Supersymmetric Higgs boson with General Flavour Violation

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INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

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Outline

1. MSSM with General Flavour Violation

2. Impact of δ^{u}_{LR} on the Higgs boson mass

   a) Dependence on A_t

   b) Dependence on diagonal terms splitting

3. Experimental limits on δ^{u}_{LR}

4. Conclusions

MSSM with GFV

Minimal Flavour Violation → **General** Flavour Violation

SCKM basis

$$Y_u^{\mathrm{diag}} = V_R^u Y_u^T V_L^{u\dagger}$$

$$Y_{u,d}, \quad (m_u^2)_{LR}, \quad (m_q^2)_{LL}, \quad (m_u^2)_{RR}$$

diagonal

CKM – the only source of FV

$$(m_q^2)_{LL} = V_L^d m_q^2 V_L^{d\dagger}$$

$$(m_u^2)_{RR} = V_R^u m_u^2 V_R^{u\dagger}$$

$$(m_u^2)_{LR} = \frac{v_2}{\sqrt{2}} V_R^u (T_u) V_L^{u\dagger}$$

- off-diagonal terms appears if **diagonal non-universal** (~ mass splitting)
- non-zero arbitrary off-diagonal terms

MSSM with GFV

$$\mathcal{M}^2_{\tilde{u}} = \tilde{m}^2 \left(\begin{array}{ccc|ccc} \alpha_2 & (\delta^u_{12})_{LL} & (\delta^u_{13})_{LL} & 0 & (\delta^u_{21})_{LR} & (\delta^u_{31})_{LR} \\ (\delta^u_{12})_{LL} & \alpha_2 & (\delta^u_{23})_{LL} & (\delta^u_{12})_{LR} & 0 & (\delta^u_{32})_{LR} \\ (\delta^u_{13})_{LL} & (\delta^u_{23})_{LL} & \alpha_3 + \frac{m_t^2}{\tilde{m}^2} & (\delta^u_{13})_{LR} & (\delta^u_{23})_{LR} & \frac{\langle v_2 \rangle \tilde{X}_t}{\sqrt{2}\tilde{m}^2} \\ \hline 0 & (\delta^u_{12})_{LR} & (\delta^u_{13})_{LR} & \alpha_2 & (\delta^u_{12})_{RR} & (\delta^u_{13})_{RR} \\ (\delta^u_{21})_{LR} & 0 & (\delta^u_{23})_{LR} & (\delta^u_{23})_{RR} & \alpha_2 & (\delta^u_{23})_{RR} \\ (\delta^u_{31})_{LR} & (\delta^u_{32})_{LR} & \frac{\langle v_2 \rangle \tilde{X}_t}{\sqrt{2}\tilde{m}^2} & (\delta^u_{13})_{RR} & (\delta^u_{23})_{RR} & \alpha_3 + \frac{m_t^2}{\tilde{m}^2} \end{array}\right)$$

Off-diagonal entries:

$$(\delta^u_{ij})_{AB} = \frac{(m_u^2)^{ij}_{AB}}{\sqrt{(m_u^2)^{ii}_{BB}(m_u^2)^{jj}_{AA}}}$$

$$\tilde{X}_t = (T_u)_{33} - Y_t \mu \cot\beta$$

$$\tilde{m}_2 = \alpha_2 \tilde{m}$$

$$\tilde{m}_3 = \alpha_3 \tilde{m}$$

Possible non-universality

Higgs mass determination

$$m_h^2 = m_{h_{tree}}^2 + \Delta m_{h_{rad}}^2$$

1-loop radiative corrections:

Haber, Hempfling '93

1) Leading-logs resumed using RGEs

2) Non-log finite corrections due to squark mixing

$$\mathcal{M}_{\tilde{u}}^2 = \tilde{m}^2 \mathbb{I} + \mathcal{M}_T^2 + \mathcal{M}_F^2$$

F-term contribution ($\sim m_t^2$)

Trilinear term contribution

$$(\Delta V_1)_{\text{finite}} = \frac{3}{64\pi^2}\frac{1}{\tilde{m}^2}\left[\text{tr}((\mathcal{M}_T^2)^2\mathcal{M}_F^2) - \frac{1}{12\tilde{m}^2}\text{tr}(\mathcal{M}_T^2)^4\right]$$

Higgs mass with GFV

GFV effects in the Higgs sector also analyzed in:

- Heinemeyer, Hollik, Merz, Penaranda '04 - $(\delta_{LL})_{23}$
- Cao, Eilam, Hikasa, Yang '06 – $(\delta_{LL})_{23},(\delta_{RL})_{23}$, Higgs mass decrease
- Arana-Catania, Heinemeyer, Herrero, Penaranda '12
- Arana-Catania, Heinemeyer, Herrero '14

} $(\delta_{LL})_{23},(\delta_{RR})_{23},(\delta_{RL})_{23},$ possible enhancement observed

1-loop GFV structure implemented in:

FeynHiggs, Spheno, SoftSusy

Universal masses, A_t=0

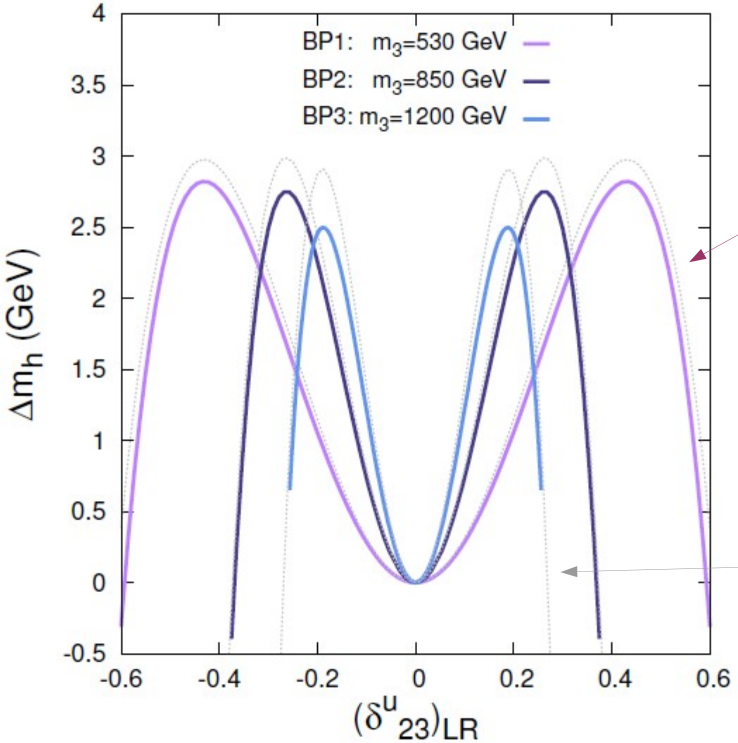
$$\Delta m_h^2((\delta^u_{23})_{LR}) = \frac{3}{4\pi^2}\left[\tilde{m}^2(\delta^u_{23})^2_{LR}\left(\frac{1}{2}Y_t^2\sin^2\beta - \frac{\tilde{m}^2(\delta^u_{23})^2_{LR}}{6v^2}\right)\right]$$

→ The same for δ^u_{13}

$$\Delta m_h^2((\delta^u_{12})_{LR}) = -\frac{3}{24\pi^2 v^2}\tilde{m}^4(\delta^u_{12})^4_{LR}$$

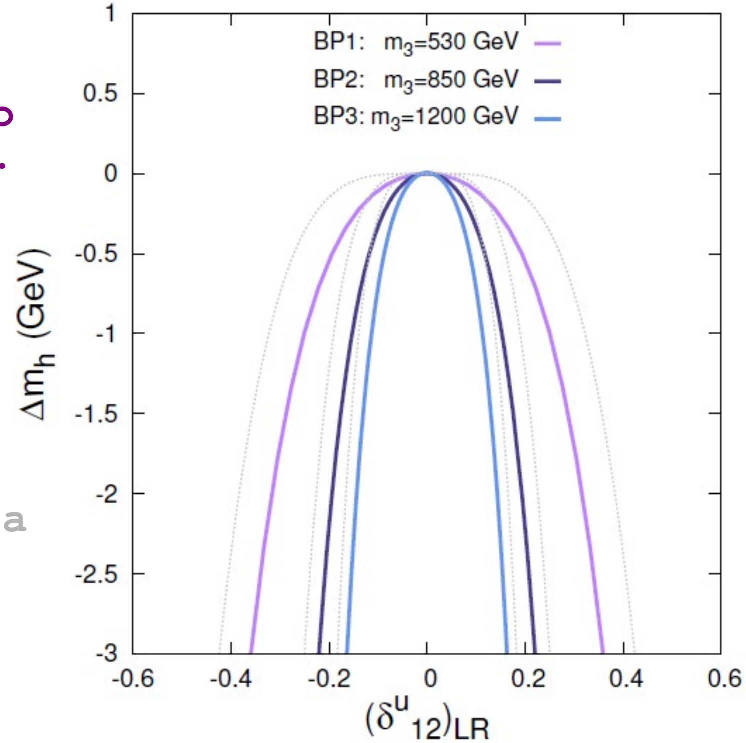
	M_1	M_2	M_3	$A_{t,b,\tau}$	μ	m_A	$\tan\beta$	$m_{\tilde{L},\tilde{e}}$	$m_{\tilde{Q}_{1,2},\tilde{u}_{1,2},\tilde{d}}$	$m_{\tilde{Q}_3,\tilde{u}_3}$
BP1	126	233	670	0	242	1860	20	5950	560	530
BP2	126	233	670	0	362	1712	30	1455	945	850
BP3	126	233	670	0	462	1512	30	2500	1300	1200

A_t - like shape



Spheno 3.2.4.

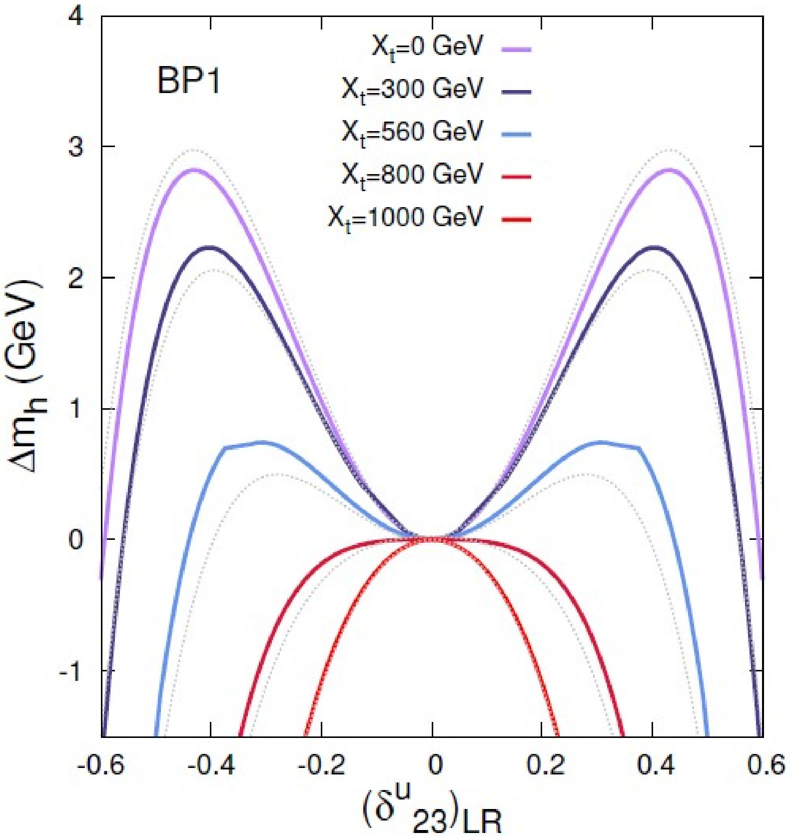
Formula



Only negative !

Universal masses, $A_t \neq 0$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\tilde{m}^2 \left[Y_t^2 \sin^2\beta \left((\delta^u_{33})^2 + \frac{1}{2}(\delta^u_{23})^2_{LR} \right) - \frac{\tilde{m}^2}{6v^2}\left((\delta^u_{33})^4 + (\delta^u_{23})^4_{LR} + 2(\delta^u_{33})^2(\delta^u_{23})^2_{LR} \right) \right]$$



$$\tilde{X}_t = (T_u)_{33} - Y_t \mu \cot\beta$$

Negative mixed term

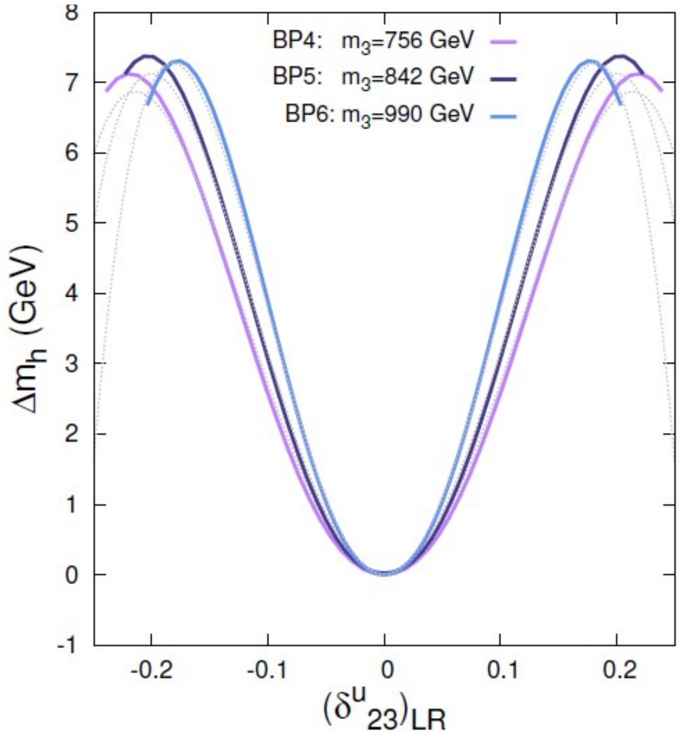
Standard A_t contribution

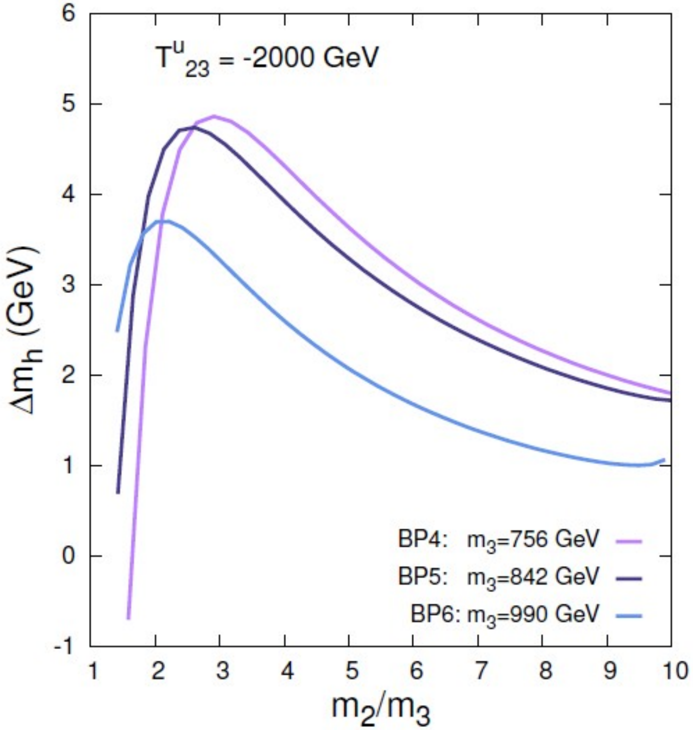
Hierarchical masses, A_t=0

$$\Delta m_h^2((\delta^u_{23})_{LR}) = \frac{3}{4\pi^2}\left\{(\delta^u_{23})^2_{LR}\frac{\tilde{m}_2^2\tilde{m}_3^2}{\tilde{m}_2^2-\tilde{m}_3^2}\left[\frac{1}{2}Y_t^2\sin^2\beta\ln\left(\frac{\tilde{m}_2^2}{\tilde{m}_3^2}\right)\right.\right.$$
$$\left.\left.+(\delta^u_{23})^2_{LR}\frac{\tilde{m}_2^2\tilde{m}_3^2}{v^2(\tilde{m}_2^2-\tilde{m}_3^2)}\left(2-\frac{\tilde{m}_2^2+\tilde{m}_3^2}{\tilde{m}_2^2-\tilde{m}_3^2}\ln\left(\frac{\tilde{m}_2^2}{\tilde{m}_3^2}\right)\right)\right]\right\}$$

Haber, Hempfling '93
for stop mixing

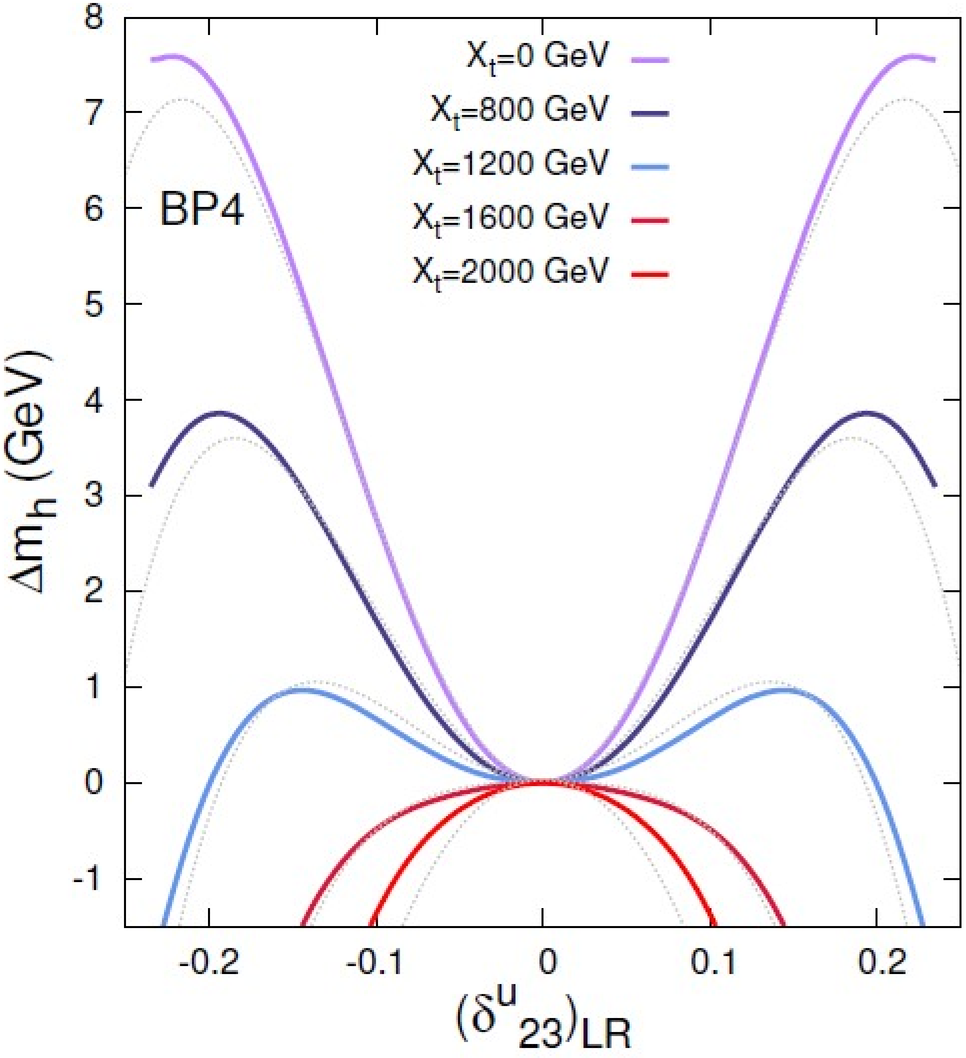
	M_1	M_2	M_3	$A_{t,b,\tau}$	μ	m_A	$\tan\beta$	$m_{\tilde{L},\tilde{e}}$	$m_{\tilde{Q}_{1,2},\tilde{u}_{1,2},\tilde{d}}$	$m_{\tilde{Q}_3,\tilde{u}_3}$
BP4	300	160	1600	0	236	1665	39	3000	5000	756
BP5	300	160	1600	0	189	1310	49	3000	5000	842
BP6	300	160	1600	0	236	1410	49	3000	5000	990





maximum at
m_2/m_3 ~ 2 - 4

Hierarchical masses, $A_t \neq 0$



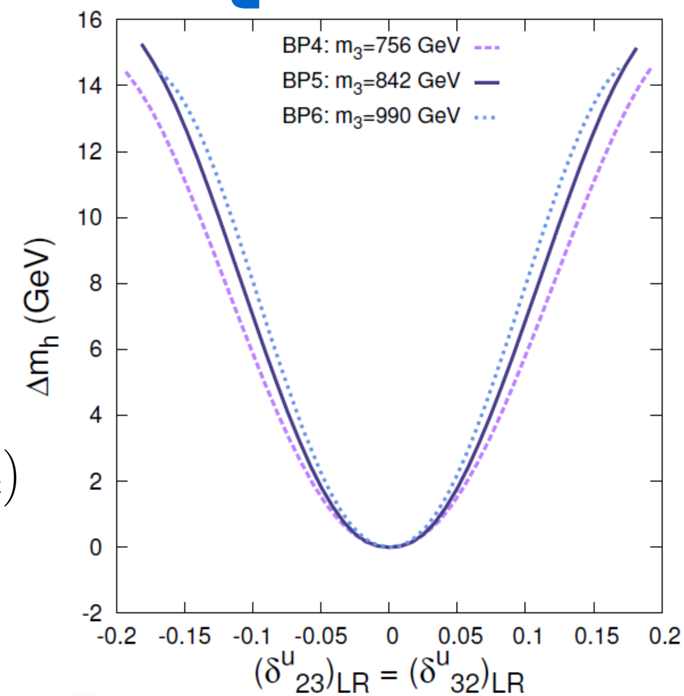
Hierarchical masses, A_t=0, $2\delta_{LR}$

$$(\delta^u_{23})_{LR} = (\delta^u_{32})_{LR}$$
$$(\delta^u_{13})_{LR} = (\delta^u_{31})_{LR}$$
$$(\delta^u_{23})_{LR} = (\delta^u_{31})_{LR}$$
$$(\delta^u_{32})_{LR} = (\delta^u_{13})_{LR}$$

Contributions add up

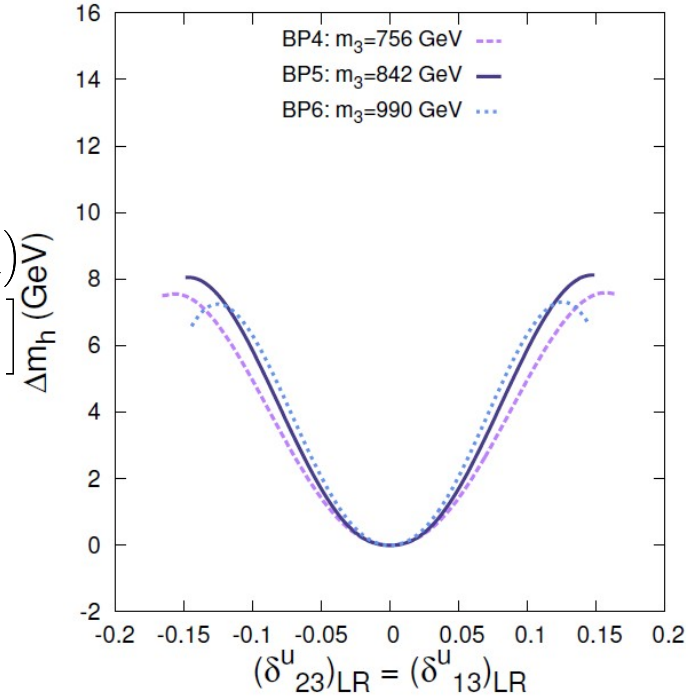
$$\Delta m_h^2 = \frac{3}{4\pi^2}\tilde{m}^2\left[Y_t^2\sin^2\beta\frac{1}{2}\left((\delta^u_{32})^2 + (\delta^u_{23})^2_{LR}\right) - \frac{\tilde{m}^2}{6v^2}\left((\delta^u_{32})^4 + (\delta^u_{23})^4_{LR}\right)\right]$$

No "mixing" term



$$(\delta^u_{23})_{LR} = (\delta^u_{13})_{LR}$$
$$(\delta^u_{32})_{LR} = (\delta^u_{31})_{LR}$$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\tilde{m}^2\left[Y_t^2\sin^2\beta\frac{1}{2}\left((\delta^u_{13})^2 + (\delta^u_{23})^2_{LR}\right) - 2\frac{\tilde{m}^2}{6v^2}\left((\delta^u_{13})^4 + (\delta^u_{23})^4_{LR}\right)\right]$$



Limits on deltas - FCNC

B - physics:

Gabbiani et al '96, Misiak et al '97, Arana-Catania et al '12, '14

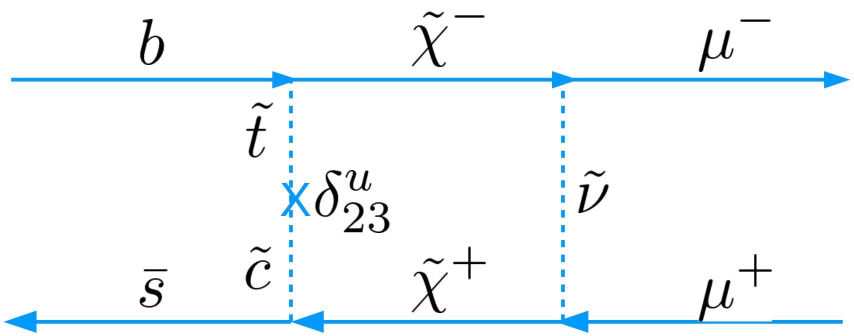
$$BR(B_s \to \mu^+\mu^-) = 2.9 \pm 0.76 \times 10^{-9}$$

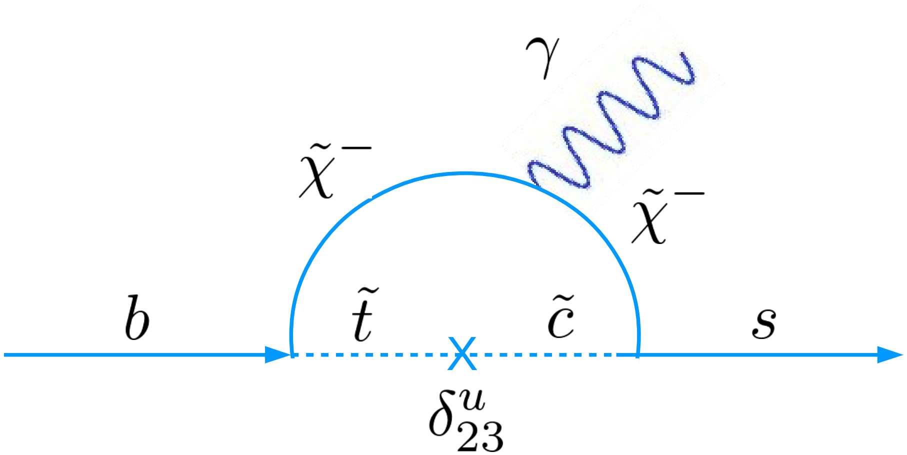
$$BR(B_d \to \mu^+\mu^-) < 7.4 \times 10^{-10}$$

$$BR(B_s \to X_s\gamma) = 3.43 \pm 0.3 \times 10^{-4}$$

$$\Delta M_{B_s} = 1.166 \pm 0.168 \times 10^{-11} \text{ GeV}$$

$\Big\}$ $(\delta^u_{23})_{LR}$, $(\delta^u_{32})_{LR}$, $(\delta^u_{13})_{LR}$, $(\delta^u_{31})_{LR}$



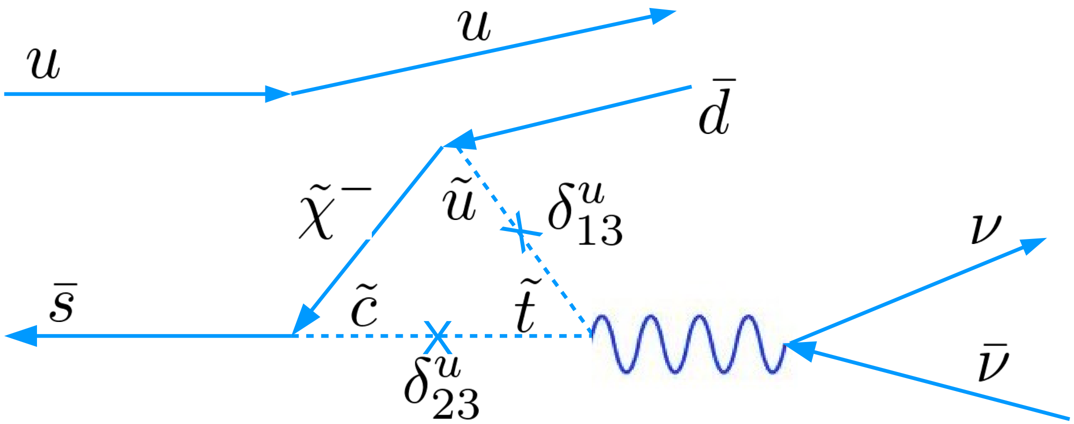


Limits on deltas - FCNC

K - decays:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73 \pm 1.15 \times 10^{-10}$$

$(\delta^u_{23})_{LR}$
$(\delta^u_{13})_{LR}$



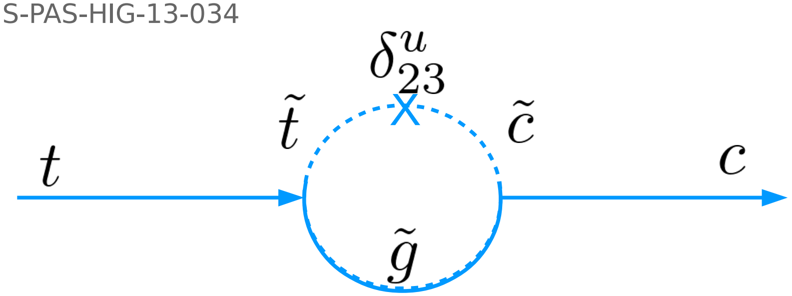
Colangelo et al '98,
Altmannshofer et al '09,
Behring et al '12,

Rare top decays:

$$BR(t \to hc) < 5.6 \times 10^{-3}$$

$(\delta^u_{23})_{LR}$
$(\delta^u_{32})_{LR}$

CMS-PAS-HIG-13-034



In MSSM:

Guasch et al '99, Cao et al '06

$$BR(t \to hc)_{\text{MSSM}} \simeq 6 \times 10^{-5}$$

Limits on deltas - FCNC

	M_1	M_2	M_3	$A_{t,b,\tau}$	μ	m_A	$\tan\beta$	$m_{\tilde{L},\tilde{e}}$	$m_{\tilde{Q}_{1,2},\tilde{u}_{1,2},\tilde{d}}$	$m_{\tilde{Q}_3,\tilde{u}_3}$
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	M_1	M_2	M_3	$A_{t,b,\tau}$	μ	m_A	$\tan\beta$	$m_{\tilde{L},\tilde{e}}$	$m_{\tilde{Q}_{1,2},\tilde{u}_{1,2},\tilde{d}}$	$m_{\tilde{Q}_3,\tilde{u}_3}$
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SUSY FLAVOR v2 (Crivellin, Rosiek, Chankowski, Dedes, Jaeger '12)

	BP1	BP2	BP3	BP4	BP5	BP6	FCNC process
$(\delta^u_{23})_{LR}$	$[-0.87 : 0.55]$	–	–	–	–	–	$b \to s\gamma$
$(\delta^u_{32})_{LR}$	$[-0.2 : 0.52]$	–	–	$[-0.15 : 0.3]$	$[-0.16 : 0.19]$	$[-0.2 : -]$	$b \to s\gamma$ $(B_s \to \mu^+\mu^-)$
$(\delta^u_{13})_{LR}$	–	–	–	–	–	–	–
$(\delta^u_{31})_{LR}$	$[-0.45 : 0.55]$	–	–	–	–	–	$K^+ \to \pi^+\nu\bar{\nu}$

due to tanβ

max. Higgs ~0.4 ~0.2 ~0.2 ~0.2

- **FCNC constraining only for light spectra**
- **Limits compatible with Higgs mass enhancement**

Conclusions

- The Higgs boson mass can be significantly enhanced by non-zero $(\delta^u_{23})_{LR}$, $(\delta^u_{32})_{LR}$, $(\delta^u_{13})_{LR}$, $(\delta^u_{31})_{LR}$
- The effect is mitigated by the presence of non-zero stop mixing term
- The effect is enhanced by the splitting of the diagonal entries
- The size of deltas is mildly constraint by the FCNC