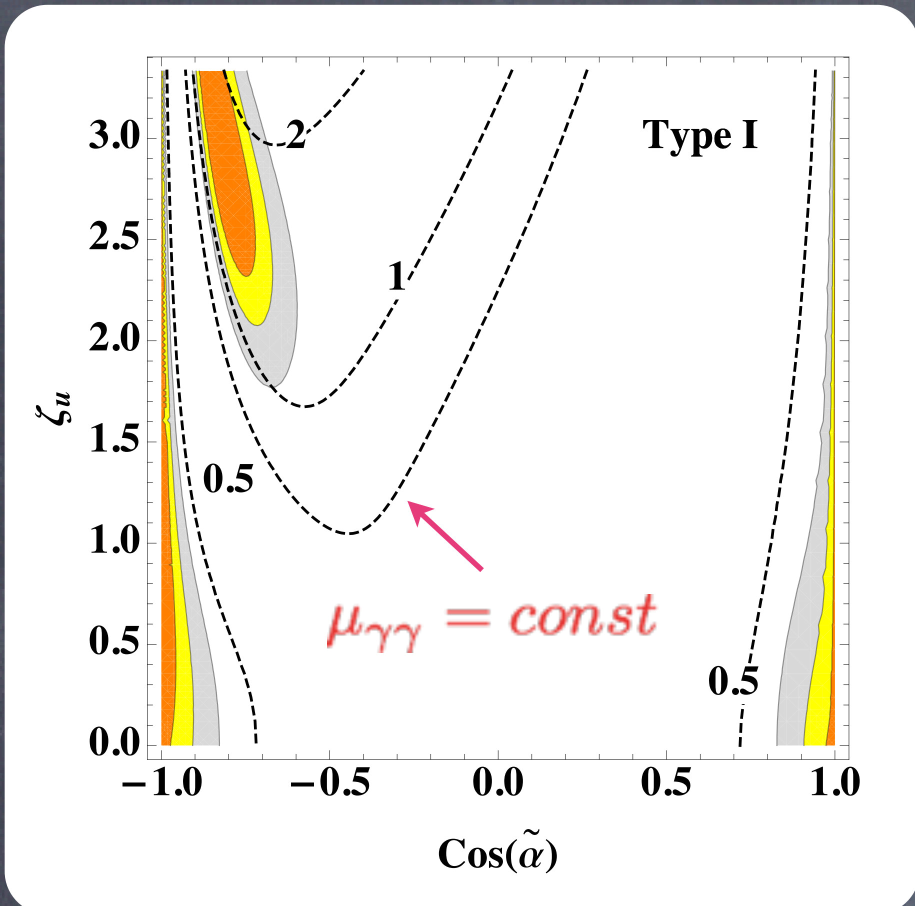


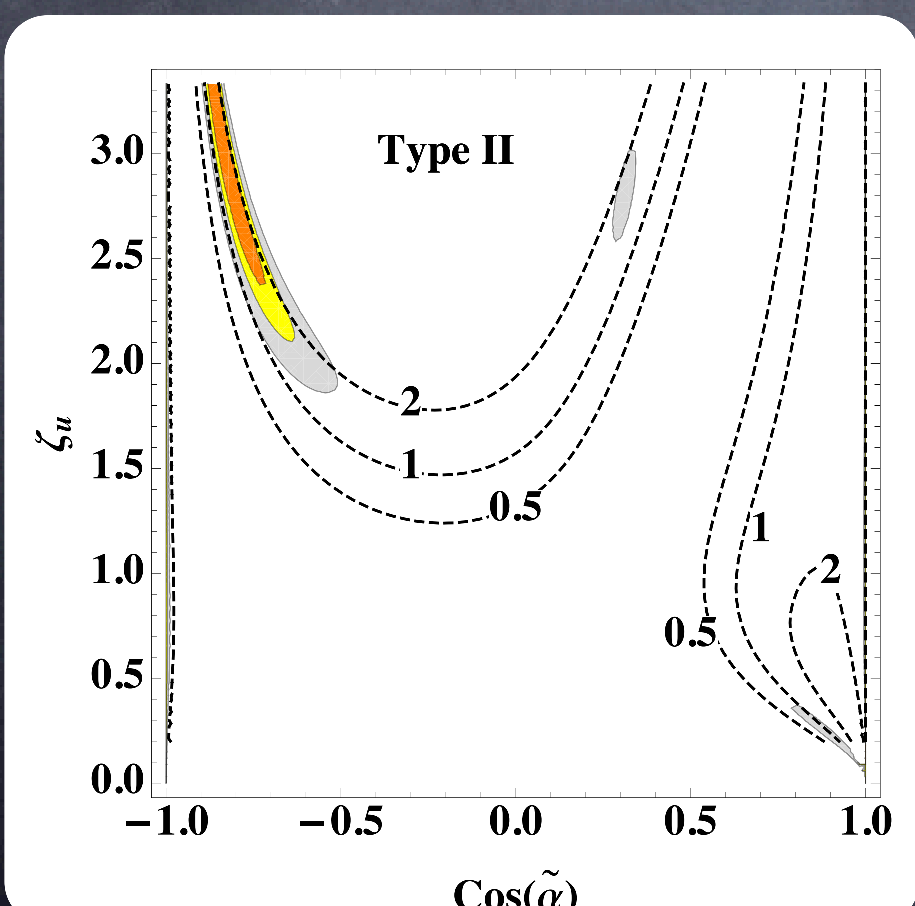
ATLAS-CONF-2013-034

Higgs signal strengths

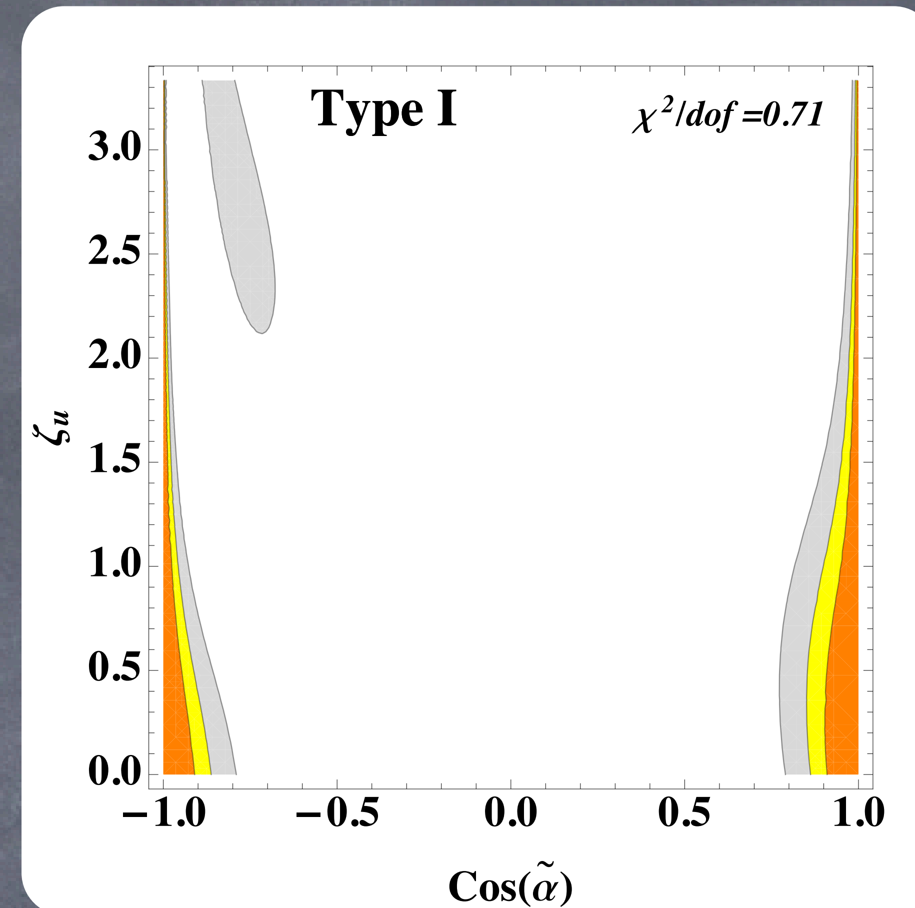
$$\mu \equiv (\sigma \times \mathrm{BR})/\mathrm{SM}$$

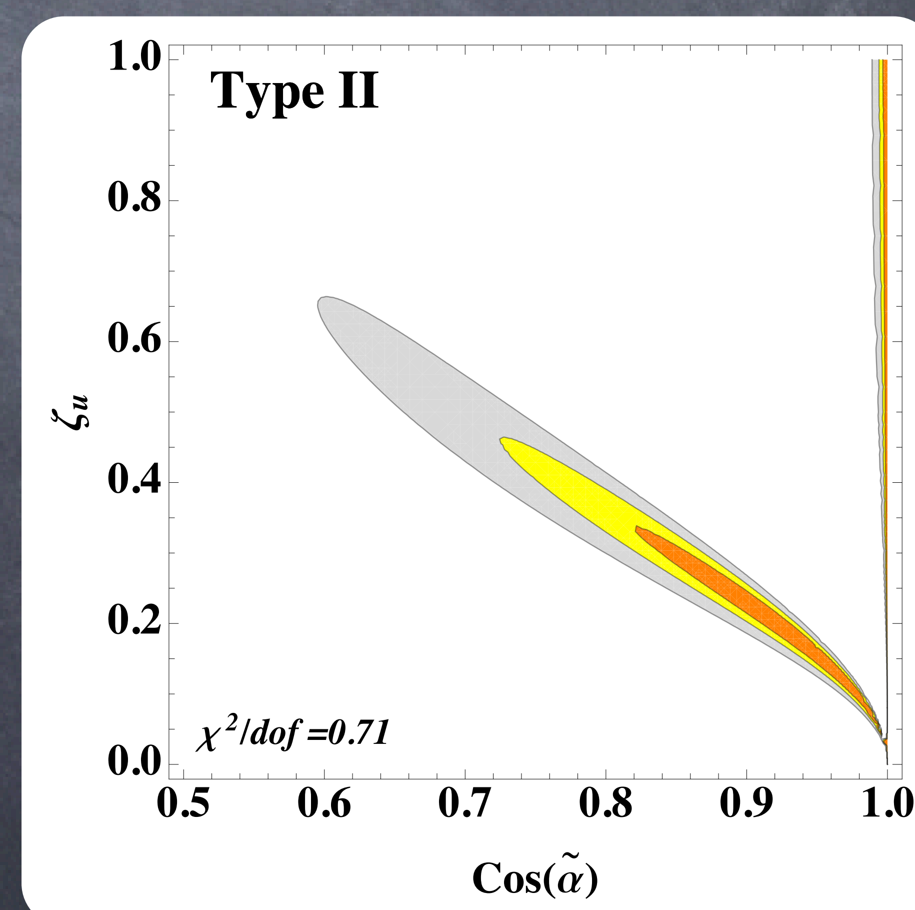
Before Moriond 2013



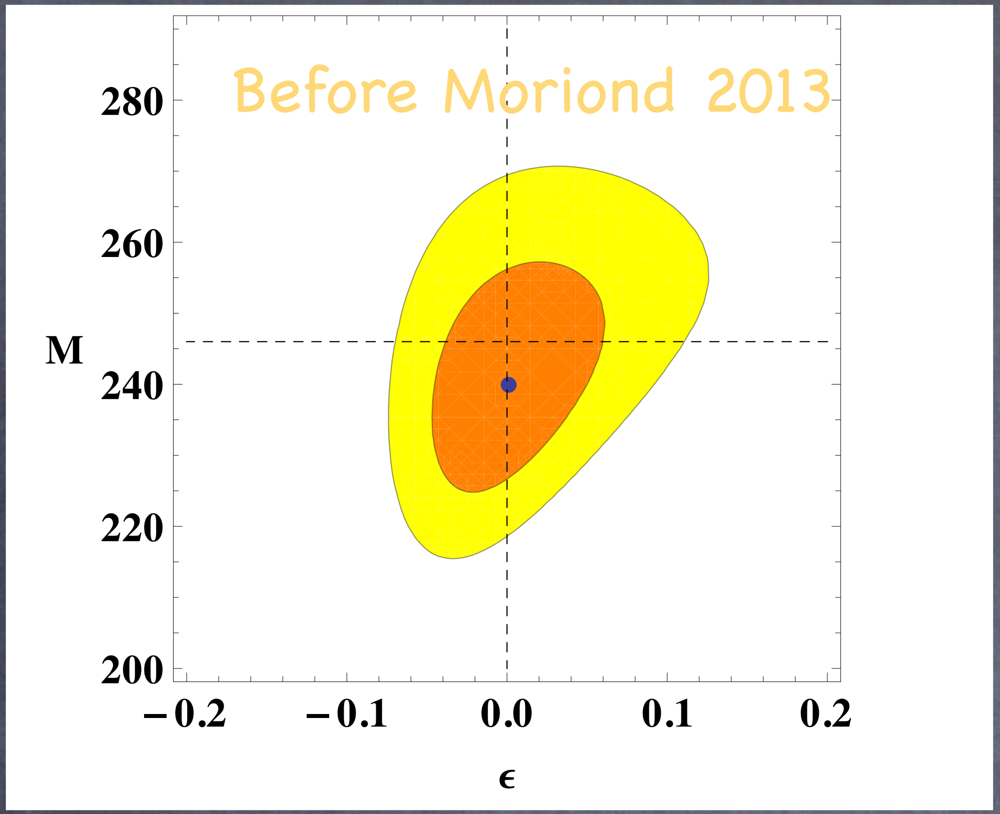


After Moriond 2013





Other parametrizations

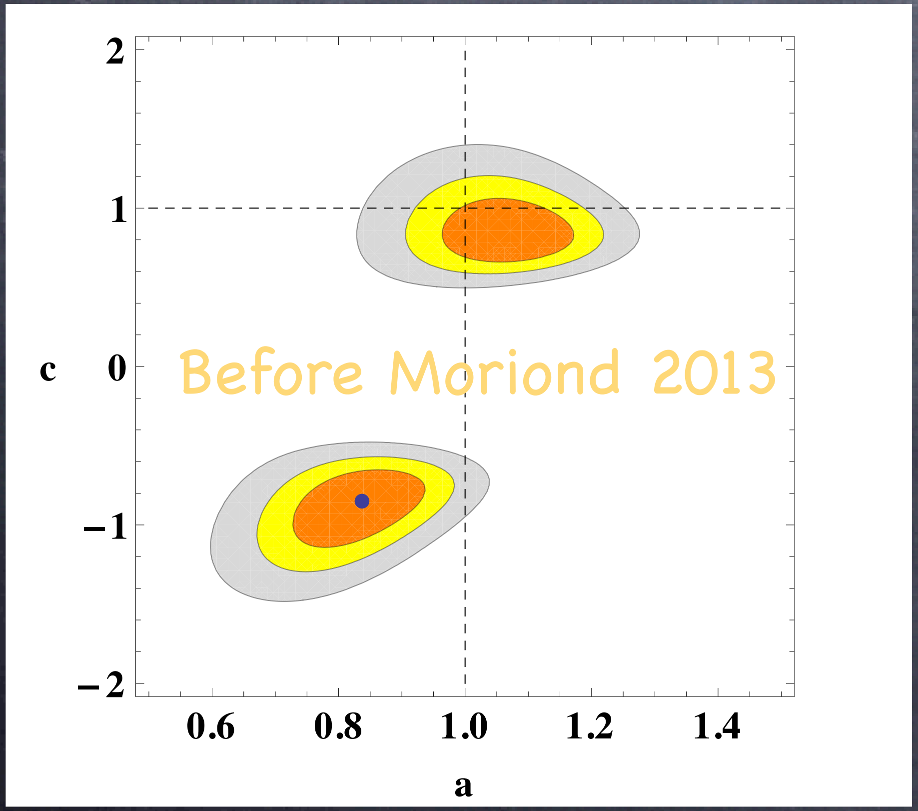


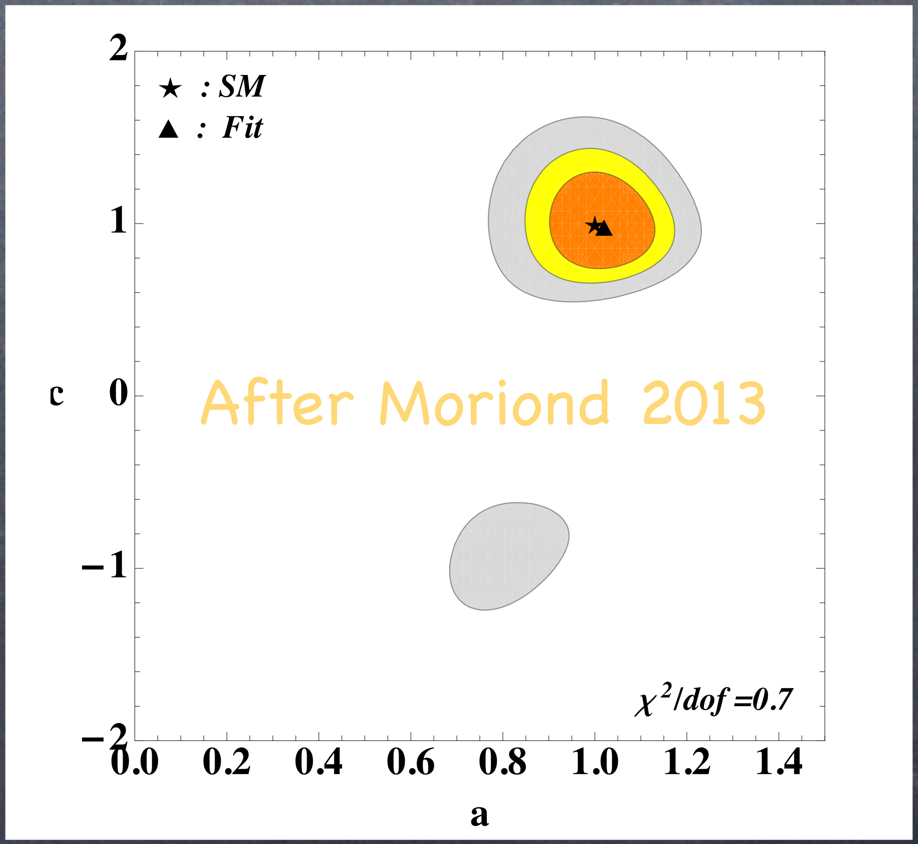
Ellis & You parametrization

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

$$\text{SM:} \qquad M = v \simeq 246 \text{ GeV}, \qquad \epsilon = 0$$

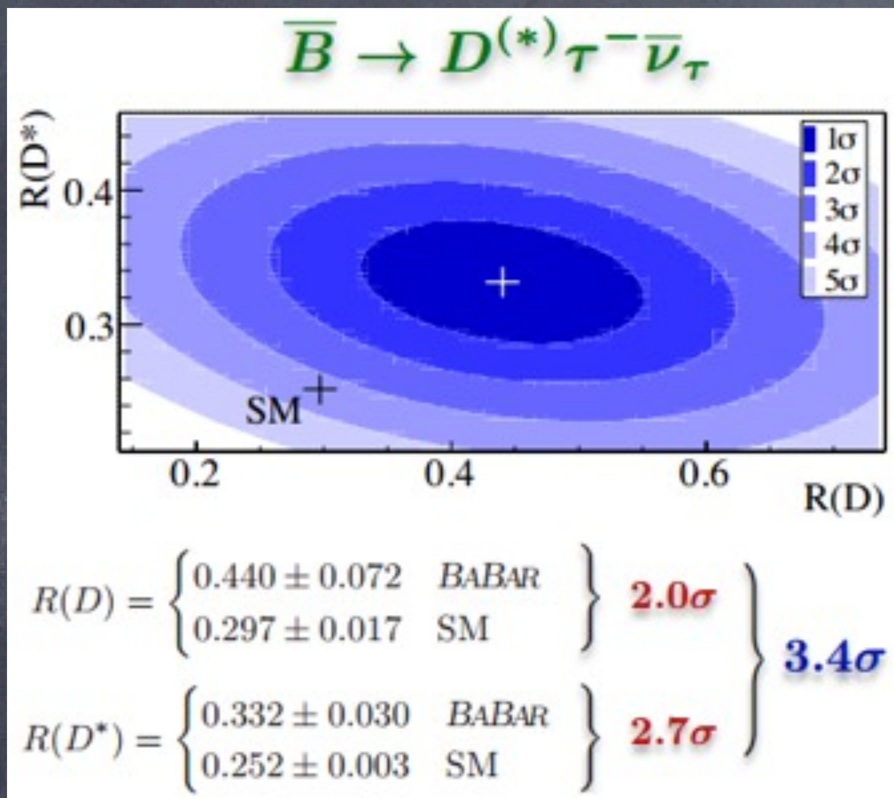
$$g_{hVV} = a\,(g_{hVV})^{\rm SM} \qquad y_{hff} = c\,(y_{hff})^{\rm SM}$$



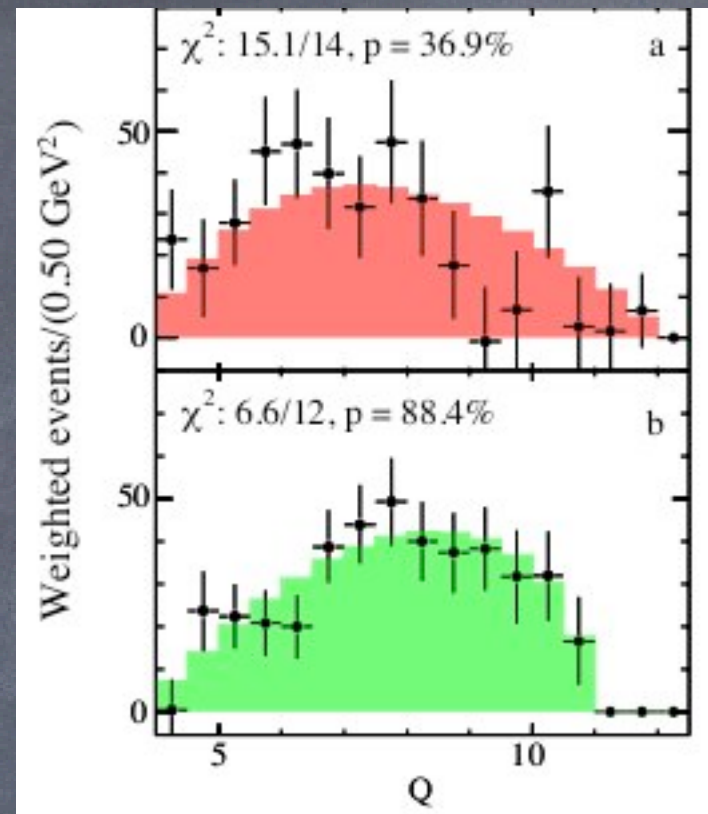


The B to D(*) Tau Nu excess in 2HDMs

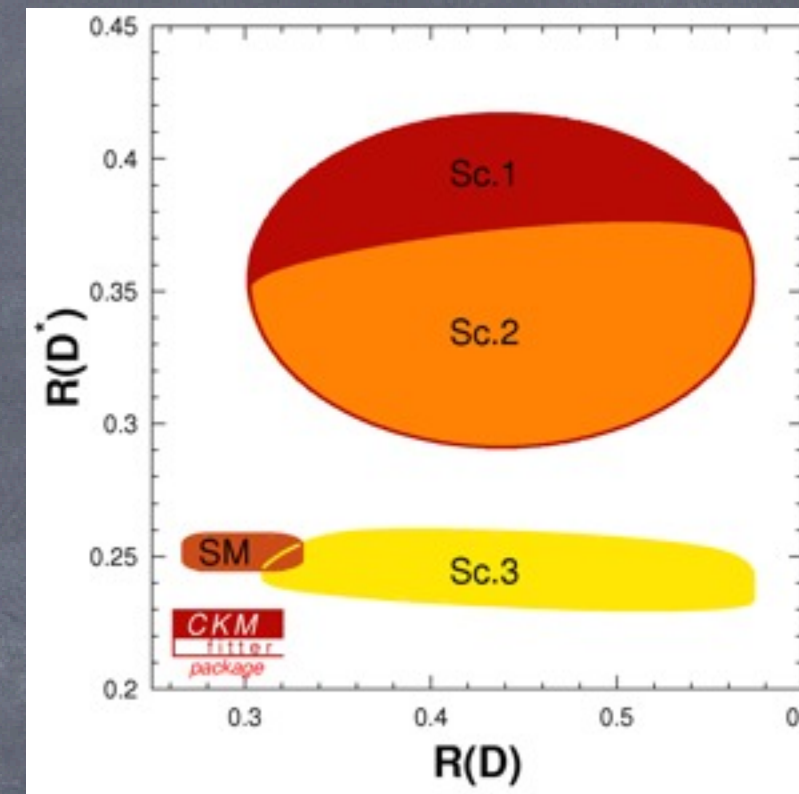
AC, M. Jung, X-Q Li, A. Pich
[JHEP 1301 (2013) 054]

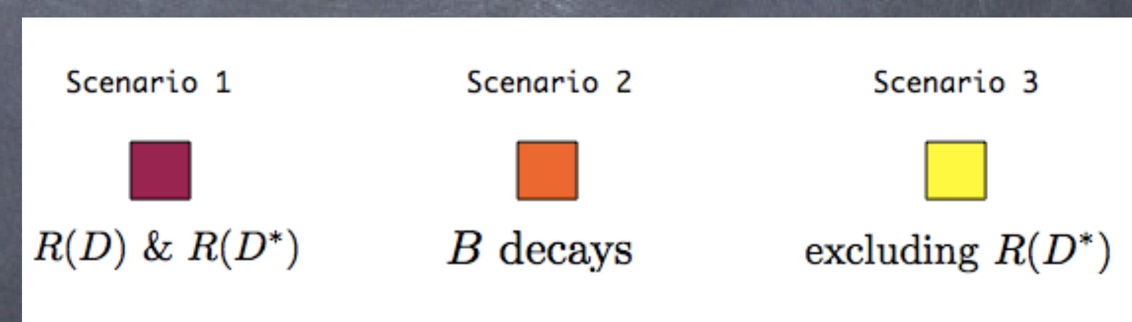


BaBar [Phys. Rev. D86 (2012) 032001]



BaBar [arXiv:1303.0571]





Requires a departure from familiy universality of the Yukawa couplings to accommodate the excess in 2HDMs

See also:

Fajfer, Kamenik, Nisandzic, Zupan [Phys.Rev.Lett. 109 (2012) 161801]

Crivellin, Greub, Kokulu [Phys.Rev. D86 (2012) 054014]

Tanaka, Watanabe [Phys. Rev. D87 (2013) 034028]

Belle update needed!

The 2HDM scalar sector

AC, V. Ilisie, A. Pich
[arXiv:1302.4022]

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

$$\begin{aligned} V &= \mu_1\, \Phi_1^\dagger\Phi_1 + \mu_2\, \Phi_2^\dagger\Phi_2 + \left[\mu_3\, \Phi_1^\dagger\Phi_2 + \mu_3^*\, \Phi_2^\dagger\Phi_1\right] \\ &+ \lambda_1 \left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ &+ \left[\left(\lambda_5\, \Phi_1^\dagger\Phi_2 + \lambda_6\, \Phi_1^\dagger\Phi_1 + \lambda_7\, \Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right] \end{aligned}$$

In the CP-conserving limit:

$$\bar{M}_h^2 = \frac{1}{2}\,(\Sigma - \Delta) , \qquad \bar{M}_H^2 = \frac{1}{2}\,(\Sigma + \Delta) , \qquad \bar{M}_A^2 = M_{H^\pm}^2 + v^2 \left(\frac{\lambda_4}{2} - \lambda_5^{\mathrm{R}}\right) ,$$

where $\quad M_{H^\pm}^2 = \mu_2 + \frac{1}{2}\,\lambda_3\, v^2$

$$\Sigma = M_{H^\pm}^2 + v^2 \left(2\,\lambda_1 + \frac{\lambda_4}{2} + \lambda_5^{\mathrm{R}}\right) ,$$

$$\Delta = \sqrt{\left[M_{H^\pm}^2 + v^2 \left(-2\,\lambda_1 + \frac{\lambda_4}{2} + \lambda_5^{\mathrm{R}}\right)\right]^2 + 4v^4(\lambda_6^{\mathrm{R}})^2} ,$$

The 2HDM scalar sector

AC, V. Ilisie, A. Pich
[arXiv:1302.4022]

Physical Higgs states and masses in the CP-violating case

To lowest order in CP-violation

$$M^2_{\varphi_i^0} = \bar{M}^2_{\varphi_i^0} + \alpha_1^{\varphi_i^0}\,(\lambda_5^I)^2 + \alpha_2^{\varphi_i^0}\,(\lambda_6^I)^2 + \alpha_3^{\varphi_i^0}\,(\lambda_5^I\lambda_6^I)$$

$$\alpha_1^{\varphi_i^0} = \frac{v^4\left(\bar{M}^2_{\varphi_i^0} - 2\lambda_1 v^2\right)}{\prod_{j\neq i}\left(\bar{M}^2_{\varphi_j^0} - \bar{M}^2_{\varphi_i^0}\right)},$$

$$\alpha_2^{\varphi_i^0} = \frac{v^4\left(2\lambda_1 v^2 + \bar{M}^2_{\varphi_i^0} - \bar{M}^2_H - \bar{M}^2_h\right)}{\prod_{j\neq i}\left(\bar{M}^2_{\varphi_j^0} - \bar{M}^2_{\varphi_i^0}\right)},$$

$$\alpha_3^{\varphi_i^0} = \frac{2v^6\lambda_6^R}{\prod_{j\neq i}\left(\bar{M}^2_{\varphi_j^0} - \bar{M}^2_{\varphi_i^0}\right)}.$$

Scalar masses receive quadratic corrections in CP-violating parameters

The 2HDM scalar sector

AC, V. Ilisie, A. Pich
[arXiv:1302.4022]

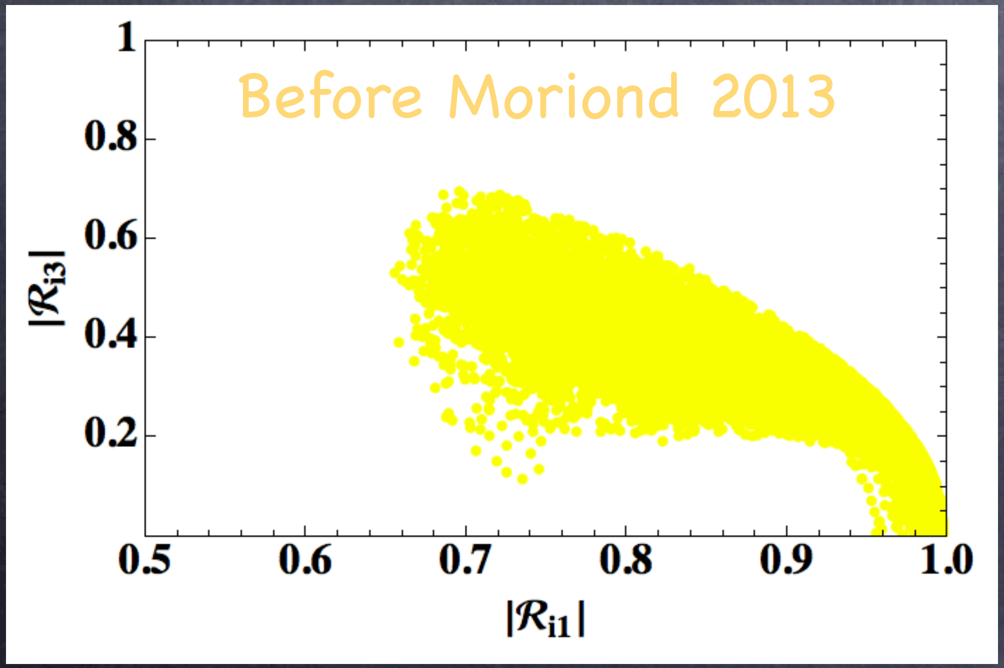
To lowest order in CP-violation

$$\begin{pmatrix} h \\ H \\ A \end{pmatrix} = \begin{pmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & \epsilon_{13} \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & 1 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

$$\epsilon_{13} = \frac{v^2}{(\bar{M}_A^2 - \bar{M}_h^2)} \left(\sin\tilde{\alpha}\,\lambda_5^{\mathrm{I}} + \cos\tilde{\alpha}\,\lambda_6^{\mathrm{I}}\right), \qquad \epsilon_{23} = \frac{v^2}{(\bar{M}_A^2 - \bar{M}_H^2)} \left(\cos\tilde{\alpha}\,\lambda_5^{\mathrm{I}} - \sin\tilde{\alpha}\,\lambda_6^{\mathrm{I}}\right),$$

$$\epsilon_{31} = -\frac{1}{2v^2} \left(\alpha_3^A\,\lambda_5^{\mathrm{I}} + 2\,\alpha_2^A\,\lambda_6^{\mathrm{I}}\right), \qquad \epsilon_{32} = -\frac{1}{2v^2} \left(2\,\alpha_1^A\,\lambda_5^{\mathrm{I}} + \alpha_3^A\,\lambda_6^{\mathrm{I}}\right)$$

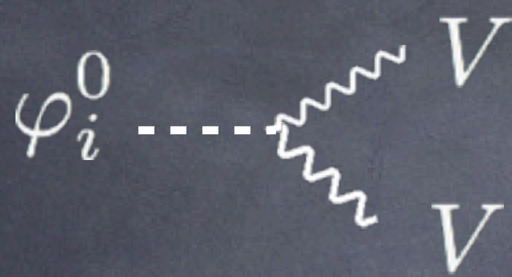
Physical states receive linear corrections in CP-violating parameters



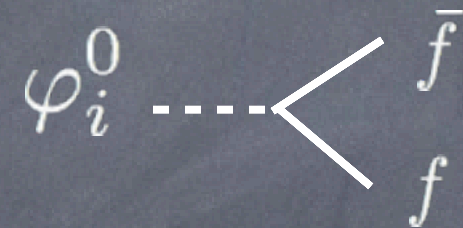
Possible CP-admixture in the 126 GeV Higgs constrained by data

LHC phenomenology in the A2HDM

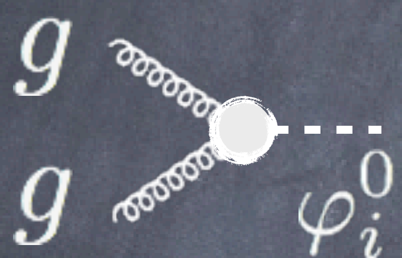
AC, V. Ilisie, A. Pich
[arXiv:1302.4022]



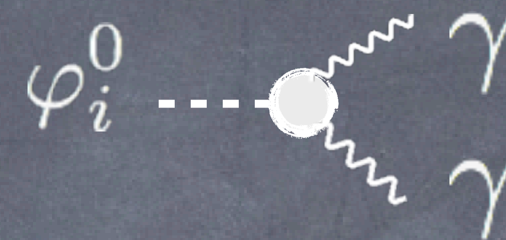
$\propto R_{i1}$



$\propto y_f^{\varphi_i^0}$



loop mediated: quarks



loop mediated: fermions, W, charged Higgs

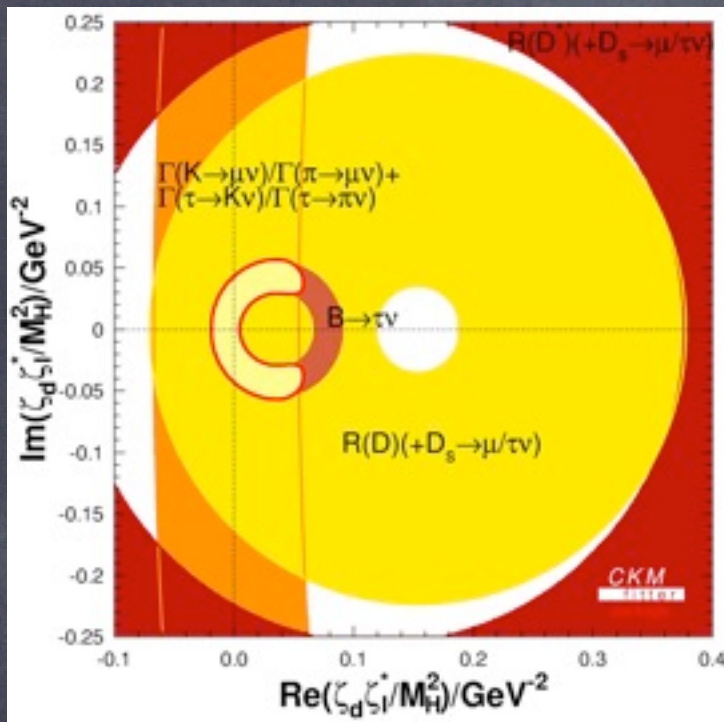
Searches for other scalar states in Nature:

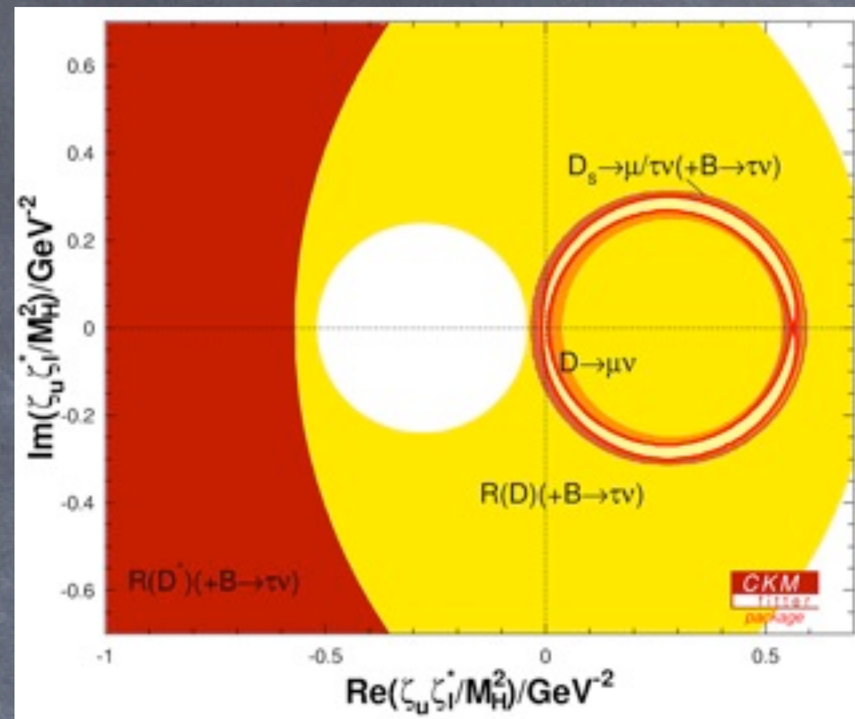
$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = 1$$

A series of sum-rules link the couplings of all neutral and charged scalars

$$\sum_{\varphi_i^0} (y_f^{\varphi_i^0})^2 = 1 \qquad \ldots$$

Flavor constraints on the A2HDM





Charged Higgs at tree-level

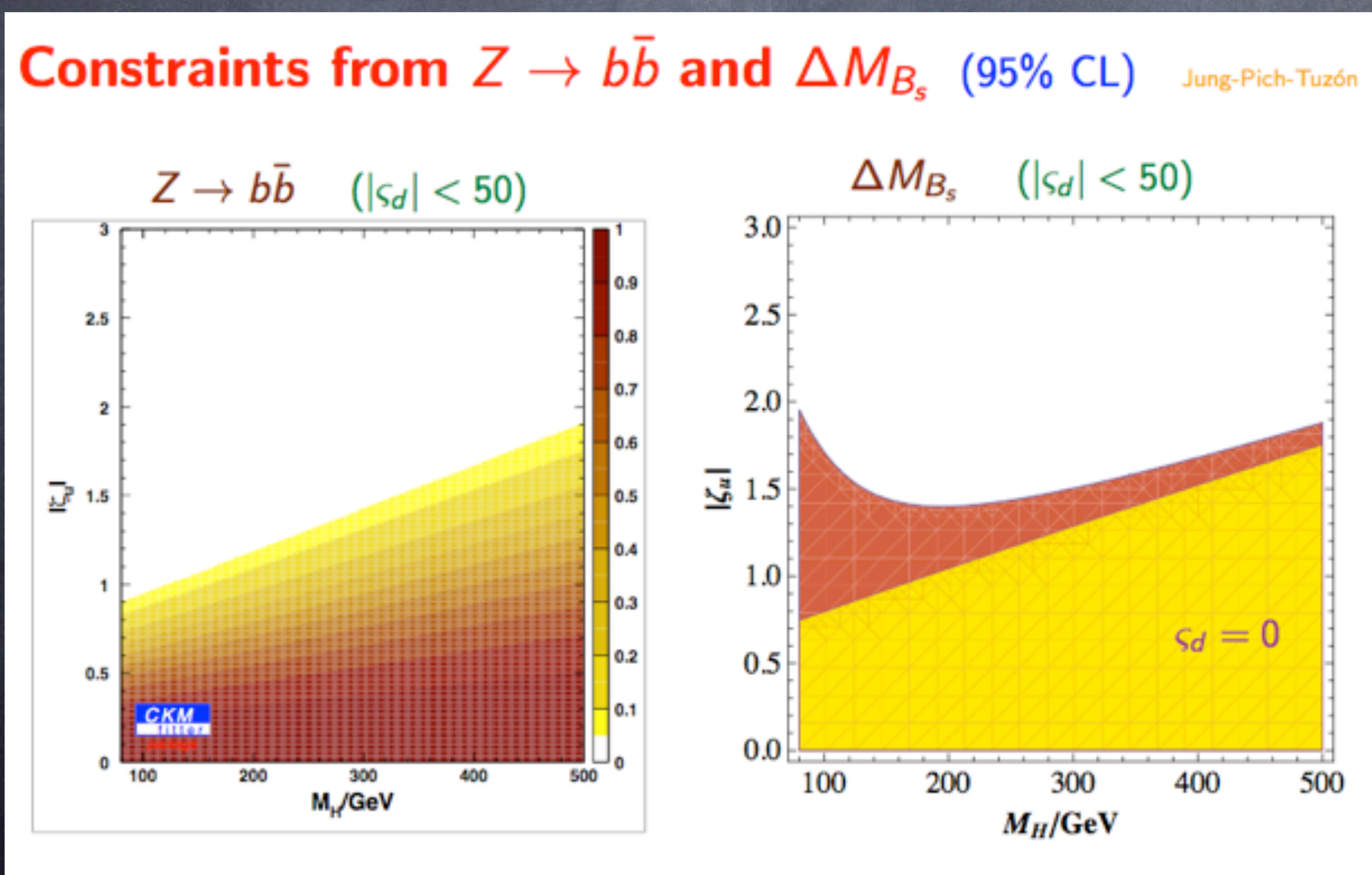
Pich, Tuzon, Phys.Rev. D80 (2009) 091702

Jung, Pich, Tuzon, JHEP 1011 (2010) 003

Jung, Pich, Tuzon, Phys. Rev. D83 (2011)

AC, Jung, X-Q Li, Pich, JHEP 1301 (2013) 054

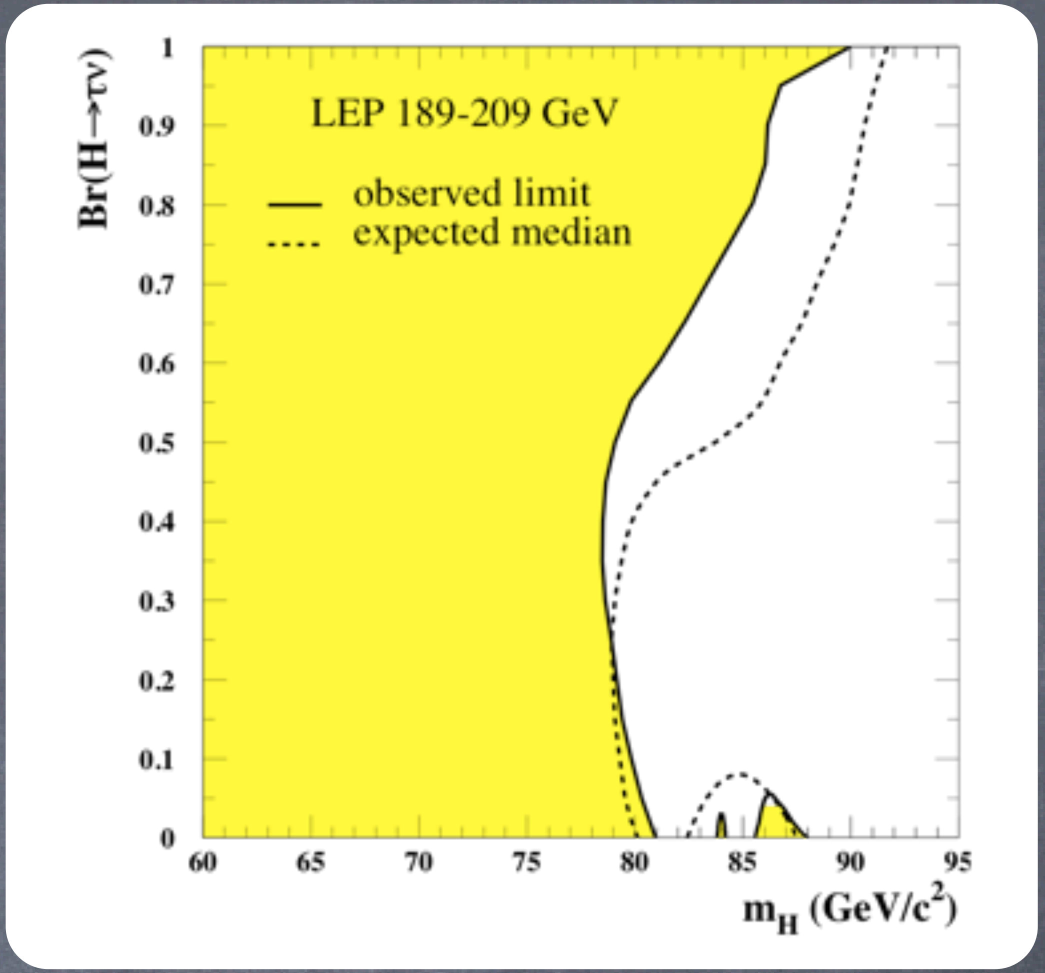
Jung, X-Q Li, Pich JHEP 1210 (2012) 063



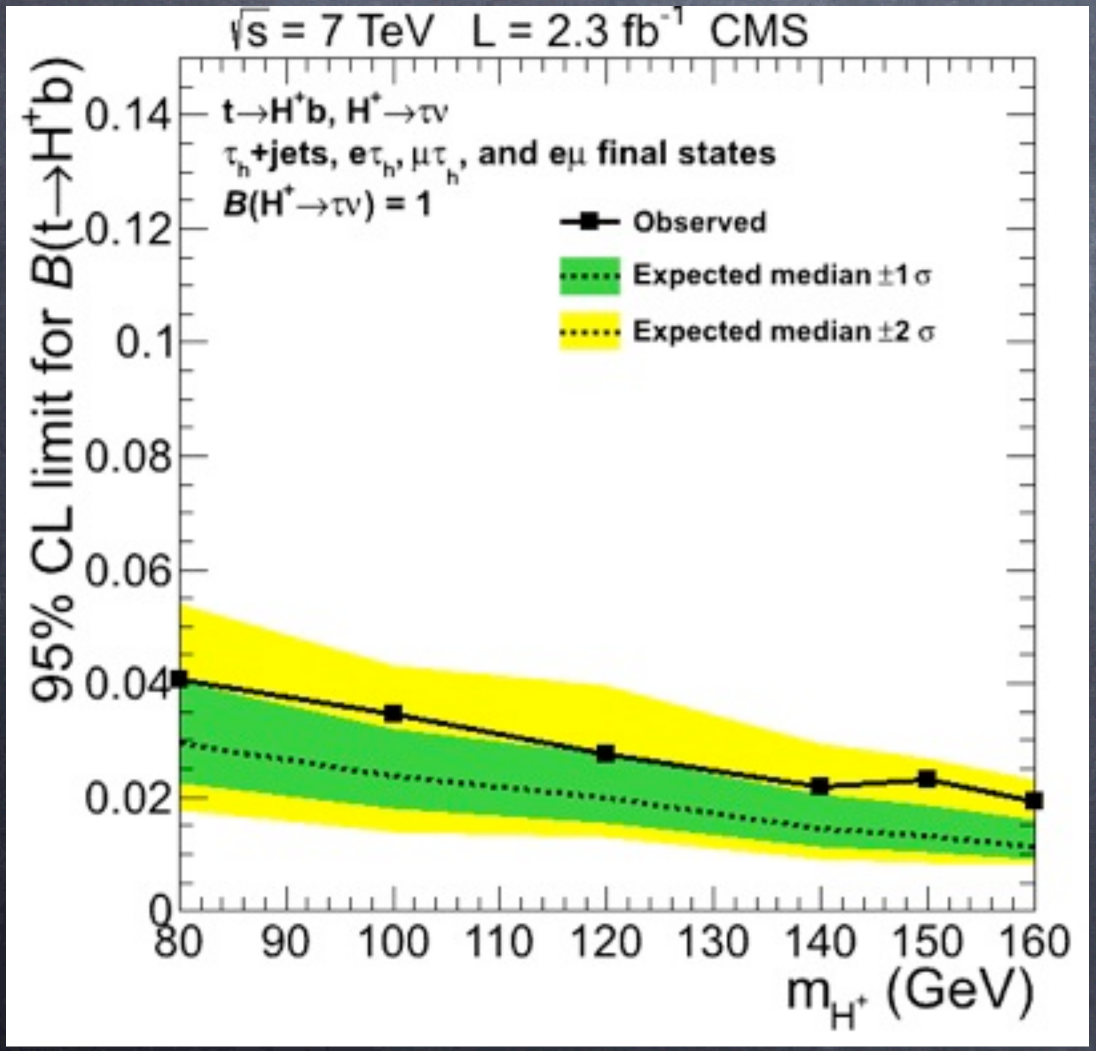
Charged Higgs at 1-loop

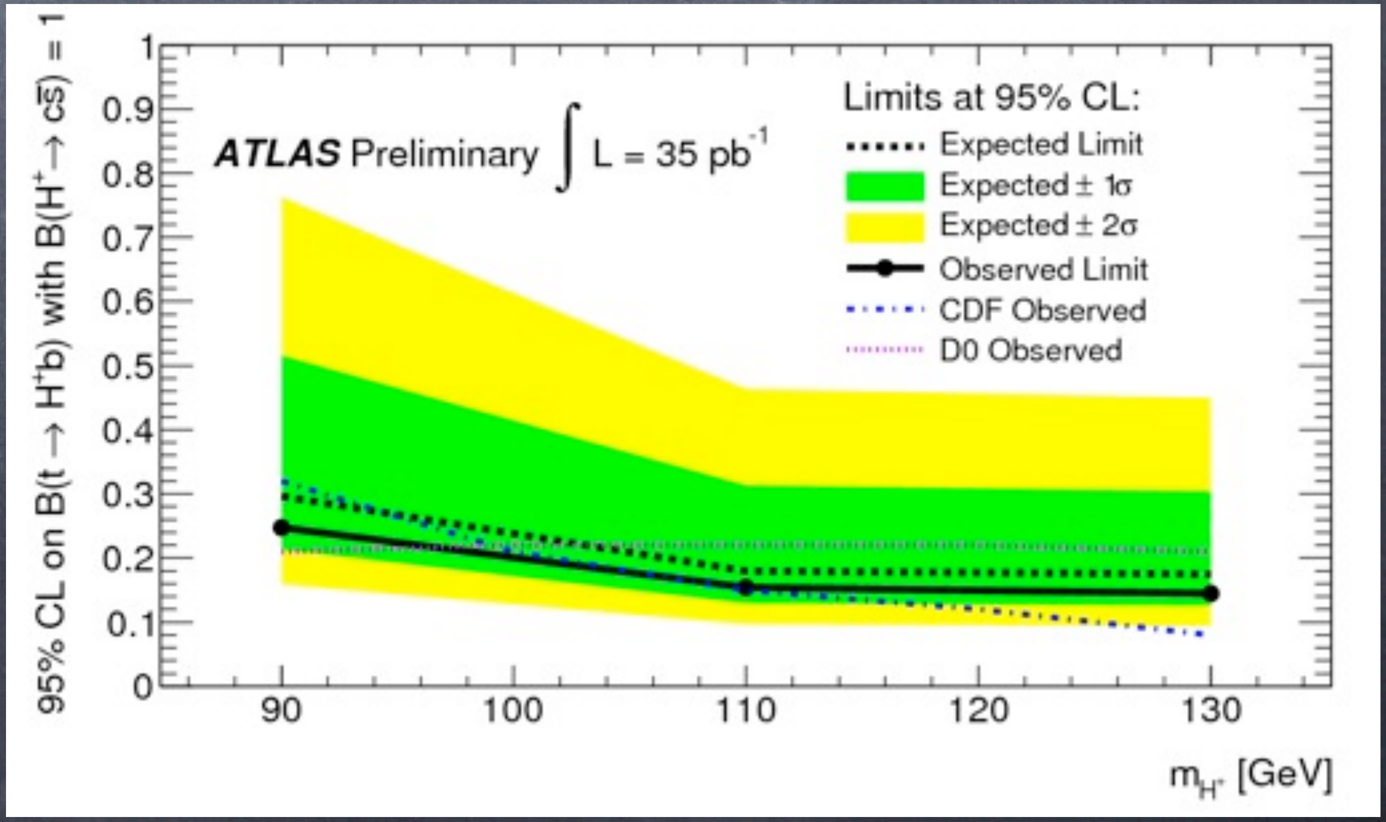
Charged Higgs searches

$$e^+e^- \to H^+H^-$$



$$t \to bW^{\pm}(H^{\pm})$$





Oblique parameters

$$\rho = M_W/(M_Z \cos\theta_W) = 1$$

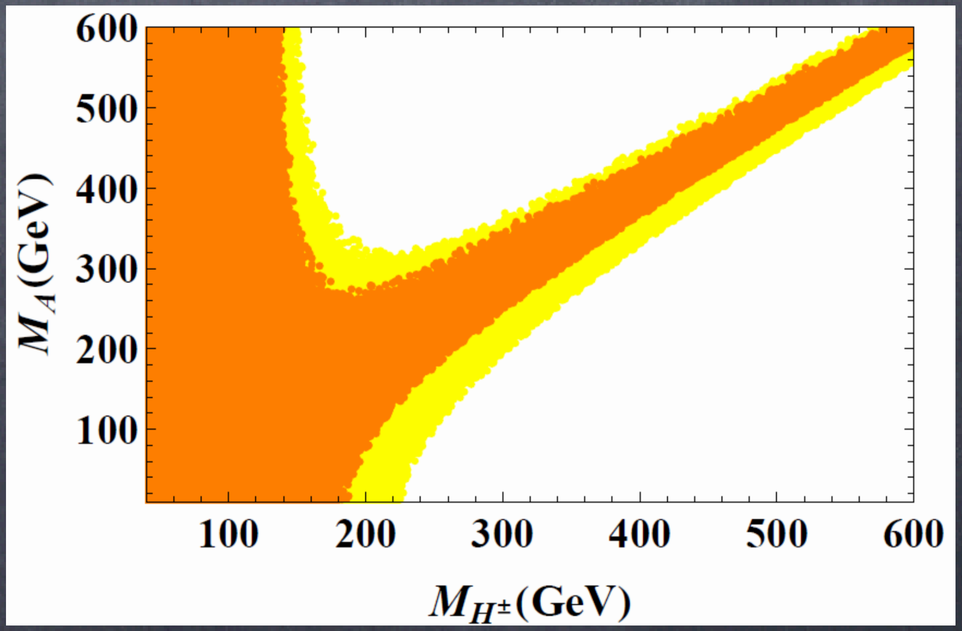
$$\downarrow$$

The mass splittings $|M_{H^\pm} - M_S|$ and $|M_{H^\pm} - M_A|$

cannot be both of $\mathcal{O}(\gtrsim v)$, with

$$M_S^2 = M_H^2 \cos^2\tilde{\alpha} + M_h^2 \sin^2\tilde{\alpha}$$

if H is at 126 GeV, h being lighter.
A fit to LHC data gives
$M_S \sim M_h$



Loop-induced FCNCs in the A2HDM

$\mathcal{L}_{\rm A2HDM}$ invariant under the phase transformation: $[\alpha_i^\nu = \alpha_i^l]$

$$f_L^i(x) \to e^{i\alpha_i^{f,L}} f_L^i(x) \quad , \quad f_R^i(x) \to e^{i\alpha_i^{f,R}} f_R^i(x)$$

$$V_{\rm CKM}^{ij} \to e^{i\alpha_i^{u,L}} V_{\rm CKM}^{ij} e^{-i\alpha_j^{d,L}} \quad , \quad M_{f,ij} \to e^{i\alpha_i^{f,L}} M_{f,ij} e^{-i\alpha_j^{f,R}}$$

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

MFV structure

$$C(\mu) = C(\mu_0) - \log(\mu/\mu_0)$$

loop-induced FCNCs vanish in the NFC limit

See:

- Pich, Tuzon, Phys.Rev. D80 (2009) 091702
- Jung, Pich, Tuzon,JHEP 1011 (2010) 003
- Ferreira, Lavoura, Silva, Phys.Lett. B688 (2010) 341-344
- Braeuninger, Ibarra, Simonetto, Phys.Lett. B692 (2010) 189-195

Models were the alignment condition is protected by symmetries

- H. Serodio, Phys. Lett. B 700 (2011) 133
- I. de Medeiros Varzielas, Phys. Lett. B 701 (2011) 597