Minimal Flavour Violation with two Higgs doublets

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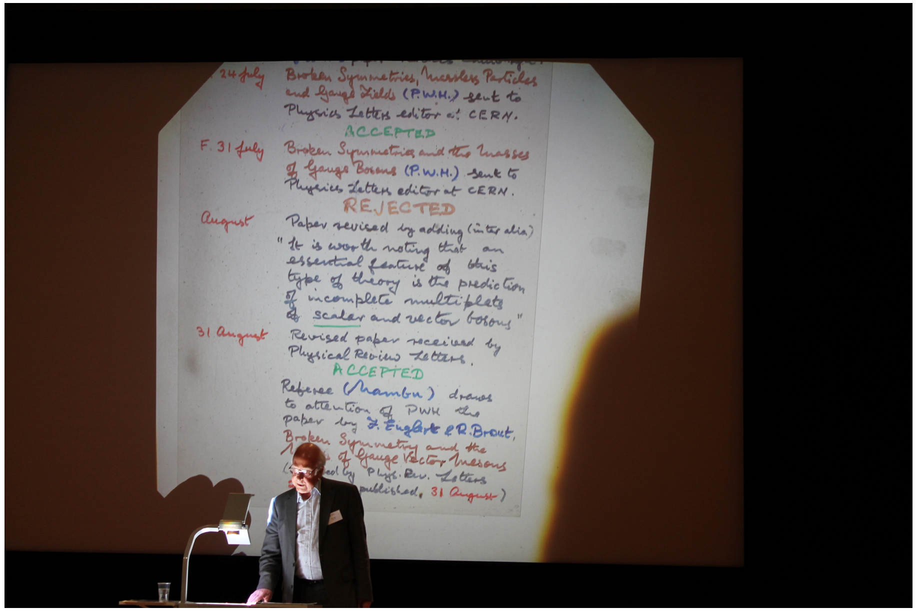
Multi Higgs Pictures

Edinburgh 85



24 July Broken Symmetries, Massless Particles and Gauge Fields (P.W.H.) sent to Physics Letters editor at CERN.

ACCEPTED

F. 31 July Broken Symmetries and the Masses of Gauge Bosons (P.W.H.) sent to Physics Letters editor at CERN.

REJECTED

August Paper revised by adding (inter alia) "It is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons"

31 August Revised paper received by Physical Review Letters.

ACCEPTED

Referee (Nambu) draws to attention of PWH the paper by F. Englert & R. Brout, Broken Symmetry and the [illegible] of Gauge Vector Mesons ([illegible]ed by Phys. Rev. Letters [illegible] published, 31 August)

↑

Stockholm
EPS HEP 2013

↙ ↘

GLORY

2013

GLORY

2013

CERN, 4 July 2013

Two Higgs Doublet Models

Despite several good motivations,
there is the need to suppress potentially dangerous FCNC:

Without HFCNC

- discrete symmetry leading to NFC

Weinberg, Glashow (1977); Paschos (1977)

- aligned two Higgs doublet model Pich, Tuzon (2009)

With HFCNC

- assume existence of suppression factors

Antaramian, Hall, Rasin (1992); Hall, Weinberg (1993); Joshipura, Rindani (1991)

- first models of this type with no ad-hoc assumptions

suppression by small elements of VCKM

Branco, Grimus, Lavoura (1996)

Minimal Flavour Violation

Notation

Yukawa interactions

$$\mathcal{L}_Y = -\overline{Q^0_L}\,\Gamma_1\,\Phi_1\,d^0_R - \overline{Q^0_L}\,\Gamma_2\,\Phi_2\,d^0_R - \overline{Q^0_L}\,\Delta_1\,\tilde{\Phi}_1\,u^0_R - \overline{Q^0_L}\,\Delta_2\,\tilde{\Phi}_2\,u^0_R + h.c.$$

$$\tilde{\Phi}_i = -i\tau_2\,\Phi_i^*$$

Quark mass matrices

$$M_d = \frac{1}{\sqrt{2}}\left(v_1\,\Gamma_1 + v_2\,e^{i\alpha}\,\Gamma_2\right)\;;\quad M_u = \frac{1}{\sqrt{2}}\left(v_1\,\Delta_1 + v_2\,e^{-i\alpha}\,\Delta_2\right)$$

Diagonalized by

$$U_{d_L}^\dagger\;M_d\;U_{dR} = D_d \equiv \mathrm{diag}\,(m_d, m_s, m_b)$$

$$U_{u_L}^\dagger\;M_u\;U_{uR} = D_u \equiv \mathrm{diag}\,(m_u, m_c, m_t)$$

Leptonic Sector

$$-\overline{L_L^0}\, \Pi_1 \Phi_1 \ell_R^0 - \overline{L_L^0}\, \Pi_2 \Phi_2 \ell_R^0 + h.c.$$

$$\left(-\overline{L_L^0}\, \Sigma_1 \tilde{\Phi}_1 \nu_R^0 - \overline{L_L^0}\, \Sigma_2 \tilde{\Phi}_2 \nu_R^0 + h.c \right)$$

$$\left(\frac{1}{2} \nu_R^{0\,T} C^{-1} M_R \nu_R^0 + h.c \right)$$

Expansion around the vev's

$$\phi_j = \begin{pmatrix} \phi_j^+ \\ \frac{e^{i\alpha_j}}{\sqrt{2}} (v_j + \rho_j + i\eta_j) \end{pmatrix}, \quad j = 1,2$$

we perform the following transformation

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = U \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} ; \quad \begin{pmatrix} G^0 \\ I \end{pmatrix} = U \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} ; \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$U = \frac{1}{v} \begin{pmatrix} v_1 e^{-i\alpha_1} & v_2 e^{-i\alpha_2} \\ v_2 e^{-i\alpha_1} & -v_1 e^{-i\alpha_2} \end{pmatrix} ; \quad v = \sqrt{v_1^2 + v_2^2} = \left(\sqrt{2}\, G_F\right)^{-1/2} \simeq 246\,\mathrm{GeV}$$

U singles out

H^0 with couplings to quarks proportional to mass matrices

G^0 neutral pseudo-goldstone boson

G^+ charged pseudo-goldstone boson

Physical neutral Higgs fields are combinations of H^0, R and I

Neutral and charged Higgs interactions for the quark sector

$$\mathcal{L}_Y(\text{quark, Higgs}) = -\bar{d}_L^0 \frac{1}{v}\left(M_d H^0 + N_d^0 R + i N_d^0 I\right) d_R^0 +$$

$$+\bar{u}_L^0 \frac{1}{v}\left[M_u H^0 + N_u^0 R + i N_u^0 I\right) u_R^0 +$$

$$+\frac{\sqrt{2}H^+}{v}\left(\bar{u}_L^0 N_d^0 d_R^0 - \bar{u}_R^0 N_u^{0\dagger} d_L^0\right) + h.c.$$

$$N_d^0 = \frac{1}{\sqrt{2}}\left(v_2 \Gamma_1 - v_1 e^{i\alpha}\Gamma_2\right), \quad N_u^0 = \frac{1}{\sqrt{2}}\left(v_2 \Delta_1 - v_1 e^{-i\alpha}\Delta_2\right)$$

Flavour structure of quark sector of 2HDM characterized by

M_d, M_u, N_d^0, N_u^0

likewise leptonic sector, Dirac neutrinos

M_ℓ, M_ν, N_ℓ^0, N_ν^0

Yukawa couplings in terms of quark mass eigenstates for H^+, H^0, R, I

$$\mathcal{L}_Y = \ldots \sqrt{2}\,\frac{H^+}{v}\,\bar{u}\left(-V N_d \gamma_R + N_u^\dagger V \gamma_L\right) d \;+ h.c. \;-$$

$$- \frac{H^0}{v}\left(\bar{u} D_u u + \bar{d} D_d d\right) -$$

$$- \frac{R}{v}\left[\bar{u}\left(N_u \gamma_R + N_u^\dagger \gamma_L\right) u + \bar{d}\left(N_d \gamma_R + N_d^\dagger \gamma_L\right) d\right] +$$

$$+ i\,\frac{I}{v}\left[\bar{u}\left(N_u \gamma_R - N_u^\dagger \gamma_L\right) u - \bar{d}\left(N_d \gamma_R - N_d^\dagger \gamma_L\right) d\right]$$

$\gamma_L = (1-\gamma_5)/2$; $\gamma_R = (1+\gamma_5)/2$ $\qquad V \equiv V_{CKM}$

Flavour changing neutral currents controlled by:

$$N_d = \frac{1}{\sqrt{2}} U_{d_L}^{\dagger} \left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2 \right) U_{d_R}$$

$$N_u = \frac{1}{\sqrt{2}} U_{u_L}^{\dagger} \left(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2 \right) U_{u_R}$$

For generic two Higgs doublet models
N_u, N_d non-diagonal arbitrary

For definiteness rewrite N_d :

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}$$

conserves flavour

leads to FCNC

The flavour structure of Yukawa couplings is not constrained by gauge invariance

All flavour changing transition in SM are mediated by charged weak currents with flavour mixing controlled by V_{CKM}

MFV essentially requires flavour and CP violation linked to known structures of Yukawa couplings

[all new flavour changing transitions are controlled by the CKM matrix]

About Minimal Flavour Violation

Buras, Gambino, Gorbahn, Jager, Silvestrini (2001)
D'Ambrosio, Giudice, Isidori, Strumia (2002)

leptonic sector

Cirigliano, Grinstein, Isidori, Wise (2005)

$G_F = U(3)^5$ largest symmetry of the gauge sector
flavour violation completely determined by Yukawa couplings

Our framework
- multi - Higgs models
- no Natural Flavour Conservation
- must obey above condition (one of the defining ingredients of MFV framework)

In order to obtain a structure for Γ_i, Δ_i such that FCNC at tree level strength completely controlled V_{CKM}

Branco, Grimus, Lavoura imposed symmetry

$$Q^0_{L_j} \to \exp(i\tau) Q^0_{L_j} \; ; \; u^0_{R_j} \to \exp(2i\tau) u^0_{R_j} \; ; \; \Phi_2 \to \exp(i\tau) \Phi_2 \, , \; \tau \neq 0, \pi$$

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} ; \; \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix} ; \; \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} ; \; \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$j = 3$

Both Higgs have non-zero Yukawa couplings in the up and down sector

Special WB chosen by the symmetry

FCNC in down sector

if instead of $u^0_{R_j} \to \exp(2i\tau) u^0_{R_j}$ impose $d^0_{R_j} \to \exp(2i\tau) d^0_{R_j}$

then FCNC in up sector

Six different BGL models

$$(N_d)_{rs} = \frac{v_2}{v_1}(D_d)_{rs} - \left(\frac{v_2}{v_1}+\frac{v_1}{v_2}\right)\underbrace{(V_{CKM}^{\dagger})_{r3}(V_{CKM})_{3s}}_{MFV}(D_d)_{ss}$$

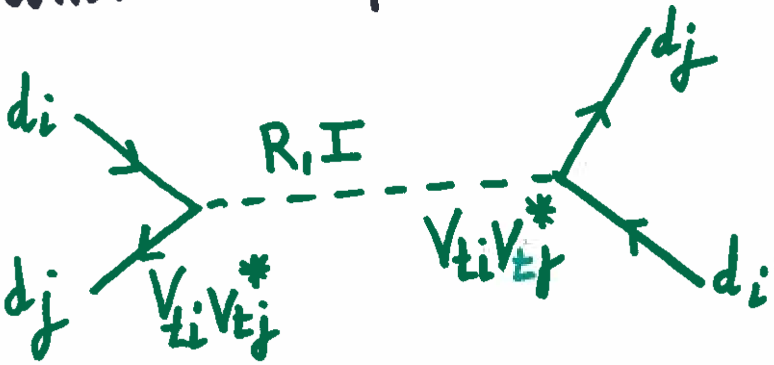
$$j = 3$$

$$N_u = -\frac{v_1}{v_2}\,\mathrm{diag}(0,0,m_t) + \frac{v_2}{v_1}\,\mathrm{diag}(m_u, m_c, 0)$$

FCNC only in the down sector
suppression by the 3rd row of V_{CKM}
dependence on V_{CKM} and $\tan\beta$ only

Strong and Natural suppression of the most constrained processes

e.g. $|V_{td}V_{ts}^{*}|^2 \sim \lambda^{10}$



Neutral couplings in BGL models

$$N_u = -\frac{v_1}{v_2}\mathrm{diag}(0,0,m_t) + \frac{v_2}{v_1}\mathrm{diag}(m_u,m_c,0)$$

Explicitely

$$N_d = \frac{v_2}{v_1}\begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

$$+\left(\frac{v_1}{v_2}+\frac{v_2}{v_1}\right)\begin{pmatrix} m_d|V_{31}|^2 & m_s V_{31}^* V_{32} & m_b V_{31}^* V_{33} \\ m_d V_{32}^* V_{31} & m_s|V_{32}|^2 & m_b V_{32}^* V_{33} \\ m_d V_{33}^* V_{31} & m_s V_{33}^* V_{32} & m_b|V_{33}|^2 \end{pmatrix}$$

It all comes from the symmetry

What is the necessary condition for N_d^0, N_u^0 to be of MFV type?

Should be functions of M_d, M_u no other flavour dependence

Furthermore, N_d^0, N_u^0 should transform appropriately under WB

$$Q_L^0 \to W_L Q_L^0 \quad , \quad d_R^0 \to W_R^d \, d_R^0 \quad , \quad u_R^0 \to W_R^u \, u_R^0$$

$$M_d \to W_L^\dagger M_d W_R^d \quad , \quad M_u \to W_L^\dagger M_u W_R^u$$

N_d^0, N_u^0 transform as M_d, M_u

$$N_d^0 \propto M_d \; ; \; (M_d M_d^\dagger) M_d \; ; \; (M_u M_u^\dagger) M_d$$

$$Y_d \; ; \; (Y_d Y_d^\dagger) Y_d \; ; \; (Y_u Y_u^\dagger) Y_d \quad \text{Yukawa}$$

see previous references

What is particular about BGL models in MFV context?

$$M_d M_d^\dagger \equiv H_d \quad ; \quad U_{d_L}^\dagger M_d U_{d_R} = D_d \quad ; \quad U_{d_L}^\dagger H_d U_{d_L} = D_d^2$$

$$D_d^2 = \mathrm{diag}(m_d^2, m_s^2, m_b^2) = m_d^2 \underbrace{\begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}}_{P_1} + m_s^2 \underbrace{\begin{pmatrix} 0 & & \\ & 1 & \\ & & 0 \end{pmatrix}}_{P_2} + m_b^2 \underbrace{\begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}}_{P_3}$$

$$D_d^2 = \sum_i m_{d_i}^2 P_i$$

$$H_d = U_{d_L} D_d^2 U_{d_L}^\dagger = \sum_i m_{d_i}^2 U_{d_L} P_i U_{d_L}^\dagger = \sum_i m_{d_i}^2 P_i^{d_L}$$

$U_{d_L} P_i U_{d_L}^\dagger$ rather than $Y_d Y_d^\dagger$ are the minimal building blocks to be used in the expansion of N_d^0, N_u^0 conforming to the MFV requirement

Botella, Nebot, Vives 2004

WB covariant definition for BGL models

$$N_d^0 = \frac{v_2}{v_1} M_d - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) P_j^\gamma M_d$$

$$N_u^0 = \frac{v_2}{v_1} M_u - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) P_j^\gamma M_u$$

together with

$$P_j^\gamma \Gamma_2 = \Gamma_2 \quad , \quad P_j^\gamma \Gamma_1 = 0$$

$$P_j^\gamma \Delta_2 = \Delta_2 \quad , \quad P_j^\gamma \Delta_1 = 0$$

γ stands for u (up) or d (down)

P_j^γ are projection operators   Botella, Nebot, Vives 2004

$$P_j^u = U_{uL} P_j U_{uL}^\dagger \qquad P_j^d = U_{dL} P_j U_{dL}^\dagger$$

$$(P_j)_{lk} = \delta_{jl}\delta_{jk} \qquad \text{e.g. } P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

BGL is the only implementation of models where Higgs FCNC are a function of V_{CKM} only (together with v_1, v_2) which are based on an Abelian symmetry obeying the sufficient conditions of having M_u block diagonal together with the existence of a matrix P such that

$$P\Gamma_2 = \Gamma_2 \quad ; \quad P\Gamma_1 = 0$$

Ferreira, Silva arXiv: 1012287

Flavour structure (quark sector)

M_d, M_u, N_d^0, N_u^0

Freedom of choice of WB

Zero textures are WB dependent

Symmetries are only apparent in particular WB

WB transformations do not change the physics

Symmetries have physical implications

Above four matrices encode breaking of flavour symmetry present in gauge sector

large redundancy of parameters

WB invariants are very useful to study flavour

$I_1 \equiv \mathrm{tr}\left(M_d N_d^{0\dagger} \right) = m_d (N_d^*)_{11} + m_s (N_d^*)_{22} + m_b (N_b^*)_{33}$

not sensitive to HFCNC

$\mathrm{Im}\, I_1$ probes phases of $(N_d)_{jj}$ (electric dipole moment d quarks)

$I_2 \equiv \mathrm{tr}\left[M_d N_d^0 , M_d M_d^\dagger \right]^2$ sensitive to off-diag elements N_d

$I_1^{CP} \propto \mathrm{Im}\, Q_{uscb}$, $V_{CKM} = U_{u_L}^\dagger U_{d_L}$

$U_{u_L} \neq U_{d_L}$ misalignment of the matrices H_d, H_u

analogously

$I_3^{CP} \equiv \mathrm{tr}\left[H_d , H_{N_d^0} \right]^3 = 6i\, \Delta_d \Delta_{N_d} \mathrm{Im}\, Q_3$, $V_3 \equiv U_{d_L}^\dagger U_{N_d^0 L}$

$H_{N_d^0} = N_d^0 N_d^{0\dagger}$

$I_2^{CP} \equiv \mathrm{tr}\left[H_u , H_{N_d^0} \right]^3 = 6i\, \Delta_u \Delta_{N_d} \mathrm{Im}\, Q_2$, $V_2 = U_{u_L}^\dagger U_{N_d^0 L}$

$I_6^{CP} \equiv \mathrm{tr}\left[H_{N_d^0} , H_{N_u^0} \right]^3$

and many more

V_{CKM}, V_2, V_3 signal misalignment in flavour space of Hermitian matrices constructed in the framework of 2HDM

So far, we have only written invariants which are sensitive to left-handed mixings

One can construct analogous invariants which are sensitive to right-handed mixings, like:

$$I_7^{CP} \equiv \mathrm{Tr}\left[H_d', H_{N_d^0}' \right]^3 = 6i\, \Delta_d \Delta_{N_d}\, \mathrm{Im}\, Q_7$$

$H_d' = M_d^\dagger M_d \quad , \quad H_{N_d^0}' = N_d^{0\dagger} N_d^0$

Q_7 rephasing invariant quartet of $U_{dR} U_{N_{dR}^0}^\dagger$

and again many more

The Minimal Flavour Violation Case

Lowest invariant sensitive to CP violation

$$I_q^{CP} \equiv \mathrm{Im}\,\mathrm{tr}\left[M_d N_d^{0\dagger} M_d M_d^\dagger M_u M_u^\dagger M_d M_d^\dagger \right]$$

must contain flavour matrices from the up and down sector

lower order in powers of mass than SM case ($\mathrm{tr}\,[H_u, H_d]^3 \propto 12$)

BGL type models have richer flavour structure parametrized by four matrices

$$I_q^{CP}(\gamma = u,\ i=3) = -\left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times$$

FCNC in down sector, P_3

$$\times (m_c^2 - m_u^2)\, \mathrm{Im}\left(V_{22}^* V_{32} V_{33}^* V_{23}\right)$$

I_q^{CP} controlled by V_{CKM} (BGL)

$I_q^{CP} \neq 0$ even if $m_t = m_c$ or $m_t = m_u$ since discrete symmetry singles out top quark

I_q^{CP} can be related to baryon asymmetry generated at EW phase transition

How to recognize a BGL (type model)?

The following relations

$$\Delta_1^\dagger \Delta_2 = 0 ; \quad \Delta_1 \Delta_2^\dagger = 0 ; \quad \Gamma_1^\dagger \Delta_2 = 0 ; \quad \Gamma_2^\dagger \Delta_1 = 0$$

are necessary and sufficient conditions for a set of Yukawa matrices Γ_i, Δ_i to be of BGL type, with Higgs mediated FCNC in the down sector

Similarly, for the leptonic sector,

In the leptonic sector, with Dirac type neutrinos, there is perfect analogy with the quark sector. The requirement that FCNC at tree level have strength completely controlled by the Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix, U is enforced by one of the following symmetries. Either

$$L^0_{Lk} \to \exp(i\tau)\ L^0_{Lk}\ , \qquad \nu^0_{Rk} \to \exp(i2\tau)\nu^0_{Rk}\ , \qquad \Phi_2 \to \exp(i\tau)\Phi_2\ ,$$

or $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \tau \neq 0, \pi$

$$L^0_{Lk} \to \exp(i\tau)\ L^0_{Lk}\ , \qquad \ell^0_{Rk} \to \exp(i2\tau)\ell^0_{Rk}\ , \qquad \Phi_2 \to \exp(-i\tau)\Phi_2\ ,$$

which imply

$$\mathcal{P}^\beta_k \Pi_2 = \Pi_2\ , \qquad \mathcal{P}^\beta_k \Pi_1 = 0\ ,$$
$$\mathcal{P}^\beta_k \Sigma_2 = \Sigma_2\ , \qquad \mathcal{P}^\beta_k \Sigma_1 = 0\ ,$$

where β stands for neutrino (ν) or for charged lepton (ℓ) respectively. In this case

$$\mathcal{P}^\ell_k = U_{\ell L} P_k U^\dagger_{\ell L}\ , \qquad \mathcal{P}^\nu_k = U_{\nu L} P_k U^\dagger_{\nu L}\ ,$$

where $U_{\nu L}$ and $U_{\ell L}$ are the unitary matrices that diagonalize the corresponding square mass matrices

$$U^\dagger_{\ell L} M_\ell M^\dagger_\ell U_{\ell L} = \mathrm{diag}\left(m^2_e, m^2_\mu, m^2_\tau\right)\ ,$$
$$U^\dagger_{\nu L} M_\nu M^\dagger_\nu U_{\nu L} = \mathrm{diag}\left(m^2_{\nu_1}, m^2_{\nu 2}, m^2_{\nu 3}\right)\ ,$$

$$M_\ell = \frac{1}{\sqrt{2}}(v_1 \Pi_1 + v_2 e^{i\theta} \Pi_2)\ , \quad M_\nu = \frac{1}{\sqrt{2}}(v_1 \Sigma_1 + v_2 e^{-i\theta} \Sigma_2)\ .$$

Scalar Potential

The softly broken Z_2 symmetric 2HDM potential

$$V(\Phi_1,\Phi_2) = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - \left(m_{12}^2 \phi_1^\dagger \phi_2 + h.c.\right) + \frac{1}{2}\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2$$

$$+ \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right) + \frac{1}{2}\left[\lambda_5 \left(\phi_1^\dagger \phi_2\right)^2 + h.c.\right]$$

$$\phi_1 \to \phi_1 \, , \quad \phi_2 \to -\phi_2$$

in our case $\phi_1 \to \phi_1$, $\phi_2 \to e^{i\tau} \phi_2$, $\tau \neq 0, \pi$ no λ_5 term

V does not violate CP neither explicitly nor spontaneously

7 free parameters : m_h, m_H, m_A, $m_{H^\pm}$, $v = \sqrt{v_1^2 + v_2^2}$, $\tan\beta$, α (H^0, R)

soft symmetry breaking prevents ungauged accidental continuous symmetry

In BGL models the Higgs potential is constrained by the imposed symmetry to be of the form:

$$\begin{aligned} V_\Phi = & \, \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 - \left(m_{12} \Phi_1^\dagger \Phi_2 + \text{ h.c. } \right) + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) \\ & + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 , \end{aligned}$$

Hermiticity would allow the coefficient
m_{12} to be complex, unlike the other coefficients of the scalar potential. However, freedom to rephase the scalar doublets allows to choose without loss of generality all coefficients real. As a result, V_Φ does not violate CP explicitly. It can also be easily shown that it cannot violate CP spontaneously. In the absence of CP violation the scalar field I does not mix with the fields R and H^0, therefore I is already a physical Higgs and the mixing of R and H^0 is parametrized by a single angle. There are two important rotations that define the two parameters, $\tan\beta$ and α, widely used in the literature:

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = \frac{1}{v} \begin{pmatrix} v_1 & v_2 \\ -v_2 & v_1 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

Our analysis:

Approximation of no mixing between R and H^0

We identify H^0 with the recently discovered Higgs field

This limit corresponds to $\beta - \alpha = \pi/2$

$v \equiv \sqrt{v_1^2 + v_2^2}$, $\tan\beta \equiv v_2/v_1$, **the quantity v is of course fixed by experiment**

Electroweak precision tests and in particular the T and S parameters lead to constraints relating the masses of the new Higgs fields among themselves

Grimus, Lavoura, Ogreid, Osland 2008

The bounds on T and S together with direct mass limits significantly restrict the masses of the new Higgs particles once the mass of charged Higgs is fixed

It is instructive to plot our results in terms of $m_{H^\pm}$ versus $\tan\beta$,

since in this context there is not much freedom left

	BGL - 2HDM				SM	
	Charged $H^{\pm}$		Neutral R, I		Tree	Loop
	Tree	Loop	Tree	Loop		
$M \to \ell\bar{\nu}, M'\ell\bar{\nu}$	✔	✓		✓	✔	✓
Universality	✔	✓		✓	✔	✓
$M^0 \to \ell_1^+\ell_2^-$		✓	✔	✓		✔
$M^0 \rightleftarrows \bar{M}^0$		✓	✔	✓		✔
$\ell_1^- \to \ell_2^-\ell_3^+\ell_4^-$		✓	✔	✓		✓
$B \to X_s\gamma$		✔		✔		✔
$\ell_j \to \ell_i\gamma$		✔		✔		✓
EW Precision		✔		✔		✔

Summary of relevant constraints

$\|g_\mu/g_e\|^2$	$1.0018(14)$	$\|g^S_{RR,\tau\mu}\|$	< 0.72
$\|g^S_{RR,\tau e}\|$	< 0.70	$\|g^S_{RR,\mu e}\|$	< 0.035
$\mathrm{Br}(B^+ \to e^+\nu)$	$< 9.8 \cdot 10^{-7}$	$\mathrm{Br}(D_s^+ \to e^+\nu)$	$< 1.2 \cdot 10^{-4}$
$\mathrm{Br}(B^+ \to \mu^+\nu)$	$< 1.0 \cdot 10^{-6}$	$\mathrm{Br}(D_s^+ \to \mu^+\nu)$	$5.90(33) \cdot 10^{-3}$
$\mathrm{Br}(B^+ \to \tau^+\nu)$	$1.15(23) \cdot 10^{-4}$	$\mathrm{Br}(D_s^+ \to \tau^+\nu)$	$5.43(31) \cdot 10^{-2}$
$\mathrm{Br}(D^+ \to e^+\nu)$	$< 8.8 \cdot 10^{-6}$		
$\mathrm{Br}(D^+ \to \mu^+\nu)$	$3.82(33) \cdot 10^{-4}$		
$\mathrm{Br}(D^+ \to \tau^+\nu)$	$< 1.2 \cdot 10^{-3}$		
$\frac{\Gamma(\pi^+\to e^+\nu)}{\Gamma(\pi^+\to\mu^+\nu)}$	$1.230(4) \cdot 10^{-4}$	$\frac{\Gamma(\tau^-\to\pi^-\nu)}{\Gamma(\pi^+\to\mu^+\nu)}$	$9703(54)$
$\frac{\Gamma(K^+\to e^+\nu)}{\Gamma(K^+\to\mu^+\nu)}$	$2.488(12) \cdot 10^{-5}$	$\frac{\Gamma(\tau^-\to K^-\nu)}{\Gamma(K^+\to\mu^+\nu)}$	$469(7)$
$\frac{\Gamma(B\to D\tau\nu)_{\mathrm{NP}}}{\Gamma(B\to D\tau\nu)_{\mathrm{SM}}}$		$\log C\ (K \to \pi\ell\nu)$	$0.194(11)$
$\frac{\Gamma(B\to D^*\tau\nu)_{\mathrm{NP}}}{\Gamma(B\to D^*\tau\nu)_{\mathrm{SM}}}$			

Tree level $H^\pm$ mediated processes

$\mathrm{Br}(\tau^- \to e^- e^- e^+)$	$< 2.7 \cdot 10^{-8}$	$\mathrm{Br}(\tau^- \to \mu^- \mu^- \mu^+)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{Br}(\tau^- \to e^- e^- \mu^+)$	$< 1.5 \cdot 10^{-8}$	$\mathrm{Br}(\tau^- \to e^- \mu^- e^+)$	$< 1.8 \cdot 10^{-8}$
$\mathrm{Br}(\tau^- \to \mu^- \mu^- e^+)$	$< 1.7 \cdot 10^{-8}$	$\mathrm{Br}(\tau^- \to \mu^- e^- \mu^+)$	$< 2.7 \cdot 10^{-8}$
$\mathrm{Br}(\mu^- \to e^- e^- e^+)$	$< 1 \cdot 10^{-12}$		
$\mathrm{Br}(K_L \to \mu^\pm e^\mp)$	$< 4.7 \cdot 10^{-12}$	$\mathrm{Br}(\pi^0 \to \mu^\pm e^\mp)$	$< 3.6 \cdot 10^{-10}$
$\mathrm{Br}(K_L \to e^- e^+)$	$< 9 \cdot 10^{-12}$		
$\mathrm{Br}(K_L \to \mu^- \mu^+)$	$< 6.84 \cdot 10^{-9}$		
$\mathrm{Br}(D^0 \to e^- e^+)$	$< 7.9 \cdot 10^{-8}$	$\mathrm{Br}(B^0 \to e^+ e^-)$	$< 8.3 \cdot 10^{-8}$
$\mathrm{Br}(D^0 \to \mu^\pm e^\mp)$	$< 2.6 \cdot 10^{-7}$	$\mathrm{Br}(B^0 \to \tau^\pm e^\mp)$	$< 2.8 \cdot 10^{-5}$
$\mathrm{Br}(D^0 \to \mu^- \mu^+)$	$< 1.4 \cdot 10^{-7}$	$\mathrm{Br}(B^0 \to \mu^- \mu^+)$	$3.6(1.6) \cdot 10^{-10}$
$\mathrm{Br}(B_s^0 \to e^+ e^-)$	$< 2.8 \cdot 10^{-7}$	$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp)$	$< 2.2 \cdot 10^{-5}$
$\mathrm{Br}(B_s^0 \to \mu^\pm e^\mp)$	$< 2 \cdot 10^{-7}$	$\mathrm{Br}(B^0 \to \tau^+ \tau^-)$	$< 4.1 \cdot 10^{-3}$
$\mathrm{Br}(B_s^0 \to \mu^- \mu^+)$	$2.9(0.7) \cdot 10^{-9}$		

Tree level R, I mediated processes (I)

$2\lvert M_{12}^K\rvert$	$< 3.5 \cdot 10^{-15}$ GeV	$2\lvert M_{12}^D\rvert$	$< 9.47 \cdot 10^{-15}$ GeV
$\lvert\epsilon_K\rvert_{NP}\Delta m_K$	$< 7.8 \cdot 10^{-19}$ GeV		
$\mathrm{Re}(\Delta_d)$	$0.823(143)$	$\mathrm{Re}(\Delta_s)$	$0.965(133)$
$\mathrm{Im}(\Delta_d)$	$-0.199(62)$	$\mathrm{Im}(\Delta_s)$	$0.00(10)$

Tree level R, I mediated processes (II)

$\mathrm{Br}(\mu \to e\gamma)$	$< 5.6 \cdot 10^{-13}$	$\mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}}^{\mathrm{NNLO}}$	$3.15(23) \cdot 10^{-4}$
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \cdot 10^{-8}$	$\mathrm{Br}(B \to X_s\gamma)$	$3.55(35) \cdot 10^{-4}$
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \cdot 10^{-8}$		
ΔT	$0.02(11)$	$F_{Zb\bar{b}}$	< 0.0024 GeV^{-1}
ΔS	$0.00(12)$		

Loop level R, I, $H^\pm$ mediated processes

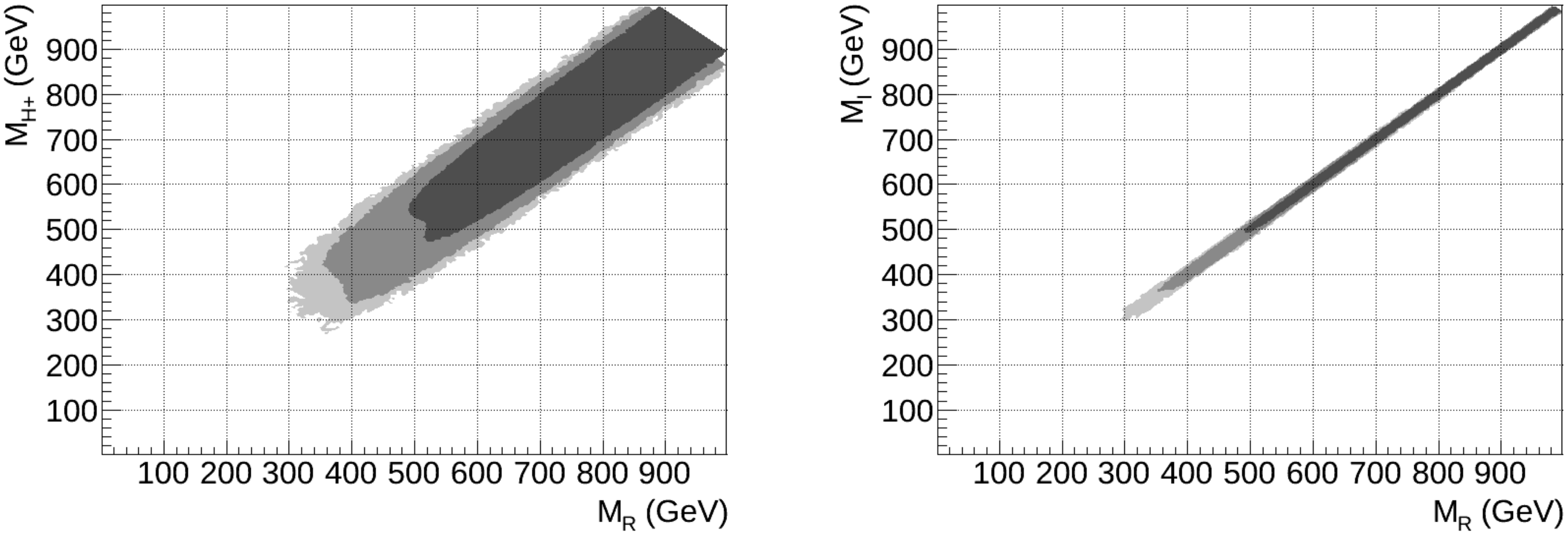
Each of the thirty six models labelled by the pair $(\gamma^{i}_{j}, \beta_{k})$

j, k refer to projectors $P_{j,k}$ in each sector γ^{i}, β

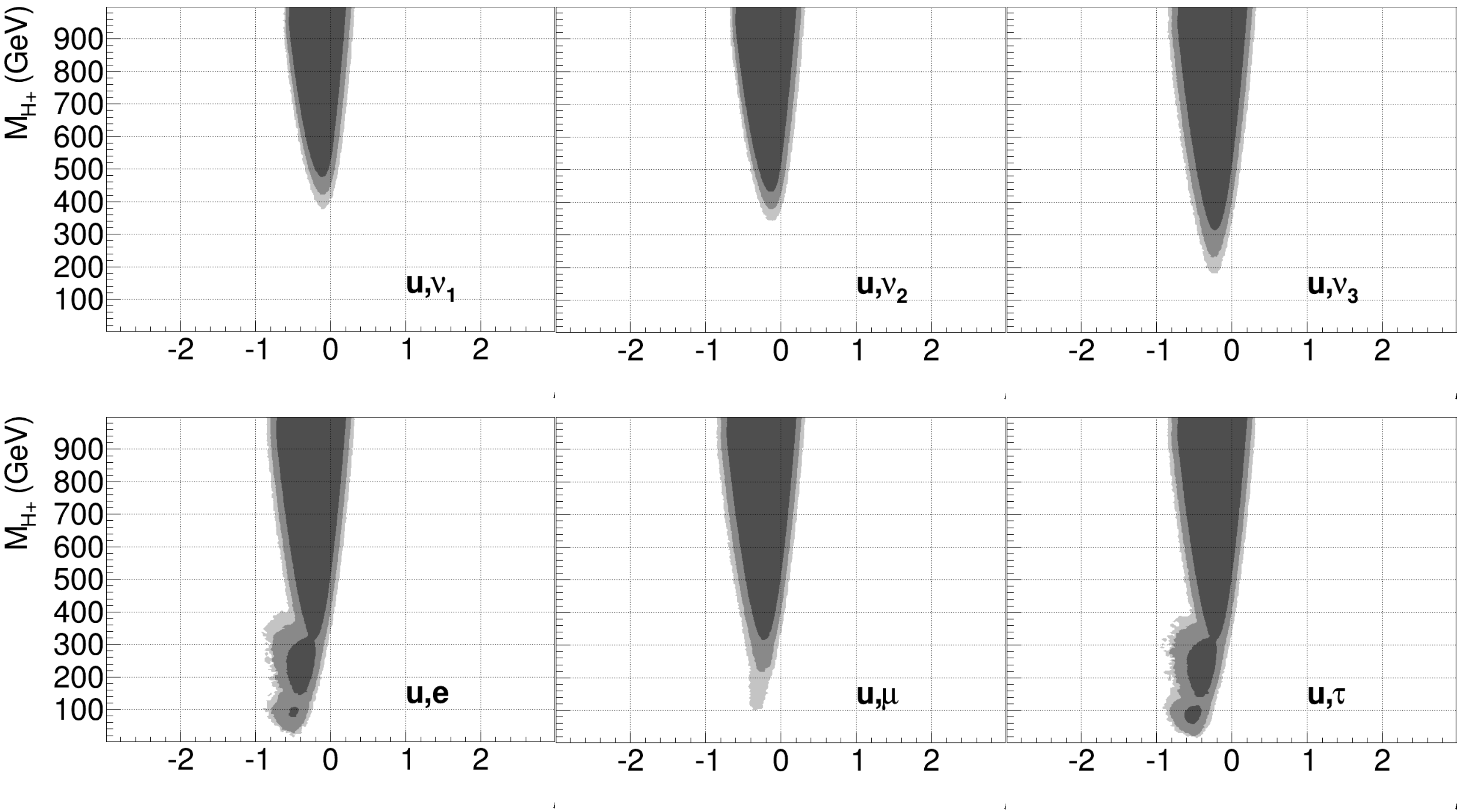
Example: $(up_3, \ell_2) = (t, \mu)$

will have no tree level NFC couplings (neutral flavour changing) in the up quark and charged lepton sectors, neutral HFC couplings in the down quark and neutrino sector controlled by

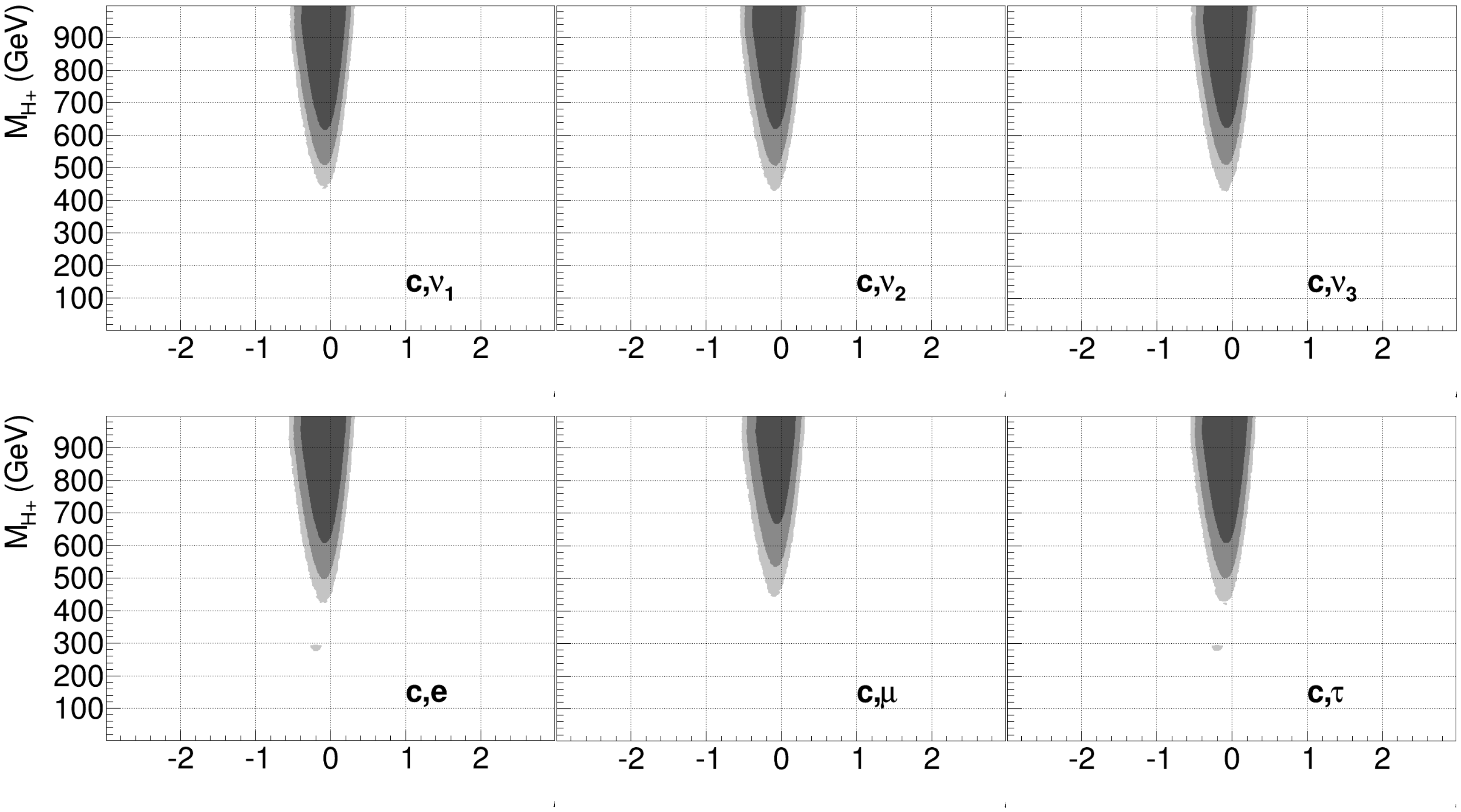
$$V_{td_i} V^{*}_{td_j} \quad \text{and} \quad U_{\mu\nu_a} U^{*}_{\mu\nu_b}$$



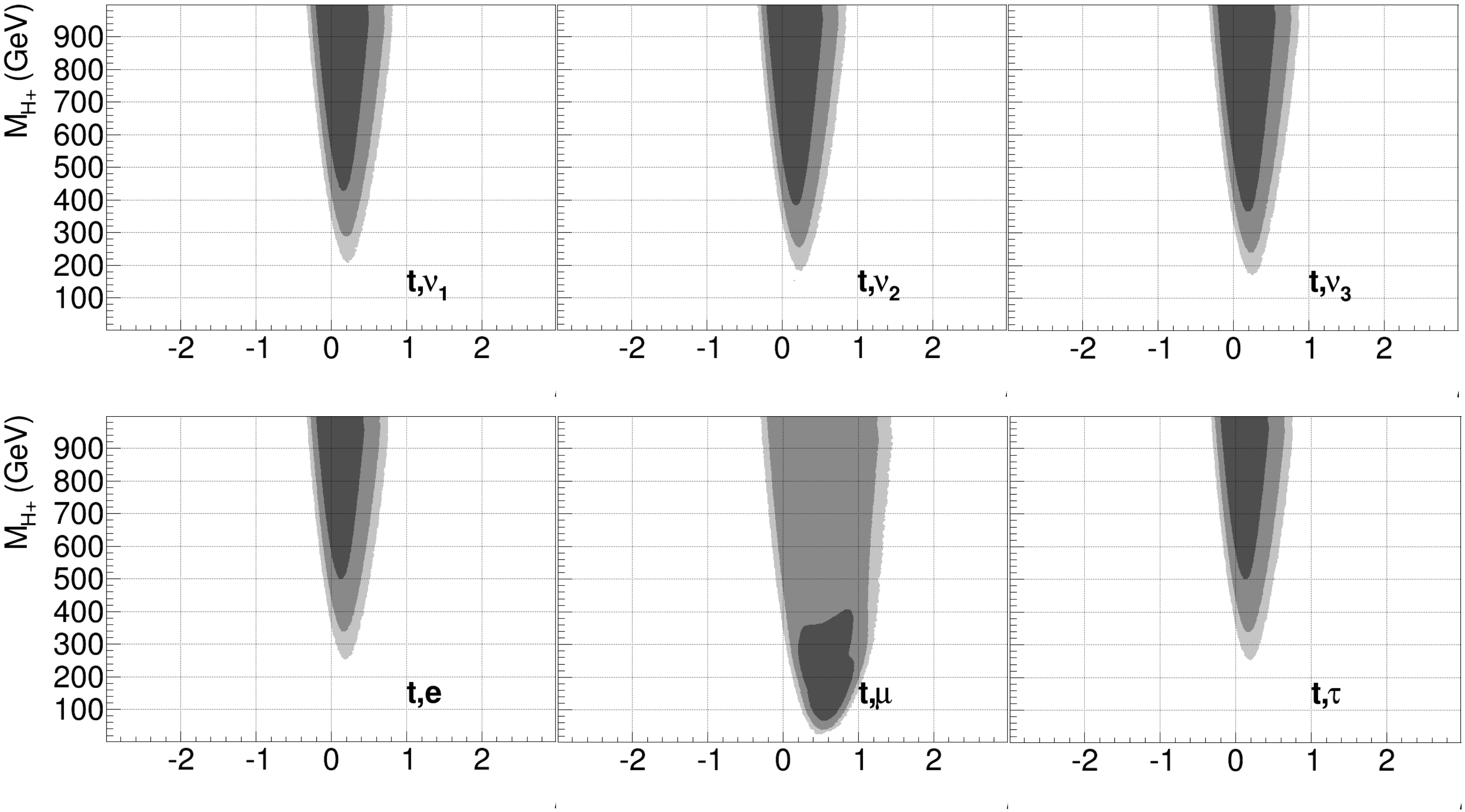
Effect of the oblique parameters constraints in model (t, τ)



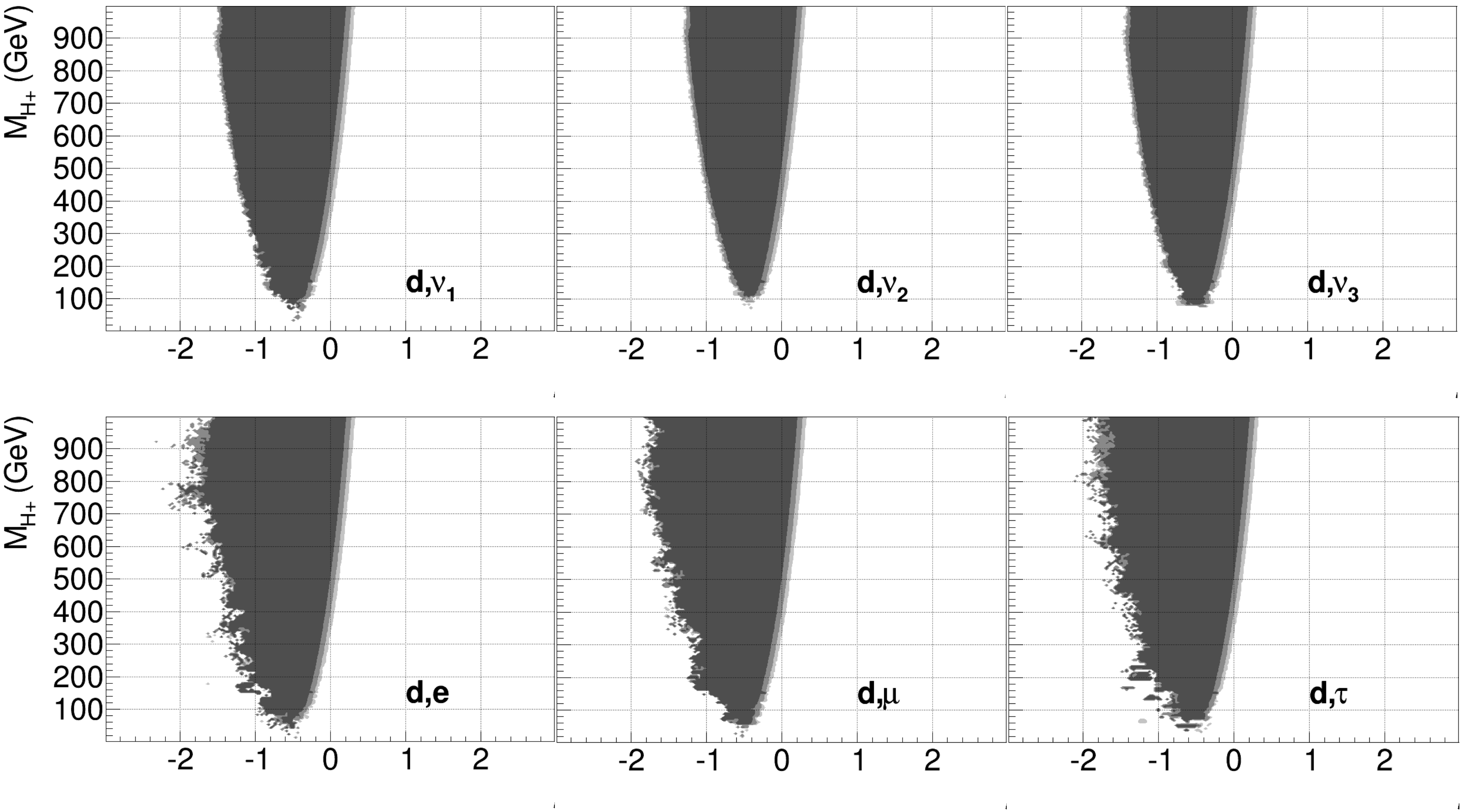
M_{H^+} vs. $\log_{10}(\tan\beta)$, u models



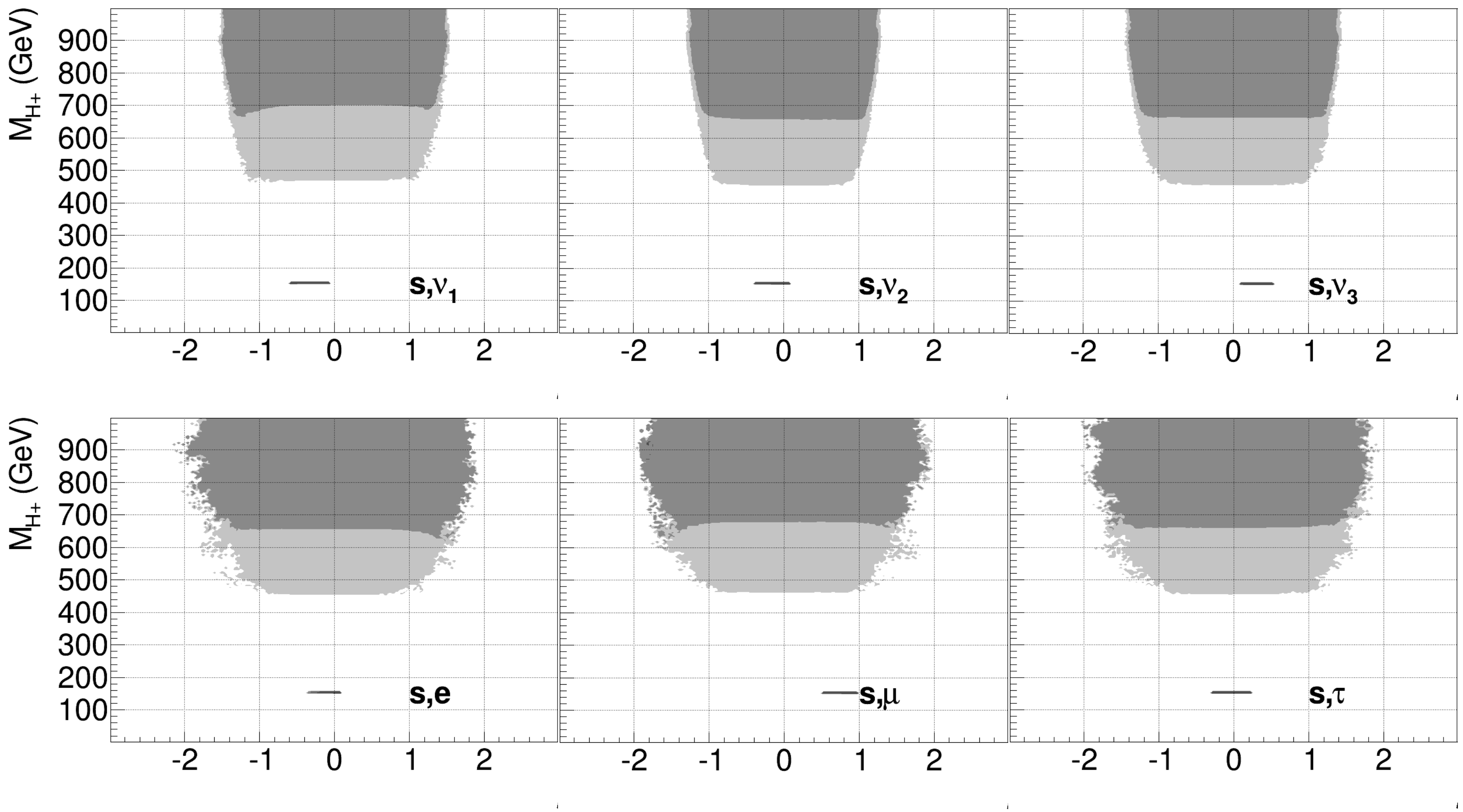
M_{H^+} vs. $\log_{10}(\tan\beta)$, c models



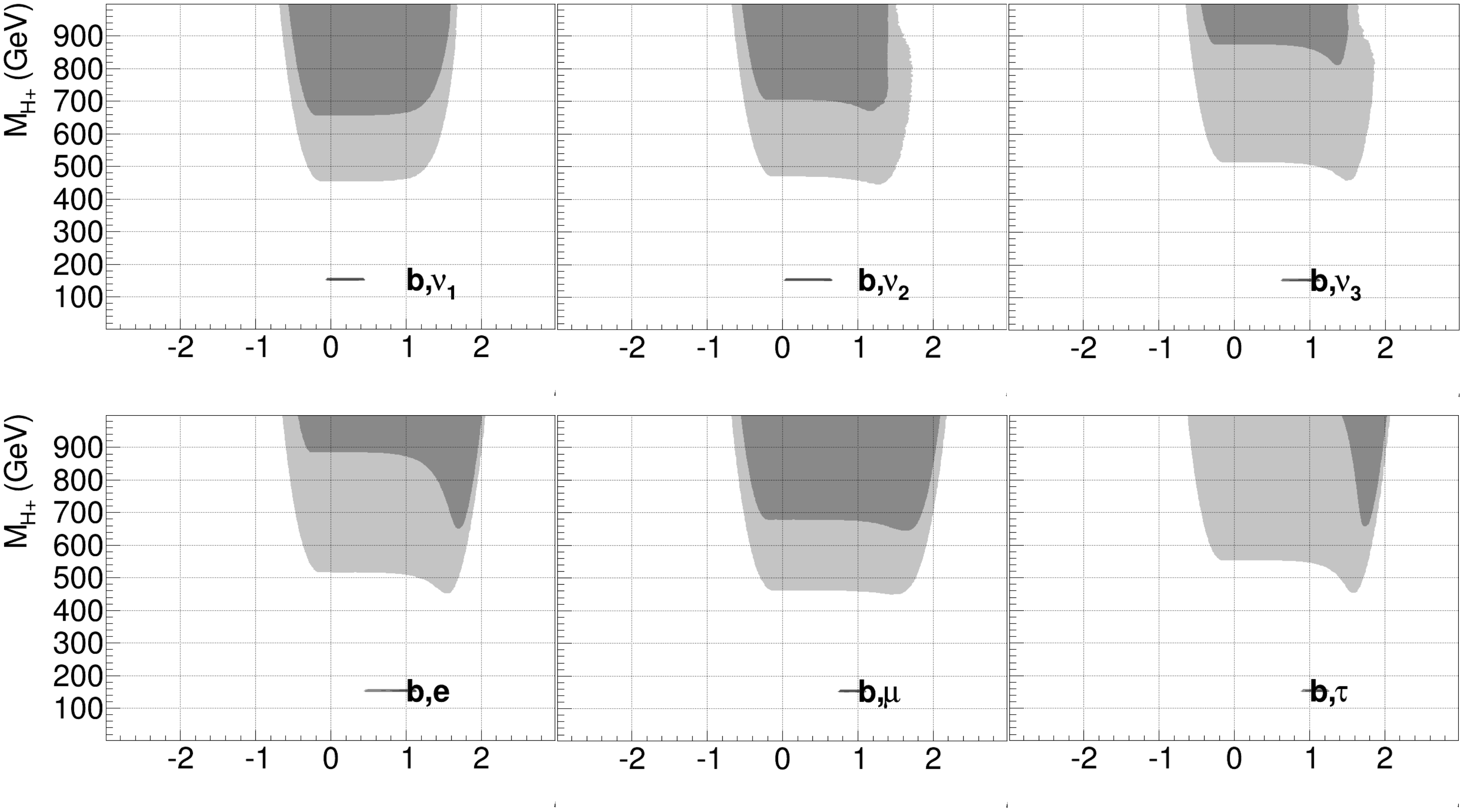
M_{H^+} vs. $\log_{10}(\tan\beta)$, t models



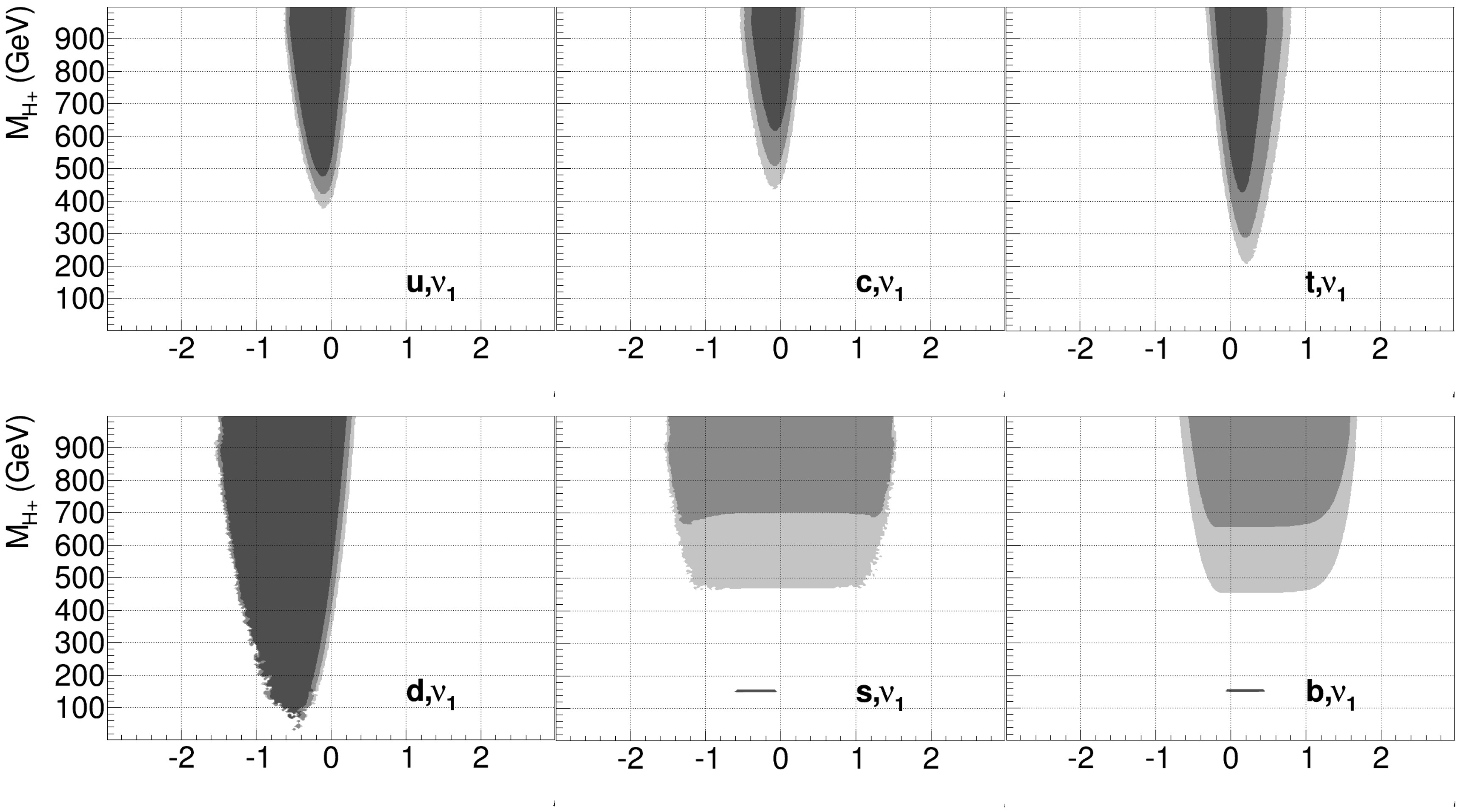
M_{H^+} vs. $\log_{10}(\tan\beta)$, d models



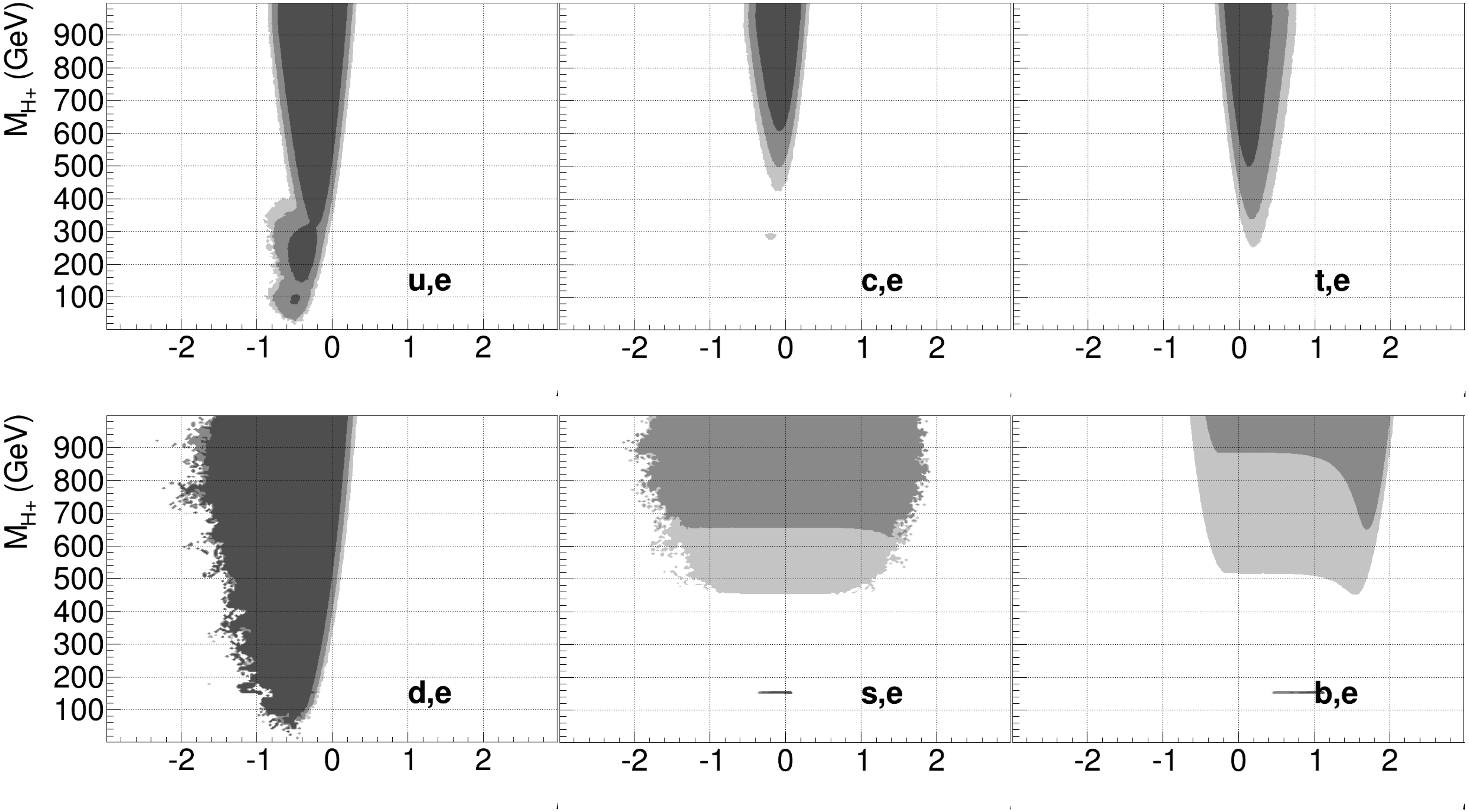
M_{H^+} vs. $\log_{10}(\tan\beta)$, s models



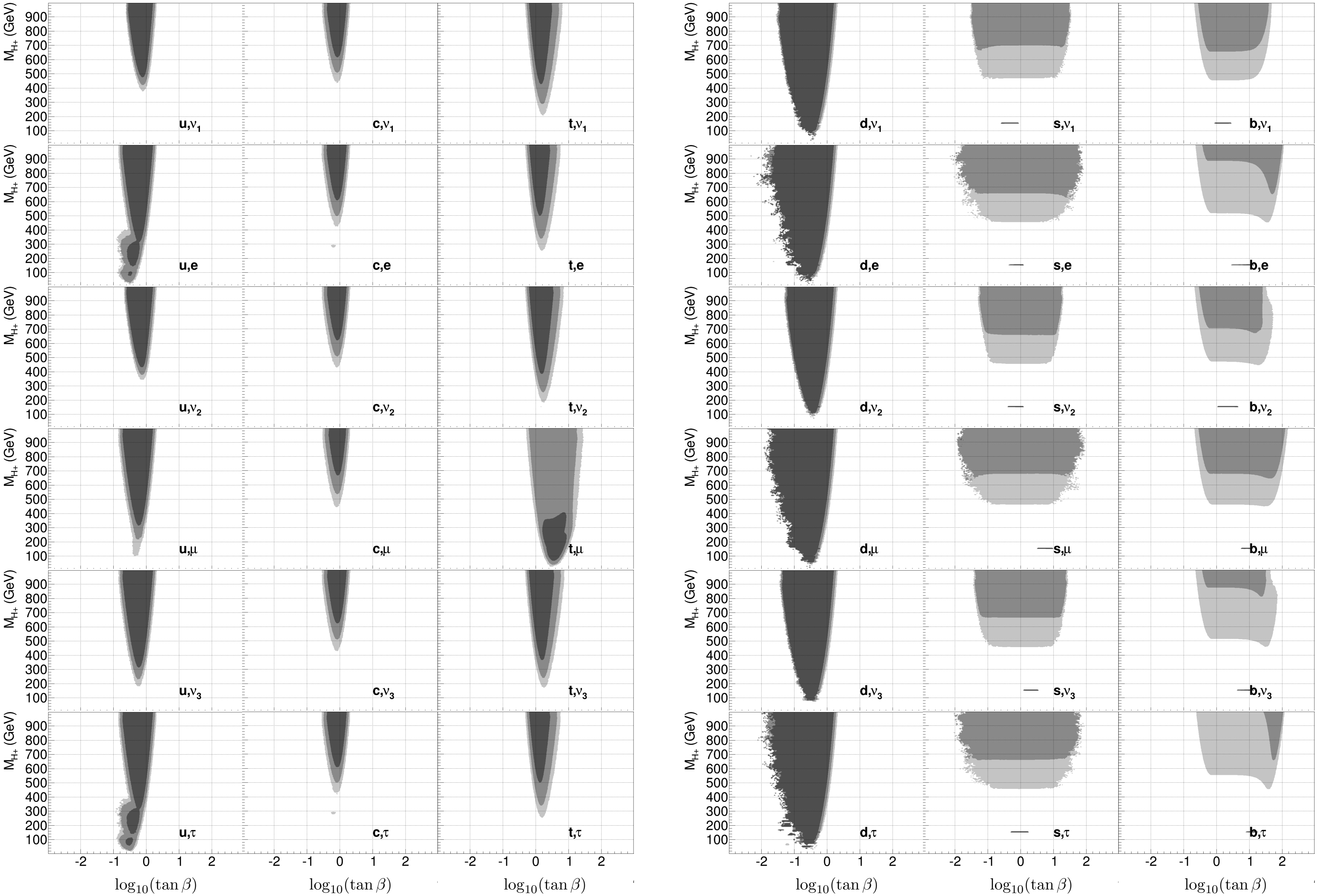
M_{H^+} vs. $\log_{10}(\tan\beta)$, b models



M_{H^+} vs. $\log_{10}(\tan\beta)$, ν_1 models



M_{H^+} vs. $\log_{10}(\tan\beta)$, e models



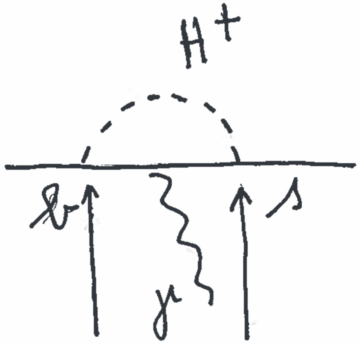
M_{H^+} (GeV)
100
200
300
400
500
600
700
800
900
u,ν_1
c,ν_1
t,ν_1
d,ν_1
s,ν_1
b,ν_1
u,e
c,e
t,e
d,e
s,e
b,e
u,ν_2
c,ν_2
t,ν_2
d,ν_2
s,ν_2
b,ν_2
u,μ
c,μ
t,μ
d,μ
s,μ
b,μ
u,ν_3
c,ν_3
t,ν_3
d,ν_3
s,ν_3
b,ν_3
u,τ
c,τ
t,τ
d,τ
s,τ
b,τ
-2
-1
0
1
2
$\log_{10}(\tan\beta)$

$m_{H^\pm} > 380$ GeV from $b \to s\gamma$ in type II 2HD

In BGL several of the models allow $m_{H^\pm} < 380$ GeV

In BGL $H^\pm$ dominates NP

$\tan\beta$ dependence $\{-1, \tan^2\beta, 1/\tan^2\beta\}$



$$\begin{pmatrix} t & & \\ & t & \\ & & -\frac{1}{t} \end{pmatrix}$$

in different positions

$t \quad t \sim t^2$
$t \quad -1/t \sim -1$ flat
$-\frac{1}{t} \quad -1/t \sim 1/t^2$

neutral scalars
- most cases, negligible contribution from R, I
- otherwise these two contributions tend to cancel out

Conclusions

HFCNC at tree level are not ruled out even allowing for scalar masses of the order of a few hundred Gev

There are several promising scenarios within the 36 models that were presented.

Bhattacharyya, Das, Kundu 2014

The LHC may bring us interesting surprises!

I thank Miguel Nebot for providing the slides with tables and plots taken from our joint paper