Indirect limits on charged Higgs bosons and their model dependence

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cHarged 2008 – Prospects for Charged Higgs Discovery at Colliders

Plan of Talk

- Two Higgs-Doublet Models (Type I, II, III)
- $B \to X_s\gamma$ in the SM, 2HDM and MSSM
- Benchmark leptonic B-decays: $B^\pm \to \tau^\pm \nu_\tau$ & $B^\pm \to \mu^\pm \nu_\mu$
- Semileptonic B-decays: $B \to D\tau^\pm \nu_\tau$
- Rare B-decays sensitive to Neutral Higgs couplings: $B_s^0 \to \mu^+\mu^-$
- Summary

Two Higgs Doublet Models

Yukawa Lagrangian

$$-\mathcal{L} = h^d_{ij}\overline{q'}_{Li}\phi_1 d'_{Rj} + h^u_{ij}\overline{q'}_{Li}\tilde{\phi}_2 u'_{Rj} + h^\ell_{ij}\overline{\ell'}_{Li}\phi_3 e'_{Rj} + h.c.$$

where $q'_L, \ell'_L, \phi_a (a = 1,2,3)$ are SU(2) doublets; $\tilde{\phi}_a = i\sigma^2\phi^*_a$; u'_R, d'_R, e'_R are SU(2) singlets; h^d, h^u, h^ℓ are 3×3 Yukawa matrices

- To avoid FCNC of the type $h^d_{ij}\overline{q'}_{Li}\phi_2 d'_{Rj}$, one imposes the Glashow-Weinberg condition that no more than one Higgs doublet couples to the same right-handed field
- When only two Higgs doublets are present, ϕ_1 and ϕ_2; it is, in general, $\phi_3 = \phi_1$ (or $\phi_3 = \phi_2$)
- After rotating the fermion fields from the current eigenstate to the mass eigenstate basis, the charged Higgs component becomes

$$-\mathcal{L} = \frac{m_{di}}{\langle\phi_1^0\rangle}\bar{u}_{Lj}\, V_{ji}\, d_{Ri}\phi_1^+ - \frac{m_{ui}}{\langle\phi_2^0\rangle}\bar{u}_{Ri}\, V_{ij}\, d_{Lj}\phi_2^+ + \frac{m_{\ell i}}{\langle\phi_3^0\rangle}\bar{\nu}_{Li}\,\ell_{Ri}\,\phi_3^+ + h.c.$$

  where V_{ij} is the CKM matrix

- In the MSSM (Minimal supersymmetric standard model), one has a doublet of Higgs fields, with $\phi_3 = \phi_1$, defines the Type II Higgs doublet model

Two Higgs Doublet Models (contd.)

- A further rotation of the charged Higgs fields to their physical basis through a unitary matrix U yields the Yukawa interactions for H^+

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left\{ \frac{m_{di}}{M_W} X \, \bar{u}_{Lj} \, V_{ji} \, d_{Ri} + \frac{m_{ui}}{M_W} Y \, \bar{u}_{Ri} \, V_{ij} \, d_{Lj} + \frac{m_{\ell i}}{M_W} Z \, \bar{\nu}_{Li} \, \ell_{Ri} \right\} + h.c.$$

with X, Y, Z defined in terms of the elements of the matrix U. In general, they are complex numbers and potential sources of CP-violating effects

- Restricting to 2HDM, the matrix U is a 2×2 matrix

$$U = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}$$

- If $\phi_1 = \phi_2$, one has the 2HDM of Type I. If both doublets contribute to the Yukawa interactions, we have a 2HDM of Type II. In both cases, the couplings X and Y are real and given by

$$\begin{aligned} X &= -\cot\beta\,, \quad & Y &= \cot\beta \quad & &(\text{Type I}) \\ X &= \tan\beta\,, \quad & Y &= \cot\beta \quad & &(\text{Type II}) \end{aligned}$$

- The calculation of $B \to X_s\gamma$ is modified by the addition of the charged Higgs contributions to the SM, modifying the matching conditions

Type III two Higgs doublet models

[Das, Kao, hep-ph/9511329; Kiers, Soni, Wu, hep-ph/9810552; Wu, Soni, hep-ph/9911419; Xiao, Lu, hep-ph/0605076; Lunghi, Soni, arXiv:0707.0212]

- Consider a special case of type-III 2HDM, called the Two-Higgs-Doublet-Model for the top quark (T2HDM), motivated by the large mass of the top quark
- In this model, there are two Higgs doublets; one of the doublets has only interactions involving the right-handed top quark, while the other one couples to the remaining right-handed fermions, and $\tan\beta_H$ is large (ratio of the vev's of the two Higgs fields)

  Yukawa interactions of the Higgses and quarks

$$\mathcal{L}_Y = -\bar{Q}_L H_1 Y_d d_R - \bar{Q}_L \tilde{H}_1 Y_u \mathbb{1}^{(12)} u_R - \bar{Q}_L \tilde{H}_2 Y_u \mathbb{1}^{(3)} u_R + \mathrm{h.c.}$$

  where H_i are the two doublets, $\tilde{H}_i = i\sigma^2 H_i^*$, $Y_{u,d}$ are Yukawa matrices $\mathbb{1}^{(12)} = \mathrm{diag}(1,1,0)$ and $\mathbb{1}^{(3)} = \mathrm{diag}(0,0,1)$
- The two complex vev's are: $v_1/\sqrt{2} = v e^{i\phi_1}\cos\beta_H/\sqrt{2}$ and $v_2/\sqrt{2} = v e^{i\phi_2}\sin\beta_H/\sqrt{2}$, with $\tan\beta_H \equiv |v_2/v_1|$
- The quark mass matrices in the mass eigenstate basis are:

$$m_d = D_L^\dagger \left(\frac{v_1^*}{\sqrt{2}} Y_d\right) D_R \,,$$

$$m_u = U_L^\dagger \left(\frac{v_1^*}{\sqrt{2}} Y_u \mathbb{1}^{(12)} + \frac{v_2^*}{\sqrt{2}} Y_u \mathbb{1}^{(3)}\right) U_R$$

  where $U_{L,R}$ and $D_{L,R}$ are unitary matrices and $V = U_L^\dagger D_L$ is the CKM matrix

Charged Higgs interactions with quarks

$$\mathcal{L}_Y^C = -\bar{u}_L V m_d d_R \frac{H_1^+}{v_1^*/\sqrt{2}} - \bar{u}_R \left(m_u V \frac{H_1^+}{v_1^*/\sqrt{2}} + \Sigma^\dagger V \left[\frac{H_2^+}{v_2^*/\sqrt{2}} - \frac{H_1^+}{v_1^*/\sqrt{2}} \right] \right) d_L$$

$$\equiv \bar{u}_L (P_{LR}^H H^+ + P_{LR}^G G^+) d_R + \bar{u}_R (P_{RL}^H H^+ + P_{RL}^G G^+) d_L + \text{h.c.}$$

where $\Sigma \equiv m_u U_R^\dagger \mathbb{1}^{(3)} U_R$

- The would be Goldstone boson $G^\pm$, the charged Higgs $H^\pm$, the heavy and light scalars H^0 and h^0, and the pseudoscalar A^0 are given by:

$$\begin{pmatrix} H_1^0 e^{-i\phi_1} \\ H_2^0 e^{-i\phi_2} \end{pmatrix} = \frac{1}{\sqrt{2}} \left[R_{\alpha_H} \begin{pmatrix} H^0 \\ h^0 \end{pmatrix} + i R_{\beta_H} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} + \begin{pmatrix} |v_1| \\ |v_2| \end{pmatrix} \right]$$

$$\begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix} = R_{\beta_H} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

with

$$R_\omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix}$$

The explicit expressions for the charged Higgs couplings are:

$$\begin{aligned} P^H_{LR} &= \frac{g_2}{\sqrt{2} m_W} \tan\beta_H \, V \, m_d \\ P^H_{RL} &= \frac{g_2}{\sqrt{2} m_W} \tan\beta_H \left[(1 + \tan^{-2}\beta_H) \Sigma^\dagger - m_u \right] V \\ P^G_{LR} &= -\frac{g_2}{\sqrt{2} m_W} V \, m_d \\ P^G_{RL} &= \frac{g_2}{\sqrt{2} m_W} m_u \, V \end{aligned}$$

- The matrix Σ depends on 4 real parameters following from the unitarity of U_R. this leads to the following charged Higgs interactions between right-handed up-quarks and left-handed down quarks

$$\frac{g_2 m_c \tan\beta_H}{\sqrt{2} m_W} \begin{pmatrix} \xi'^* \, V_{td} & \xi'^* \, V_{ts} & \xi'^* \, V_{tb} \\ \xi^* \, V_{td} - V_{cd} & \xi^* \, V_{ts} - V_{cs} & \xi^* \, V_{tb} - V_{cb} \\ V_{td} \cot^2\beta_H / \epsilon_{ct} + \epsilon_{ct} \xi V_{cd} & V_{ts} \cot^2\beta_H / \epsilon_{ct} + \epsilon_{ct} \xi V_{cs} & V_{tb} \cot^2\beta_H / \epsilon_{ct} \end{pmatrix}$$

- The four complex parameters are ξ, ξ', $\epsilon_{ct} = m_c/m_t$ and $\xi^{(\prime)} = \mathcal{O}(1)$
- The parameters of the model are: $\tan\beta_H$, α_H, $m_{H^\pm}$, m_{H^0}, m_{h^0}, m_{A^0}, ξ, ξ'

B decays sensitive to Higgs couplings

- $\mathcal{B}(B \to X_s\gamma)$ in 2 Higgs-doublet model

Effects of $\mathcal{L}_{\bar{q}bH^+}$: $(q = u,\ c,\ t)$

$$\mathcal{L}_{\bar{q}bH^+} = \frac{g}{2\sqrt{2}} \frac{\bar{m}_b}{M_W} \frac{\tan\beta}{1+\epsilon_b \tan\beta} V_{qb}\ \bar{q}(1+\gamma_5)b\ H^+$$

- $\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau)$
- $\mathcal{B}(B \to D\tau^\pm \nu_\tau)$
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; sensitive to neutral Higgs couplings

The Standard Candle: $B \to X_s\gamma$

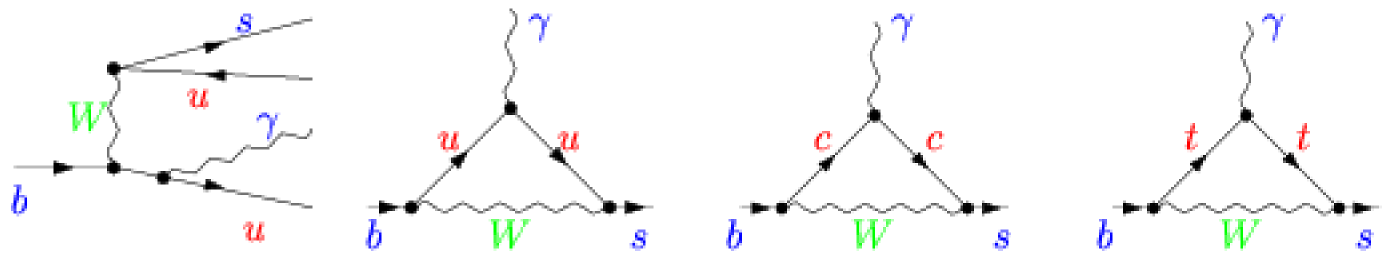
Interest in the rare decay $B \to X_s\gamma$ transcends B Physics!

- Already well measured; more precise measurements anticipated at B- and SuperB-factories

Theoretical Interest:

- A monumental theoretical effort has gone in improving the perturbative precision; $B \to X_s\gamma$ in NNLO completed in 2006
  - First estimate of $\mathcal{B}(B \to X_s\gamma)$: Misiak et al. (17 authors), hep-ph/0609232
  - Analysis of $\mathcal{B}(B \to X_s\gamma)$ at NNLO with a cut on Photon energy, T. Becher and M. Neubert, hep-ph/0610067
- Non-perturbative effects under control thanks to HQET
- Sensitivity to new physics; hence constrains parameters of the BSM models such as Supersymmetry
- A crucial input in a large number of precision tests of the SM in $b \to s$ processes, such as $B \to X_s\ell^+\ell^-$

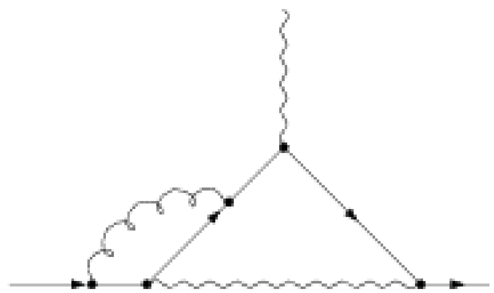
Examples of the leading electroweak diagrams for $B \to X_s \gamma$



$$\left|\frac{V_{ub}V_{us}}{V_{cb}}\right| \simeq \left|\frac{V_{ub}V_{us}}{V_{ts}}\right| \simeq 2\%$$

$$\sim +200\% \qquad \sim -100\%$$

In the amplitude, after including LO QCD effects.



- QCD logarithms $\alpha_s \ln \frac{M_W^2}{m_b^2}$ enhance $BR(B \to X_s\gamma)$ more than twice
- Effective field theory (obtained by integrating out heavy fields) used for resummation of such large logarithms

The effective Lagrangian for $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

$$\mathcal{L} = \mathcal{L}_{QCD\times QED}(q,l) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i$$

$(q = u, d, s, c, b,\ l = e, \mu, \tau)$

$$O_i = \begin{cases} (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b), & i = 1, 2, & |C_i(m_b)| \sim 1 \\ (\bar{s}\Gamma_i b)\Sigma_q(\bar{q}\Gamma_i' q), & i = 3, 4, 5, 6, & |C_i(m_b)| < 0.07 \\ \frac{e m_b}{16\pi^2}\bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, & i = 7, & C_7(m_b) \sim -0.3 \\ \frac{g m_b}{16\pi^2}\bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}, & i = 8, & C_8(m_b) \sim -0.15 \\ \frac{e^2}{16\pi^2}(\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma^\mu \gamma_5 l), & i = 9, 10 & |C_i(m_b)| \sim 4 \end{cases}$$

Three steps of the calculation:

Matching: Evaluating $C_i(\mu_0)$ at $\mu_0 \sim M_W$ by requiring equality of the SM and the effective theory Green functions

Mixing: Deriving the effective theory RGE and evolving $C_i(\mu)$ from μ_0 to $\mu_b \sim m_b$

Matrix elements: Evaluating the on-shell amplitudes at $\mu_b \sim m_b$

Wilson Coefficients

Wilson Coefficients of Four-Quark Operators

	$C_1(\mu_b)$	$C_2(\mu_b)$	$C_3(\mu_b)$	$C_4(\mu_b)$	$C_5(\mu_b)$	$C_6(\mu_b)$
LL	-0.257	1.112	0.012	-0.026	0.008	-0.033
NLL	-0.151	1.059	0.012	-0.034	0.010	-0.040

Wilson Coefficients of Other Operators

	$C_7^{\rm eff}(\mu_b)$	$C_8^{\rm eff}(\mu_b)$	$C_9(\mu_b)$	$C_{10}(\mu_b)$
LL	-0.314	-0.149	2.007	0
NLL	-0.308	-0.169	4.154	-4.261
NNLL	-0.290		4.214	-4.312

- Obtained for the following input:

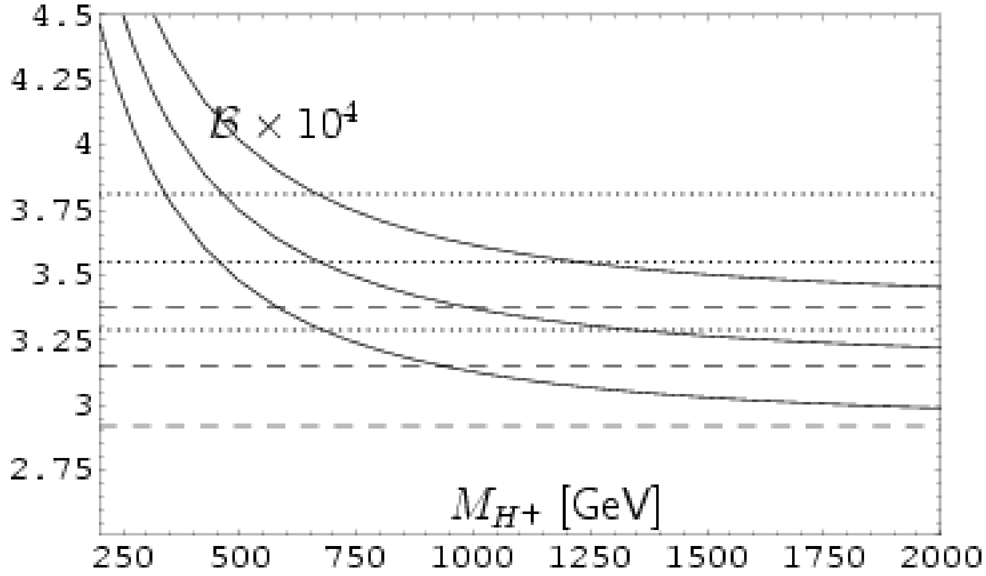
$$\mu_b = 4.6 \text{ GeV} \qquad \bar{m}_t(\bar{m}_t) = 167 \text{ GeV}$$

$$M_W = 80.4 \text{ GeV} \qquad \sin^2\theta_W = 0.23$$

- Three-loop running is used for α_s coupling with $\Lambda_{\overline{\rm MS}}^{(5)} = 220$ MeV

$\mathcal{B}(\bar{B} \to X_s \gamma)$: Experiment vs. SM & 2HDM

[Misiak et al., hep-ph/0609232]



[$\cdots$ (exp); – – – – (SM); solid (2HDM)]

- Experiment ($E_\gamma > 1.6$ GeV): $\mathcal{B}(\bar{B} \to X_s \gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$
- NNLO SM: $\mathcal{B}(\bar{B} \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$
  (Parametric Update: $(3.30 \pm 0.24) \times 10^{-4}$ Gambino, Giordano [arXiv:0805.0271])
- SM is below the experiments by about 1 σ
- In 2HDM, preferred value is $M_{H^+} \simeq 650$ GeV

Matching Conditions in 2Higgs Doublet Models

- The charged Higgs contribution enters the calculations via Matching Conditions

$$C_i^{\rm eff}(\mu_W) = C_i^{0,\,\rm eff}(\mu_W) + \frac{\alpha_s(\mu_W)}{4\pi} C_i^{1,\,\rm eff}(\mu_W)$$

- LO Wilson coefficients with explicit dependence on the couplings $\mathbf{X}$ and $\mathbf{Y}$:

$$\begin{aligned}
C_2^{0,\,\rm eff}(\mu_W) &= 1; \quad C_i^{0,\,\rm eff}(\mu_W) = 0 \quad (i = 1,3,4,5,6) \\
C_7^{0,\,\rm eff}(\mu_W) &= C^0_{7,SM} + |\mathrm{Y}|^2\, C^0_{7,YY} + (\mathrm{X}\,\mathrm{Y}^*)\, C^0_{7,XY} \\
C_8^{0,\,\rm eff}(\mu_W) &= C^0_{8,SM} + |\mathrm{Y}|^2\, C^0_{8,YY} + (\mathrm{X}\,\mathrm{Y}^*)\, C^0_{8,XY}
\end{aligned}$$

- The LO SM-functions are ($x = m_t^2/M_W^2$):

$$\begin{aligned}
C^0_{7,SM} &= \frac{x}{24}\left[\frac{-8x^3 + 3x^2 + 12x - 7 + (18x^2 - 12x)\ln x}{(x-1)^4}\right] \\
C^0_{8,SM} &= \frac{x}{8}\left[\frac{-x^3 + 6x^2 - 3x - 2 - 6x\ln x}{(x-1)^4}\right]
\end{aligned}$$

- Model dependence of the 2HDM is encoded in $\mathbf{Y}$ and $\mathbf{X}\,\mathbf{Y}^*$:

$$\begin{aligned}
Y^2 &= \tfrac{1}{\tan^2\beta}, \quad XY = -\tfrac{1}{\tan^2\beta} \quad &(\text{Type I}) \\
Y^2 &= \tfrac{1}{\tan^2\beta}, \quad XY = 1 \quad &(\text{Type II})
\end{aligned}$$

- The LO 2HDM-functions are $(y = m_t^2/m_H^2)$:

$$C^0_{7,YY} = \frac{1}{3}\, C^0_{7,SM}(x \to y); \quad C^0_{8,YY} = \frac{1}{3}\, C^0_{8,SM}(x \to y);$$

$$C^0_{7,XY} = \frac{1}{12}\, y \left[\frac{-5y^2 + 8y - 3 + (6y-4)\ln y}{(y-1)^3}\right]$$

$$C^0_{8,XY} = \frac{1}{4}\, y \left[\frac{-y^2 + 4y - 3 - 2\ln y}{(y-1)^3}\right]$$

- NLO pieces $C_i^{1,\text{eff}}(\mu_W)$ are (see Borzumati and Greub, hep-ph/9802391):

$$C_1^{1,\,\text{eff}}(\mu_W) = 15 + 6\ln\frac{\mu_W^2}{M_W^2}$$

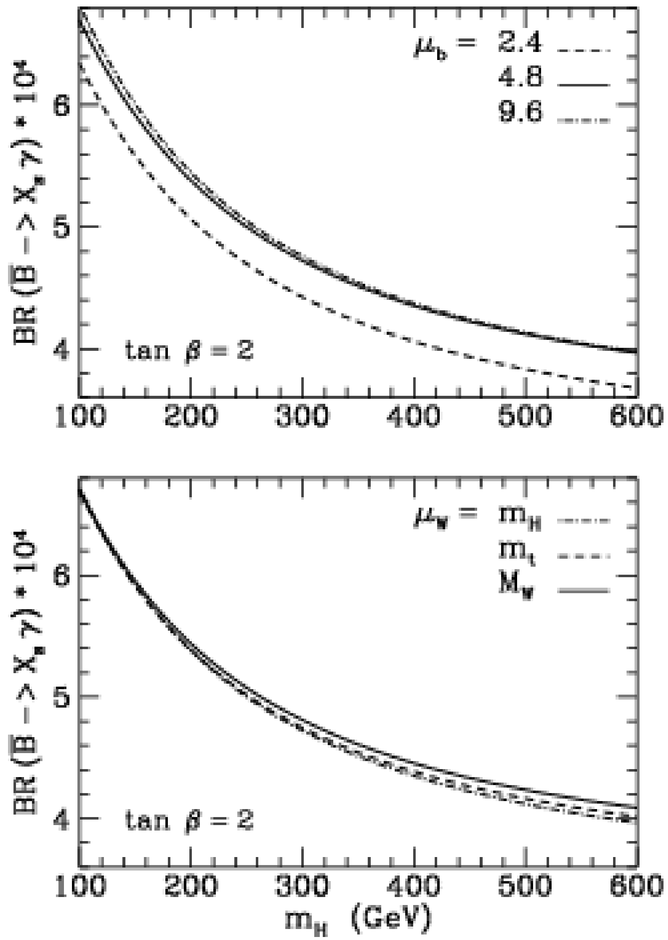
$$C_4^{1,\,\text{eff}}(\mu_W) = E_0 + \frac{2}{3}\ln\frac{\mu_W^2}{M_W^2} + |Y|^2\, E_H$$

$$C_i^{1,\,\text{eff}}(\mu_W) = 0 \qquad (i = 2,3,5,6)$$

$$C_7^{1,\,\text{eff}}(\mu_W) = C^{1,\,\text{eff}}_{7,SM}(\mu_W) + |Y|^2\, C^{1,\,\text{eff}}_{7,YY}(\mu_W) + (X\,Y^*)\, C^{1,\,\text{eff}}_{7,XY}(\mu_W)$$

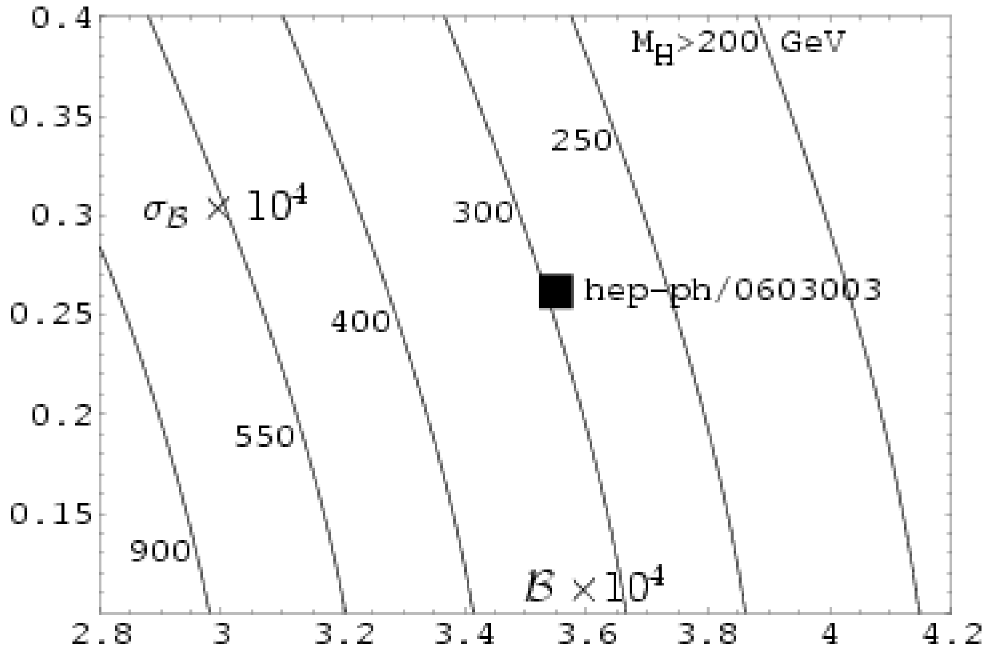
$$C_8^{1,\,\text{eff}}(\mu_W) = C^{1,\,\text{eff}}_{8,SM}(\mu_W) + |Y|^2\, C^{1,\,\text{eff}}_{8,YY}(\mu_W) + (X\,Y^*)\, C^{1,\,\text{eff}}_{8,XY}(\mu_W)$$

$BR(\bar{B} \to X_s\gamma)$ in Type II 2HDM



95% C.L. Lower Bound on M_{H^+} in 2HDM from $\mathcal{B}(\bar{B} \to X_s \gamma)$

[Misiak et al., hep-ph/0609232]



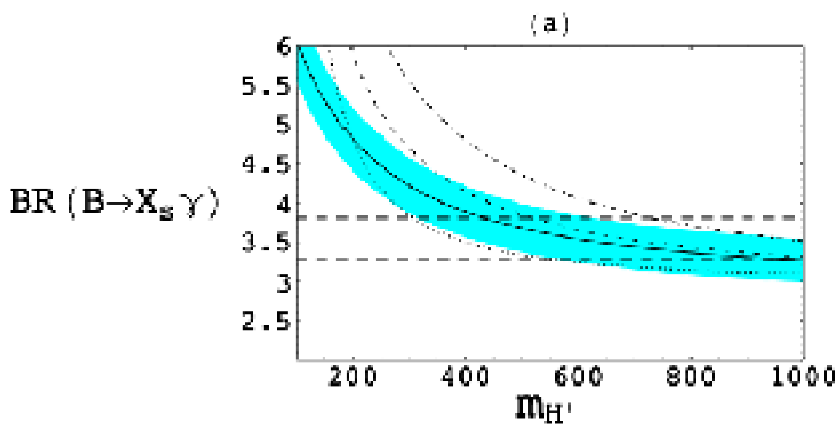
- 95% C.L. lower bound is around 295 GeV

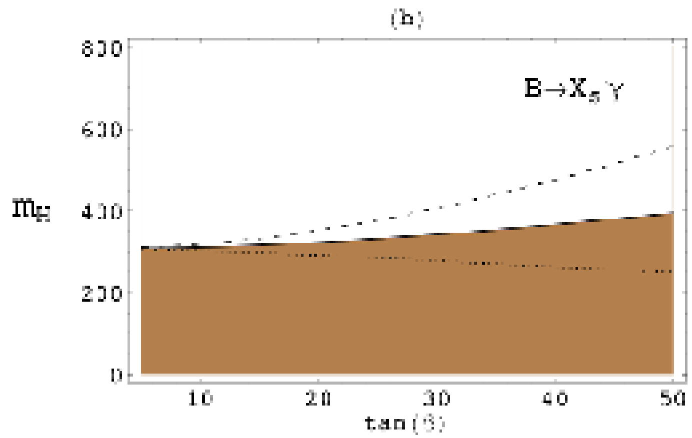
Bounds on $m_{H^\pm}, \tan\beta_H$ in T2HDM from $\mathcal{B}(B \to X_s\gamma)$

[Lunghi & Soni, arXiv: 0707.0212]

(a): The curves correspond to the values: $(\tan\beta_H, \xi) = (10, 0)$ (solid), $(50, 0)$ (dashed), $(50, 1)$ (dotted) and $(50, -1)$ (dotted-dashed)

(b) portion of $(\tan\beta_H, m_{H^\pm})$ excluded at 68% C.L. (shaded for $\xi = 0$), dotted $(\xi = 1)$, dashed $(\xi = -1)$





$B^\pm \to \tau^\pm \nu_\tau$ & $B \to D\tau^\pm \nu_\tau$ and $H^\pm$

- Effective Hamiltonian for $b \to q\tau\nu_\tau$ involving the $\bar{q}bW^+$ and $\bar{q}bH^+$ couplings

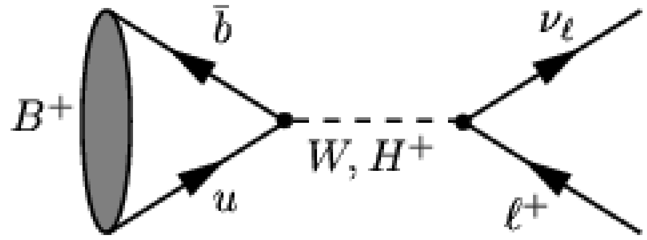
$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{qb} \left\{ \bar{q}\gamma_\mu(1-\gamma_5) b \bar{\tau}\gamma^\mu(1-\gamma_5)\nu_\tau - \frac{\bar{m}_b m_\tau}{m_B^2} \bar{q}\left[g_S + g_P\, \gamma_5\right] b \bar{\tau}(1-\gamma_5)\nu_\tau \right\}$$

  with $g_s = g_P = \frac{m_B^2}{m_{H^+}^2} \frac{\tan^2\beta}{(1+\epsilon_b \tan\beta)(1+\epsilon_\tau \tan\beta)}$

- In the SM, with $f_B = 216 \pm 38$ MeV, $\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau) = (1.25 \pm 0.41) \times 10^{-4}$ [Cf. $\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau)^{\rm exp} = (1.4 \pm 0.4) \times 10^{-4}$]
- In the 2Higgs doublet model, $\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau)$ is sensitive to g_P: $\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau) \propto V_{ub}^2 f_B^2 |1 - g_P|^2$; leads to constraints on the parameters $(m_{H^+}, \tan\beta)$
- $\mathcal{B}(B \to D\tau^\pm \nu_\tau)$ is sensitive to the coupling g_S
- Current SM estimates [Nierste, Trine, Westhoff]
  $\mathcal{B}(B^- \to D^0 \tau^- \bar{\nu}_\tau) = (0.71 \pm 0.09)\%$
  $\mathcal{B}(\bar{B}^0 \to D^+ \tau^- \bar{\nu}_\tau) = (0.66 \pm 0.08)\%$
  $R = \frac{\mathcal{B}(B \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D e \bar{\nu}_e)} = 0.31 \pm 0.02$

- $R^{\rm exp} = 0.416 \pm 0.117 \pm 0.052$; leads to constraints on the parameters $(m_{H^+}, \tan\beta)$

$B^\pm \to \tau^\pm \nu_\tau$, $B^\pm \to \mu^\pm \nu_\mu$ and $H^\pm$



- Lagrangian for $b\bar{u} \to \ell^- \bar{\nu}_\ell$ induced by W^- & H^-

$$\frac{G_F}{\sqrt{2}} V_{ub} \left([\overline{u}\gamma_\mu(1-\gamma_5)b]\,[\overline{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell] - R_\ell\,[\overline{u}(1+\gamma_5)b]\,[\overline{l}(1-\gamma_5)\nu_\ell] \right)$$

with $R_\ell = \tan^2\beta\,(m_b m_\ell / m^2_{H^\pm})$

- Defining the decay constant:

$$< 0|\overline{u}\gamma^\mu\gamma^5 b|B^- > \equiv i f_B p_B^\mu; \qquad < 0|\overline{u}\gamma^5 b|B^- > \equiv -i f_B (m_B^2/m_b)$$

yields the decay amplitude and the tree–level partial width [W.S. Hou, '93]

$$\mathcal{M} = -\frac{G_F}{\sqrt{2}} V_{ub} f_B \left[m_l - R_l (m_B^2/m_b) \right] \bar{l}(1-\gamma_5)\nu_\ell$$

$$\Gamma(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_l^2 f_B^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_l^2}{m_B^2} \right)^2 r_H$$

where $r_H = [1 - \tan^2\beta (m_B^2 / m^2_{H^\pm})]^2$

Remarks

- The factor m_ℓ^2 reflects the helicity suppression of the $W^\pm$ contribution, and the Yukawa coupling of $H^\pm \ell^\mp \nu_\ell$
- $H^\pm$ & $W^\pm$ contributions interfere destructively;
  Enhancement of these contributions $(r_H > 1)$ requires
  $\tan\beta/m_{H^\pm} > 0.27\,\mathrm{GeV}^{-1}$
- In the tree–level approximation, the b quark Yukawa coupling y_b is related to m_b: $y_b = \sqrt{2} m_b / v_1$
- At the 1-loop level, the relationship between y_b and the running quark mass m_b modified due to the SUSY-QCD contributions [Hall, Rattazzi, Sarid; Carena et al., Hempfling]
- In addition to the HRS correction, there are also corrections to the $H^\pm ub$ vertex. The effects of both corrections can be encoded in an effective Lagrangian by multiplying the tree–level Lagrangian by the factor $1/(1 + \epsilon_b \tan\beta)$ [Buras et al.]

$$\mathcal{L}_{\bar{q}bH^+} = \frac{g}{2\sqrt{2}} \frac{\bar{m}_b}{M_W} \frac{\tan\beta}{1+\epsilon_b \tan\beta} V_{qb}\ \bar{q}(1+\gamma_5) b\ H^+$$

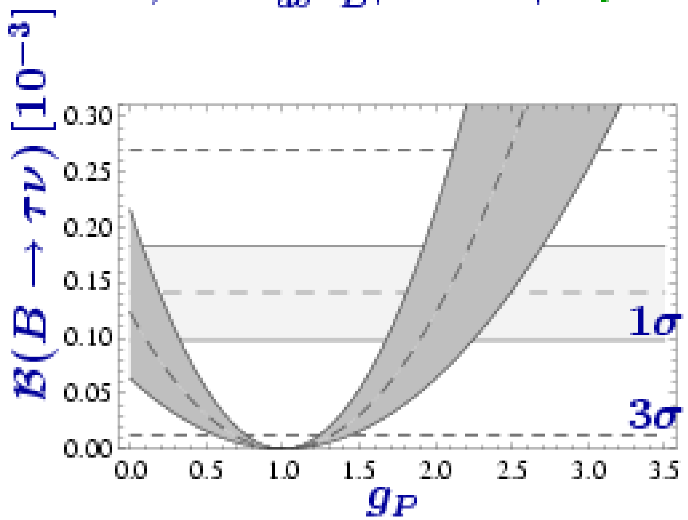
- Analogous corrections are present for the $H^\pm \tau^\mp \nu_\tau$ and $H^\pm \mu^\mp \nu_\mu$, but are small

- Effective Hamiltonian for $b \to q\tau\nu_\tau$ involving the $\bar{q}bW^+$ and $\bar{q}bH^+$ couplings

$$H_{\text{eff}}(b \to q\tau\nu_\tau) = \frac{G_F}{\sqrt{2}} V_{qb} \Big\{ \bar{q}\gamma_\mu(1-\gamma_5) b \bar{\tau}\gamma^\mu(1-\gamma_5)\nu_\tau - \frac{\bar{m}_b m_\tau}{m_B^2} \left[g_S + g_P\, \gamma_5 \right] b\bar{\tau}(1-\gamma_5)\nu_\tau \Big\}$$

with $g_s = g_P = \frac{m_B^2}{m_{H^+}^2} \frac{\tan^2\beta}{(1+\epsilon_b \tan\beta)(1+\epsilon_\tau \tan\beta)}$

- In the SM, with $f_B = 216 \pm 38$ MeV, $\mathcal{B}(B^\pm \to \tau^\pm\nu_\tau) = (1.25 \pm 0.41) \times 10^{-4}$
  [Cf. $\mathcal{B}(B^\pm \to \tau^\pm\nu_\tau)^{\text{exp}} = (1.4 \pm 0.4) \times 10^{-4}$]
- In the 2Higgs doublet model, $\mathcal{B}(B^\pm \to \tau^\pm\nu_\tau)$ is sensitive to g_P:
  $\mathcal{B}(B^\pm \to \tau^\pm\nu_\tau) \propto V_{ub}^2 f_B^2 |1 - g_P|^2$; [Nierste et al.]



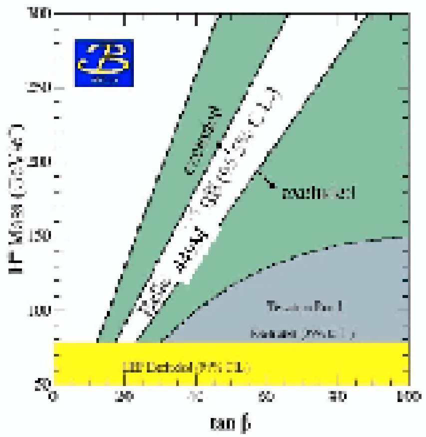
Constraints on M_H vs. $\tan\beta$ in 2Higgs doublet model from $B^\pm \to \tau^\pm \nu_\tau$

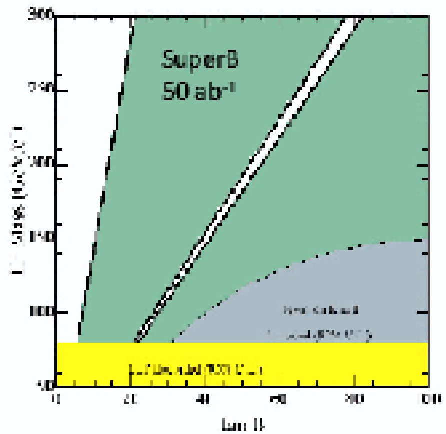
[Courtesy: B. Golob (Belle)]

B → τν

$$Br(B^+ \to \tau\nu) = (1.79 \pm^{0.56}_{0.49} \pm^{0.46}_{0.51}) \cdot 10^{-4}$$ Belle, PRL97, 251802 (2006), 414 fb^{-1}

$$Br(B^+ \to \tau\nu) = (1.65 \pm^{0.38}_{0.37} \pm^{0.35}_{0.37}) \cdot 10^{-4}$$ Belle, ICHEP06, 600 fb^{-1}, preliminary





Charged-Higgs effects in $B \to D\tau^{\pm}\nu_\tau$

- $\mathcal{B}(B \to D\tau^{\pm}\nu_\tau)$ is sensitive to the coupling g_S
- $B \to D\ell\nu_\ell$, $(\ell = e,\, \mu,\, \tau)$ involves the hadronic matrix elements of the vector and scalar currents, V_1 and S_1

$$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = V_1(w)\frac{m_B + m_D}{2\sqrt{m_B m_D}}\left[p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2}q^\mu\right] + S_1(w)(1+w)\sqrt{m_B m_D}\,\frac{m_B - m_D}{q^2}q^\mu$$

$$\langle D(p_D)|\bar{c}b|\bar{B}(p_B)\rangle = S_1(w)(1+w)\sqrt{m_B m_D}\,\frac{m_B - m_D}{\overline{m}_b(\mu) - \overline{m}_c(\mu)}$$

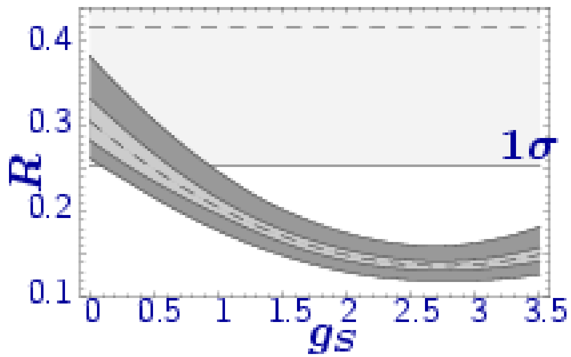
where $w = \frac{m_B^2 + m_D^2 - q^2}{2m_D m_B}$ Heavy quark symmetry implies:

$$S_1(1) \;=\; V_1(1) \;=\; 1 + \mathcal{O}(1/m_c, \alpha_s)$$

- Current SM estimates [Nierste, Trine, Westhoff]
  $\mathcal{B}(B^- \to D^0\tau^-\bar{\nu}_\tau) = (0.71 \pm 0.09)\%$
  $\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau) = (0.66 \pm 0.08)\%$

$$R = \frac{\mathcal{B}(B \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D e \bar{\nu}_e)} = 0.31 \pm 0.02$$

- $R^{\text{exp}} = 0.416 \pm 0.117 \pm 0.052$; leads to constraints on the parameters $(m_{H^+}, \tan\beta)$



$B_s \to \mu^+\mu^-$ in the SM

- Effective Hamiltonian

$$\mathcal{H}_{eff} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{ts}{}^* V_{tb} \sum_i \left[C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)\right]$$

$$\mathcal{O}_{10} = (\bar{s}_\alpha\gamma^\mu P_L b_\alpha)\left(\bar{l}\gamma_\mu\gamma_5 l\right), \qquad \mathcal{O}'_{10} = (\bar{s}_\alpha\gamma^\mu P_R b_\alpha)\left(\bar{l}\gamma_\mu\gamma_5 l\right)$$

$$\mathcal{O}_S = m_b\,(\bar{s}_\alpha P_R b_\alpha)\left(\bar{l}l\right), \qquad \mathcal{O}'_S = m_s\,(\bar{s}_\alpha P_L b_\alpha)\left(\bar{l}l\right)$$

$$\mathcal{O}_P = m_b\,(\bar{s}_\alpha P_R b_\alpha)\left(\bar{l}\gamma_5 l\right), \qquad \mathcal{O}'_P = m_s\,(\bar{s}_\alpha P_L b_\alpha)\left(\bar{l}\gamma_5 l\right)$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right) = \frac{G_F^2\alpha^2 m_{B_s}^2 f_{B_s}^2 \tau_{B_s}}{64\pi^3}|V_{ts}{}^*V_{tb}|^2\sqrt{1-4\hat{m}_\mu^2} \times \left[\left(1-4\hat{m}_\mu^2\right)|F_S|^2 + |F_P + 2\hat{m}_\mu^2 F_{10}|^2\right]$$

where $\hat{m}_\mu = m_\mu/m_{B_s}$ and

$$F_{S,P} = m_{B_s}\left[\frac{C_{S,P}m_b - C'_{S,P}m_s}{m_b+m_s}\right], \qquad F_{10} = C_{10} - C'_{10}$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.61 \pm 0.39)\times 10^{-9}$$

[Blanke et al., arxiv:0805.4393]

$$f_{B_s} = (245 \pm 25)\ \text{MeV}$$

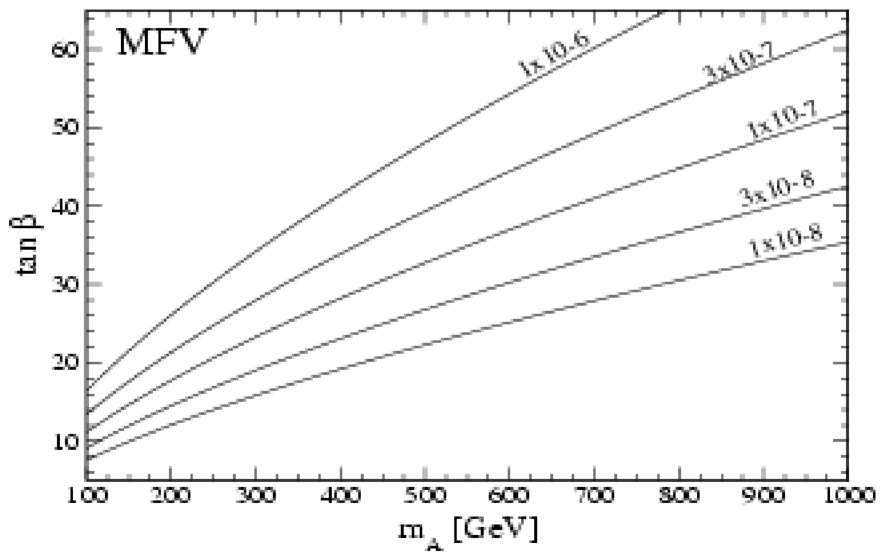
$B_s \to \mu^+\mu^-$ in Minimal Flavor Violation SUSY Models

- Higgsino contribution to $\mathcal{B}(B_s \to \mu^+\mu^-)$ [Babu, Kolda; Kane, Kolda, Lennon;...]

$$\mathcal{B}(B_s \to \mu^+\mu^-) \simeq \frac{G_F^2}{8\pi}\,\eta_{\rm QCD}^2 m_{B_s}^3 f_{B_s}^2 \tau_{B_s} m_b^2\, m_\mu^2 \left(\frac{\tan^2\beta}{\cos^4\beta}\right)\left(\frac{\kappa_{\widetilde{H}}^2}{m_A^4}\right).$$

- $\eta_{\rm QCD} \simeq 1.5$ is the QCD correction due to the RG between the SUSY and B_s scales

$$\kappa_{\widetilde{H}} = -\frac{G_F\, m_t^2\, V_{ts}V_{tb}}{4\sqrt{2}\pi^2 \sin^2\beta}\,\mu A_t\, f(\mu^2, m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2)$$



B Physics Observables & MSSM

Ellis et al. [arxiv:0709.00982]

WMAP-Compliant Benchmark Surfaces for MSSM

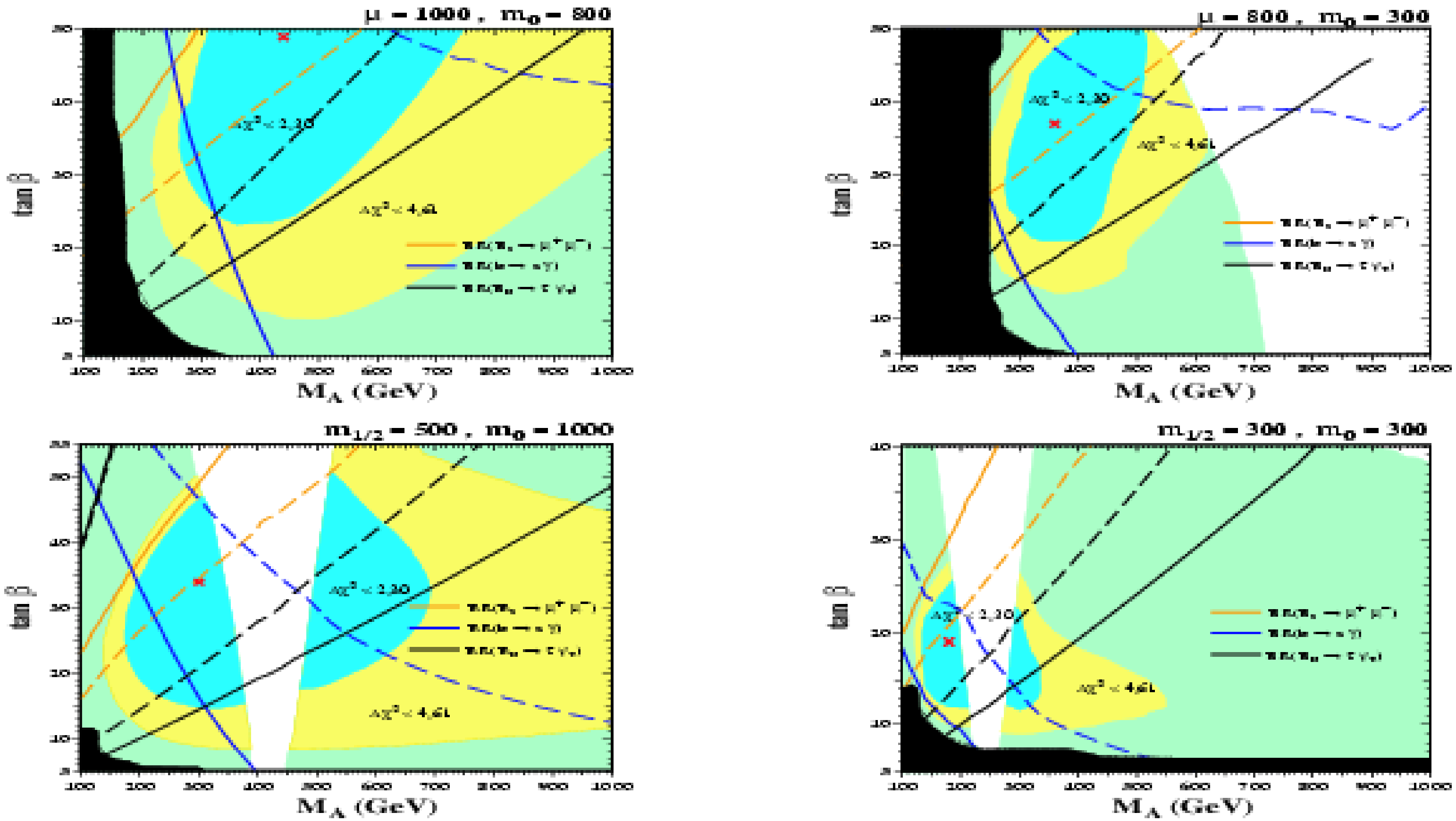
- The four NUHM benchmark surfaces obtained by fixing some parameters and allowing M_A and $\tan\beta$ to vary freely.

	$m_{1/2}$	m_0	A_0	μ	$\chi^2_{\rm min}$
P1	$\sim \frac{9}{8} M_A$	800	0	1000	7.1
P2	$\sim 1.2 M_A$	300	0	800	3.1
P3	500	1000	0	250 … 400	7.4
P4	300	300	0	200 … 350	5.6

B Physics Observables & MSSM

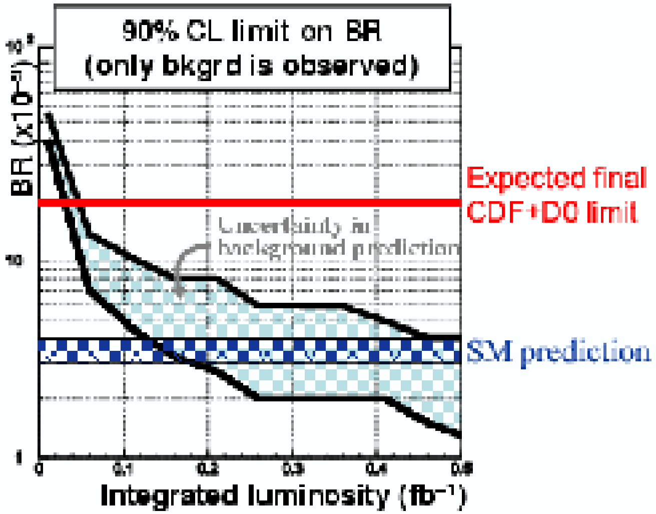
Ellis et al. [arxiv:0709.00982]

WMAP-Compliant Benchmark Surfaces for MSSM

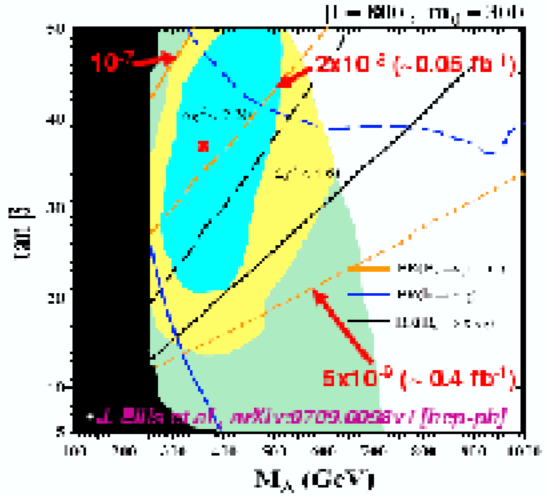


Mitesh Patel, LHCb

$B_s \to \mu\mu$ at LHCb



Exclusion:
0.1 fb^{-1} ⇒ BR < 10^{-8}
0.5 fb^{-1} ⇒ < SM



With SM Branching ratio
2 fb^{-1} ⇒ 3σ evidence
6 fb^{-1} ⇒ 5σ observation

With 0.1fb^{-1} can measure BR 9 (15)×10^{-9} at 3 (5)σ

With 0.5fb^{-1} can measure BR 5 (9)×10^{-9} at 3 (5)σ

9

Summary

- Charged Higgs bosons are present in a variety of extensions of the standard model; their profile (masses, couplings to the quarks and leptons) will be the subject of intense investigations at the LHC
- They also impact on low energy processes, such as the decays $B \to X_s \gamma$, $B \to X_s \ell^+ \ell^-$, $B^\pm \to \tau^\pm \nu_\tau$, $B \to D \tau^\pm \nu_\tau$ and many more. Their contributions are, however, model dependent
- The decay $B_s^0 \to \mu^+ \mu^-$ is sensitive to the neutral Higgs sector in 2HDMs, in particular, embedded in SUSY. Experiments at the LHC are sensitive to the SM branching ratio for this mode. Its measurement will provide valuable constraints on the BSM model parameters
- Hope that the synergy of high energy frontier and low energy precision physics, which worked so well in piecing together the SM yielding precise knowledge of the CKM matrix, will continue to hold sway in the LHC era, providing valuable information on the flavour aspects of the next Paradigm!