The Higgs sector of the NMFV MSSM at the ILC

Miguel Arana Catania

Higgs Boson masses and B-Physics Constraints
in Non-Minimal Flavor Violating SUSY scenarios

M. Arana-Catania, S. Heinemeyer, M.J. Herrero and S. Peñaranda

http://arxiv.org/hep-ph/1109.nnnn

The path to NMFV

1. SUSY scenarios with NMFV

2. Constraints from B-Physics

3. Radiative corrections to Higgs masses

4. Higgs mases and B-Physics constraints

SUSY scenarios with NMFV

Quark sector: Interaction basis ⟶ Mass basis

Squark sector: Interaction basis ⟶ SCKM basis

$$\begin{pmatrix} \tilde{u}_{L,R} \\ \tilde{c}_{L,R} \\ \tilde{t}_{L,R} \end{pmatrix} = V^u_{L,R} \begin{pmatrix} \tilde{u}^{\rm int}_{L,R} \\ \tilde{c}^{\rm int}_{L,R} \\ \tilde{t}^{\rm int}_{L,R} \end{pmatrix} \;, \qquad \begin{pmatrix} \tilde{d}_{L,R} \\ \tilde{s}_{L,R} \\ \tilde{b}_{L,R} \end{pmatrix} = V^d_{L,R} \begin{pmatrix} \tilde{d}^{\rm int}_{L,R} \\ \tilde{s}^{\rm int}_{L,R} \\ \tilde{b}^{\rm int}_{L,R} \end{pmatrix}$$

$$V_{\rm CKM} = V^u_L V^{d\dagger}_L .$$

$$\begin{aligned} {\rm diag}\{m^2_{\tilde{u}_1}, m^2_{\tilde{u}_2}, m^2_{\tilde{u}_3}, m^2_{\tilde{u}_4}, m^2_{\tilde{u}_5}, m^2_{\tilde{u}_6}\} &= R^{\tilde{u}}\, \mathcal{M}^2_{\tilde{u}}\, R^{\tilde{u}\dagger} \\ {\rm diag}\{m^2_{\tilde{d}_1}, m^2_{\tilde{d}_2}, m^2_{\tilde{d}_3}, m^2_{\tilde{d}_4}, m^2_{\tilde{d}_5}, m^2_{\tilde{d}_6}\} &= R^{\tilde{d}}\, \mathcal{M}^2_{\tilde{d}}\, R^{\tilde{d}\dagger} \end{aligned}$$

SUSY scenarios with NMFV

$$\mathcal{M}_{\tilde{q}}^2 = \begin{pmatrix} M^2_{\tilde{q}\,LL} & M^2_{\tilde{q}\,LR} \\ M^{2\,\dagger}_{\tilde{q}\,LR} & M^2_{\tilde{q}\,RR} \end{pmatrix}$$

$$\begin{aligned} M^2_{\tilde{u}\,LL\,ij} &= m^2_{\tilde{U}_L\,ij} + \left(m^2_{u_i} + (T_3^u - Q_u \sin^2\theta_W) M_Z^2 \cos 2\beta\right)\delta_{ij}\,, \\ M^2_{\tilde{u}\,RR\,ij} &= m^2_{\tilde{U}_R\,ij} + \left(m^2_{u_i} + Q_u \sin^2\theta_W\, M_Z^2 \cos 2\beta\right)\delta_{ij}\,, \\ M^2_{\tilde{u}\,LR\,ij} &= \left\langle \mathcal{H}_2^0 \right\rangle \mathcal{A}^u_{ij} - m_{u_i}\mu \cot\beta\,\delta_{ij}\,,\,, \end{aligned}$$

$$m^2_{\tilde{U}_L} = \begin{pmatrix} m^2_{\tilde{U}_{L11}} & 0 & 0 \\ 0 & m^2_{\tilde{U}_{L22}} & \delta^{LL}_{23} m_{\tilde{U}_{L22}} m_{\tilde{U}_{L33}} \\ 0 & \delta^{LL}_{23} m_{\tilde{U}_{L22}} m_{\tilde{U}_{L33}} & m^2_{\tilde{U}_{L33}} \end{pmatrix}$$

$$v_2 \mathcal{A}^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \delta^{LR}_{ct} m_{\tilde{U}_{L22}} m_{\tilde{U}_{R33}} \\ 0 & \delta^{RL}_{ct} m_{\tilde{U}_{R22}} m_{\tilde{U}_{L33}} & m_t A_t \end{pmatrix}$$

$$m^2_{\tilde{U}_R} = \begin{pmatrix} m^2_{\tilde{U}_{R11}} & 0 & 0 \\ 0 & m^2_{\tilde{U}_{R22}} & \delta^{RR}_{ct} m_{\tilde{U}_{R22}} m_{\tilde{U}_{R33}} \\ 0 & \delta^{RR}_{ct} m_{\tilde{U}_{R22}} m_{\tilde{U}_{R33}} & m^2_{\tilde{U}_{R33}} \end{pmatrix}$$

$$m^2_{\tilde{D}_L} = V^\dagger_{\rm CKM}\, m^2_{\tilde{U}_L}\, V_{\rm CKM}$$

SUSY scenarios with NMFV

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
SPS1 a	250	100	-100	10	0	0	112	394	394	402
SPS1 b	400	200	0	30	0	0	116	526	526	532
SPS2	300	1450	0	10	0	0	115	1443	1443	1445
SPS3	400	90	0	10	0	0	115	573	572	578
SPS4	300	400	0	50	0	0	114	404	404	414
SPS5	300	150	-1000	5	0	0	111	694	694	698
VHeavyS	800	800	-800	5	0	0	120	1524	1524	1526
HeavySLightH	600	600	0	5	-1.86	$+1.86$	114	223	219	233
BFP	530	110	-370	27	-84.7	-84.7	120	507	507	514

Some of the scenarios excluded or with big tensions with LHC data. But nevertheless chosen for the study, since they have been studied at length.

Constraints from B-Physics

$$\mathrm{BR}(B \to X_s \gamma)$$

$$\mathrm{BR}(B_s \to \mu^+ \mu^-)$$

$$B_s - \bar{B}_s \qquad \Delta M_{B_s}$$

Constraints from B-Physics

$$\mathrm{BR}(B \to X_s \gamma)$$

$$\mathrm{BR}(B \to X_s l^+ l^-)$$

$$\mathrm{BR}(B_s \to \mu^+ \mu^-)$$

$$B_s - \bar{B}_s \qquad \Delta M_{B_s}$$

Constraints from B-Physics

$$\mathrm{BR}(B \to X_s\gamma)$$

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\mathrm{CKM}}^{ts*} V_{\mathrm{CKM}}^{tb} \sum_{i=1}^{8} (C_i O_i + C_i' O_i')$$

$$O_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}_L \sigma^{\mu\nu} b_R\right) F_{\mu\nu}$$

$$O_8 = \frac{g_3}{16\pi^2} m_b \left(\bar{s}_L \sigma^{\mu\nu} T^a b_R\right) G^a_{\mu\nu}$$

Loops with Higgs bosons

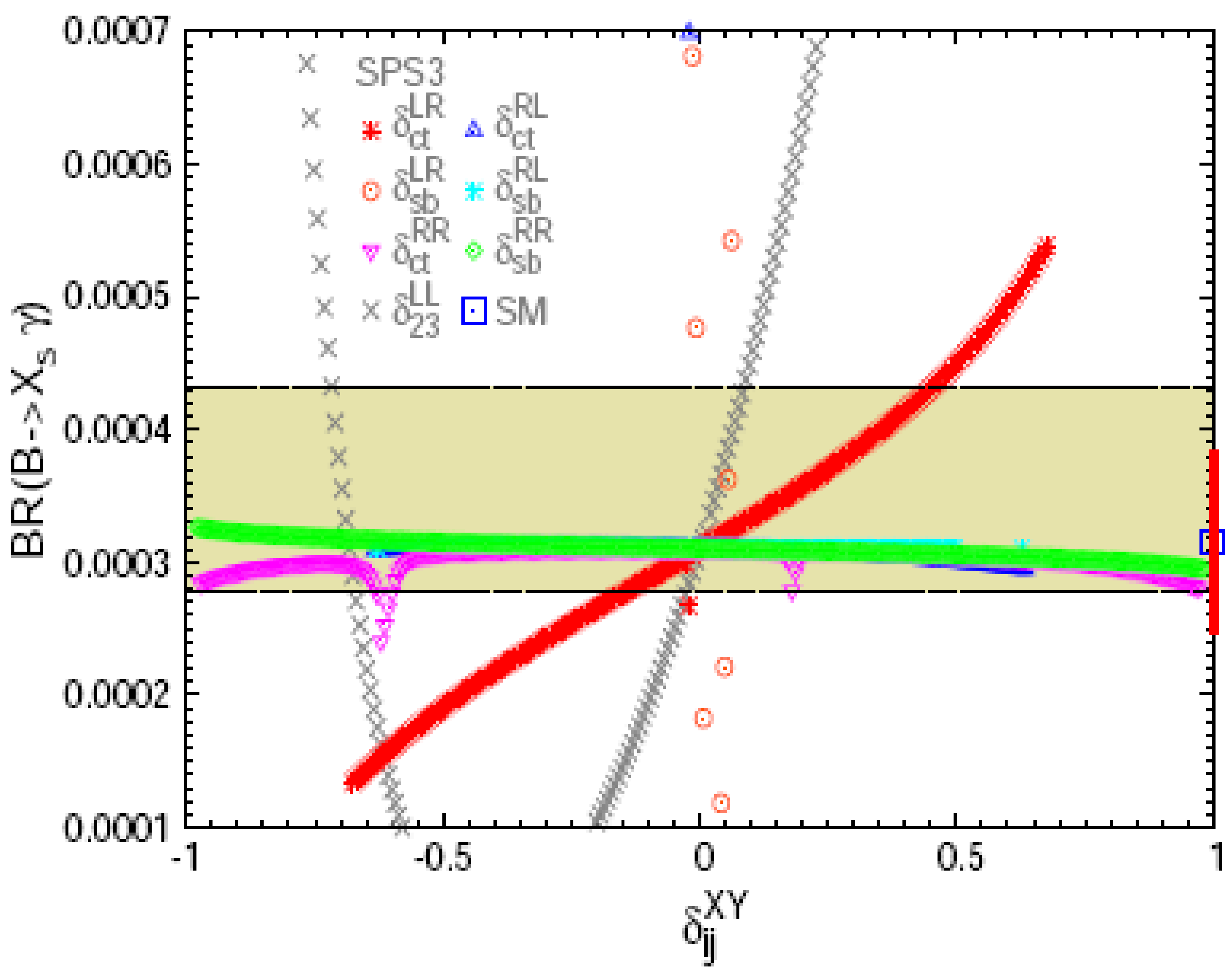
Loops with charginos

Loops with gluinos

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{exp}} = (3.55 \pm 0.26) \times 10^{-4}$$

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$

Constraints from B-Physics



points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
SPS3	400	90	0	10	0	0	115	573	572	578

Constraints from B-Physics

$$\mathrm{BR}(B_s \to \mu^+\mu^-)$$

$$\mathcal{H}_{\mathrm{eff}} = -\frac{G_F \alpha}{\sqrt{2}\pi} V_{\mathrm{CKM}}^{ts*} V_{\mathrm{CKM}}^{tb} \sum_i (C_i O_i + C'_i O'_i)$$

$$O_{10} = (\bar{s}\gamma^\nu P_L b)\,(\bar{\mu}\gamma_\nu\gamma_5\mu)\,,$$
$$O_S = m_b\,(\bar{s}P_R b)\,(\bar{\mu}\mu)\,,$$
$$O_P = m_b\,(\bar{s}P_R b)\,(\bar{\mu}\gamma_5\mu)\,,$$

Box diagrams

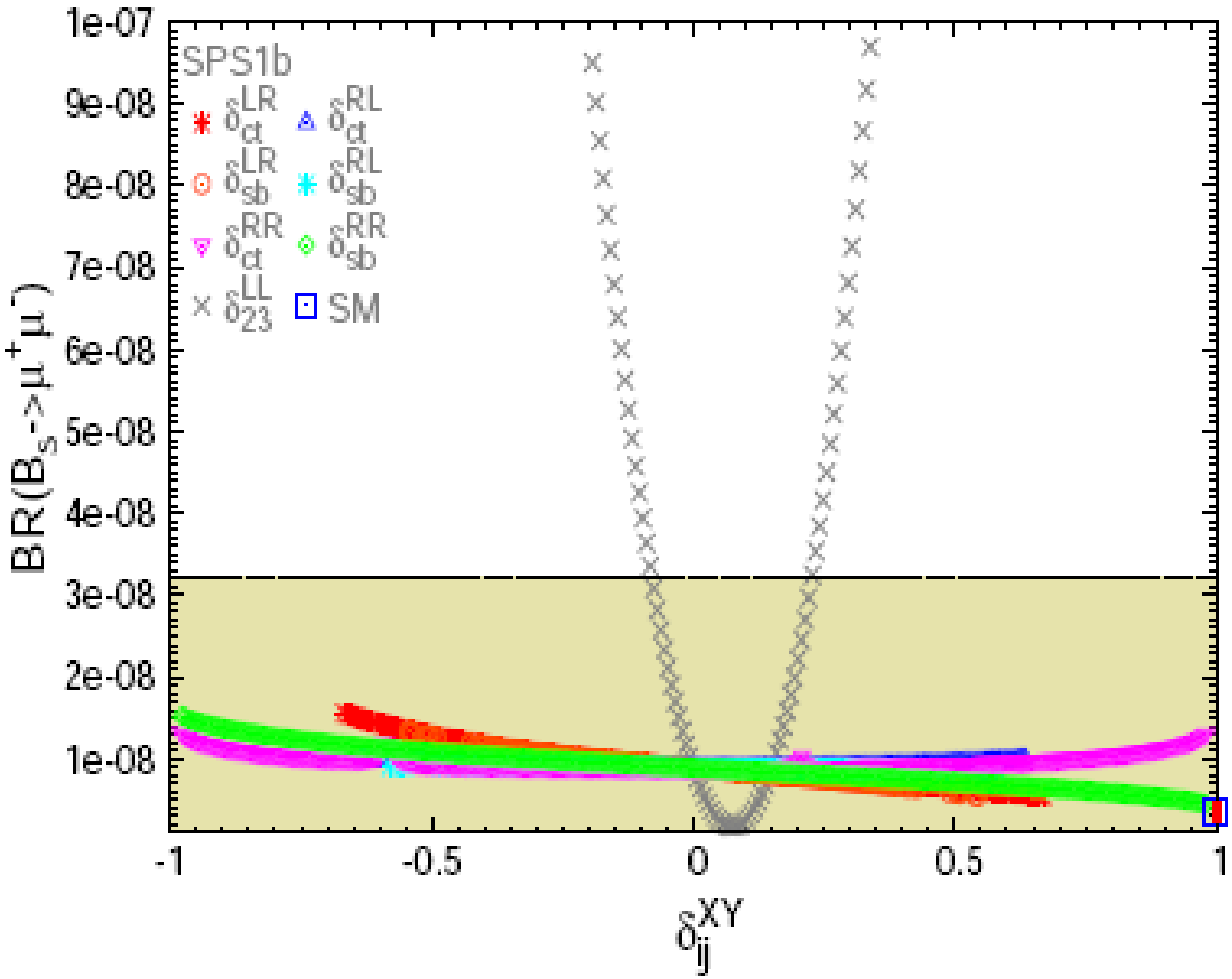
Z-penguin diagrams

Neutral Higgs penguin diagrams

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} < 3.2 \times 10^{-8} \quad (90\%\ \mathrm{CL})$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.6 \pm 0.4) \times 10^{-9}$$

Constraints from B-Physics



points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
SPS1 b	400	200	0	30	0	0	116	526	526	532

Constraints from B-Physics

ΔM_{B_s}

$$\mathcal{H}_{\rm eff} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{\rm CKM}^{tb*} V_{\rm CKM}^{ts}\right)^2 \sum_i C_i O_i .$$

$$O^{VLL} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha)(\bar{b}^\beta \gamma^\mu P_L s^\beta).$$

$$O_1^{LR} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha)(\bar{b}^\beta \gamma^\mu P_R s^\beta), \qquad O_2^{LR} = (\bar{b}^\alpha P_L s^\alpha)(\bar{b}^\beta P_R s^\beta),$$

$$O_1^{SLL} = (\bar{b}^\alpha P_L s^\alpha)(\bar{b}^\beta P_L s^\beta), \qquad O_2^{SLL} = (\bar{b}^\alpha \sigma_{\mu\nu} P_L s^\alpha)(\bar{b}^\beta \sigma^{\mu\nu} P_L s^\beta),$$

$$\langle \bar{B}_s | \mathcal{H}_{\rm eff} | B_s \rangle = \frac{G_F^2}{48\pi^2} M_W^2 m_{B_s} f_{B_s}^2 \left(V_{\rm CKM}^{tb*} V_{\rm CKM}^{ts}\right)^2 \sum_i P_i C_i (\mu_W) .$$

$$\Delta M_{B_s} = 2 |\langle \bar{B}_s | \mathcal{H}_{\rm eff} | B_s \rangle|,$$

Box diagrams

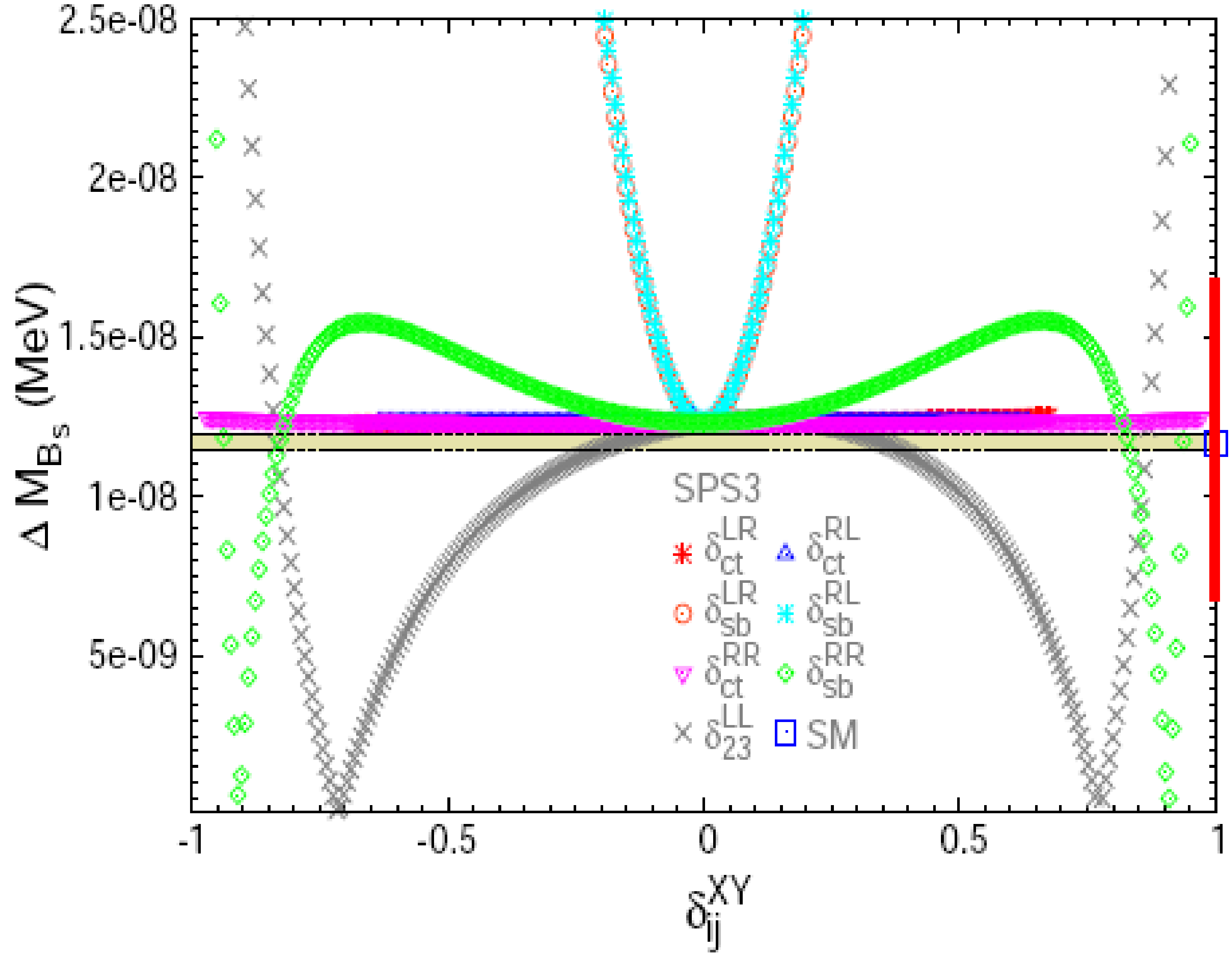
Z-penguin diagrams

Neutral Higgs double penguin diagrams

$$\Delta M_{B_s \rm exp} = (117.0 \pm 0.8) \times 10^{-10} \ {\rm MeV} \ ,$$

$$\Delta M_{B_s \rm SM} = (117.1^{+17.2}_{-16.4}) \times 10^{-10} \ {\rm MeV} \ .$$

Constraints from B-Physics



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Constraints from B-Physics

$\mathrm{BR}(B \to X_s \gamma)$ set strict bounds on δ_{sb}^{LR} δ_{23}^{LL}
and not so strict on δ_{ct}^{LR}

$\mathrm{BR}(B_s \to \mu^+ \mu^-)$ set bounds for large $\tan\beta$

ΔM_{B_s} sensitivity depends on the point

larger sensitivity to the sb sector

General larger sensitivity with large $\tan\beta$
and low soft-SUSY breaking masses

Excluded MFV points can be recovered in NMFV

Radiative corrections to Higgs masses

$$\left[p^2 - m^2_{h,\mathrm{tree}} + \hat{\Sigma}_{hh}(p^2)\right]\left[p^2 - m^2_{H,\mathrm{tree}} + \hat{\Sigma}_{HH}(p^2)\right] - \left[\hat{\Sigma}_{hH}(p^2)\right]^2 = 0$$

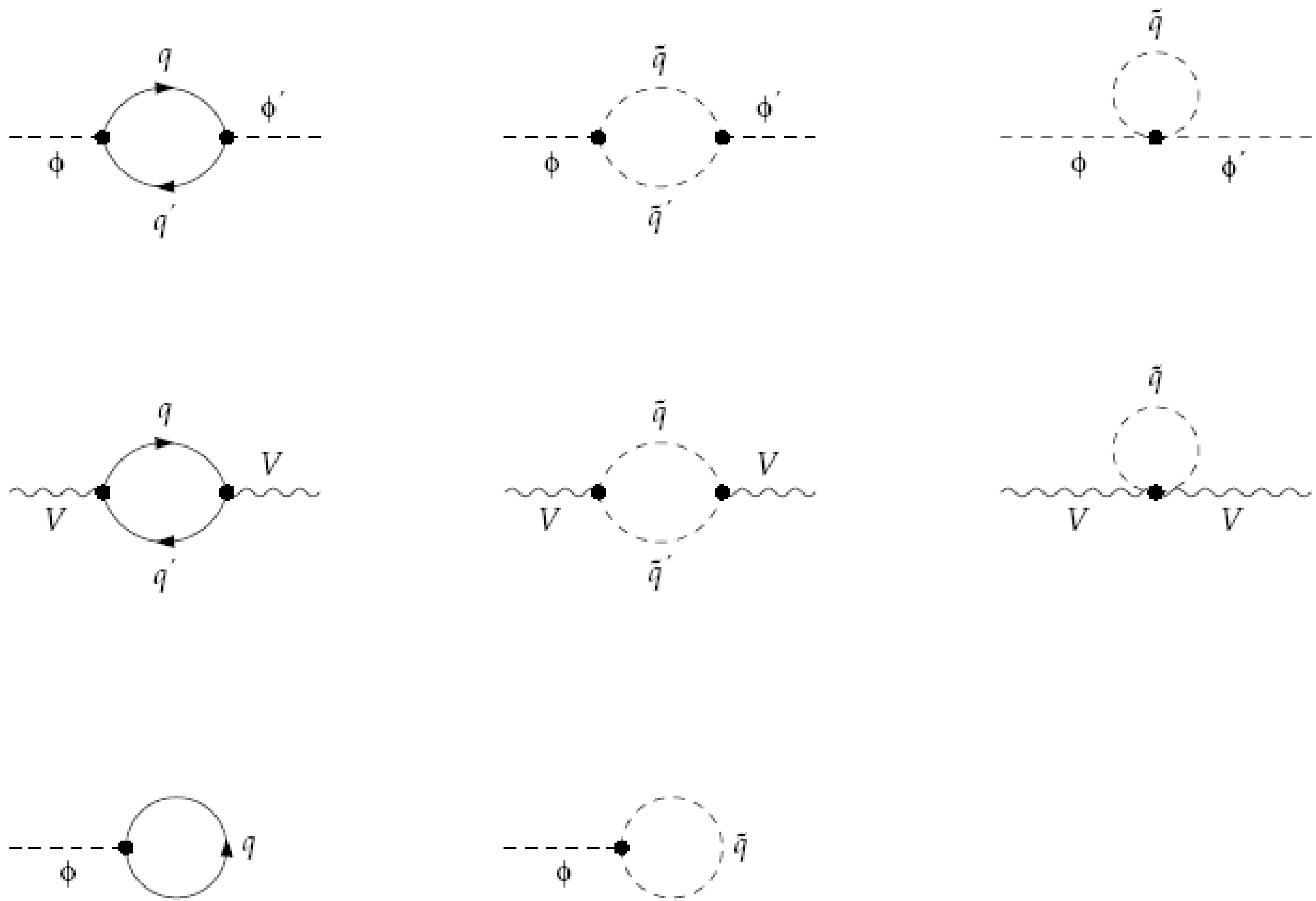
$$p^2 - m^2_{H^\pm,\mathrm{tree}} + \hat{\Sigma}_{H^-H^+}\left(p^2\right) = 0$$

Feynman diagrammatic approach

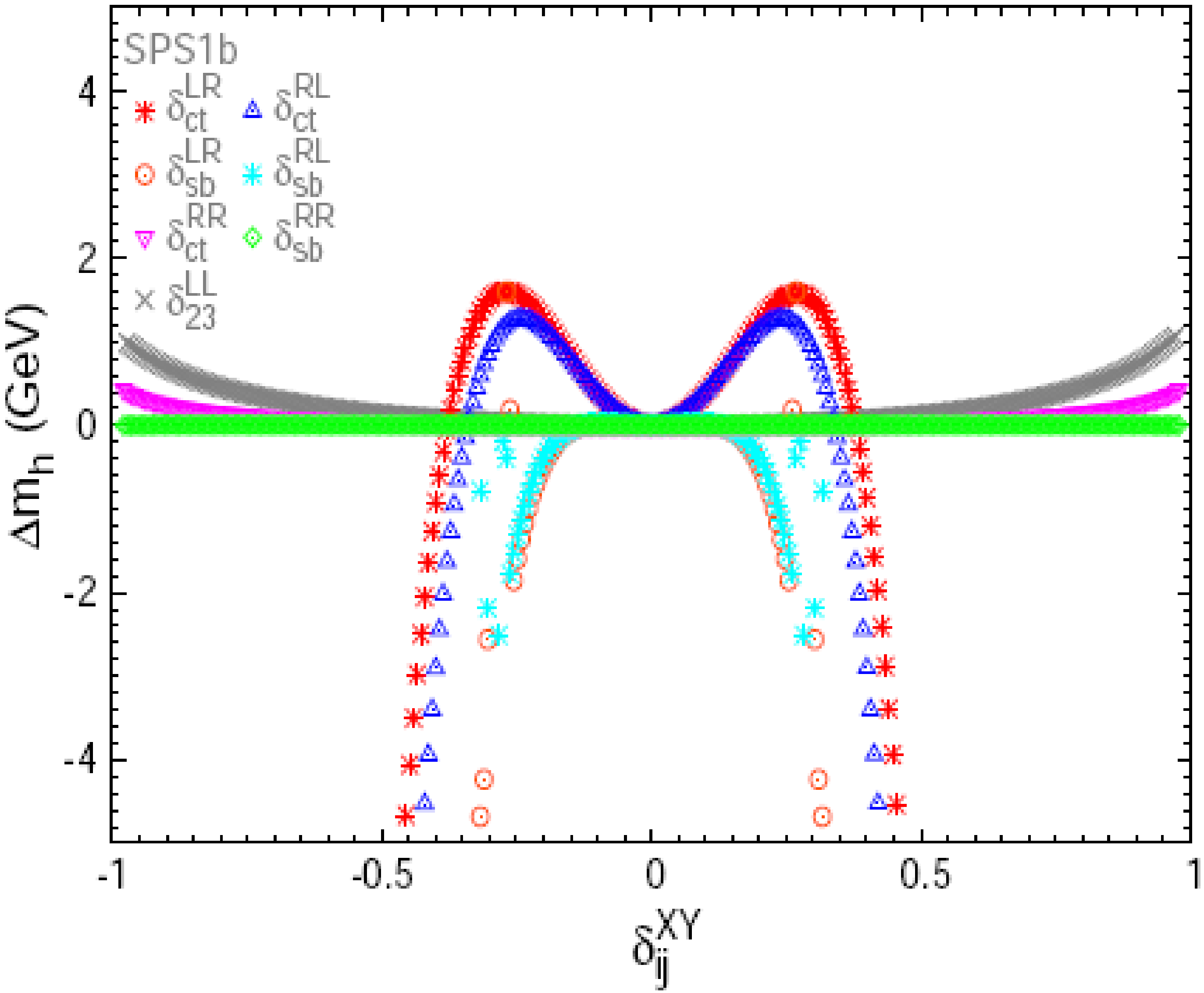
Masses are determined as poles of the propagators (FeynHiggs)

Radiative corrections to Higgs masses

$$\Sigma_{\phi\phi'} = \Sigma^{2q}_{\phi\phi'} + \Sigma^{2\tilde{q}}_{\phi\phi'} + \Sigma^{1\tilde{q}}_{\phi\phi'} \qquad \Sigma_{VV} = \Sigma^{2q}_{VV} + \Sigma^{2\tilde{q}}_{VV} + \Sigma^{1\tilde{q}}_{VV} \qquad T_{\phi} = T^{q}_{\phi} + T^{\tilde{q}}_{\phi}$$



Radiative corrections to Higgs masses



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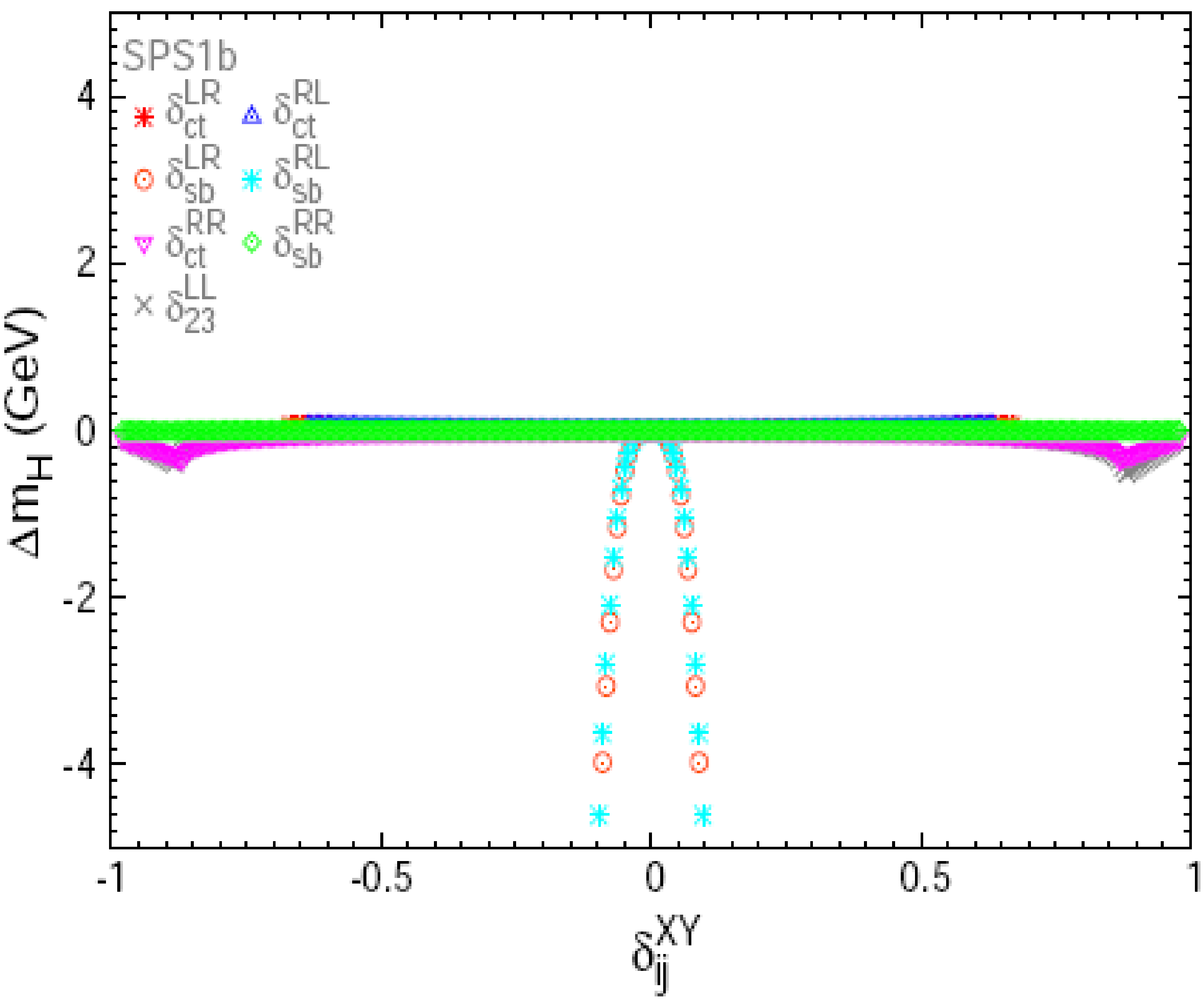

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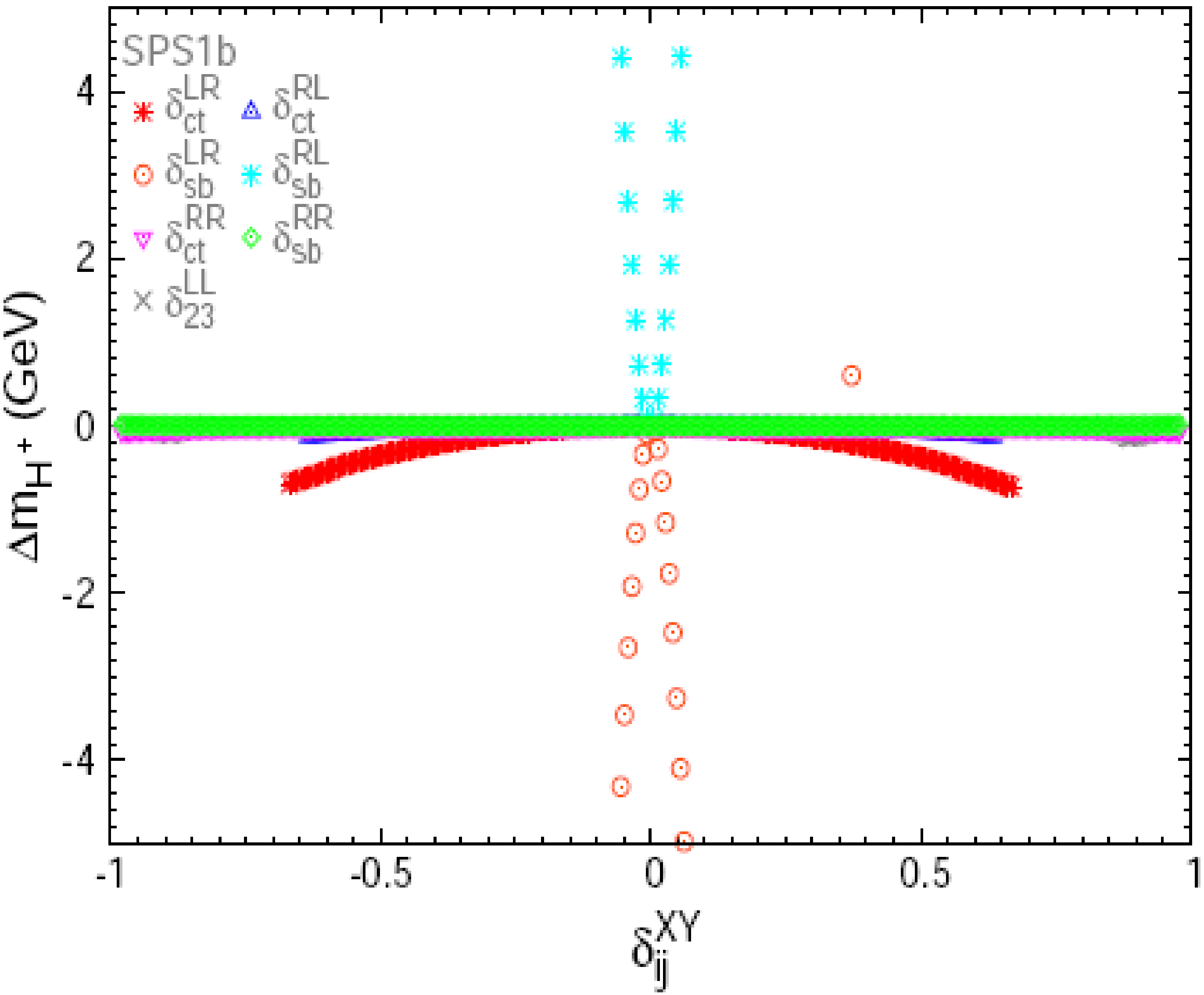

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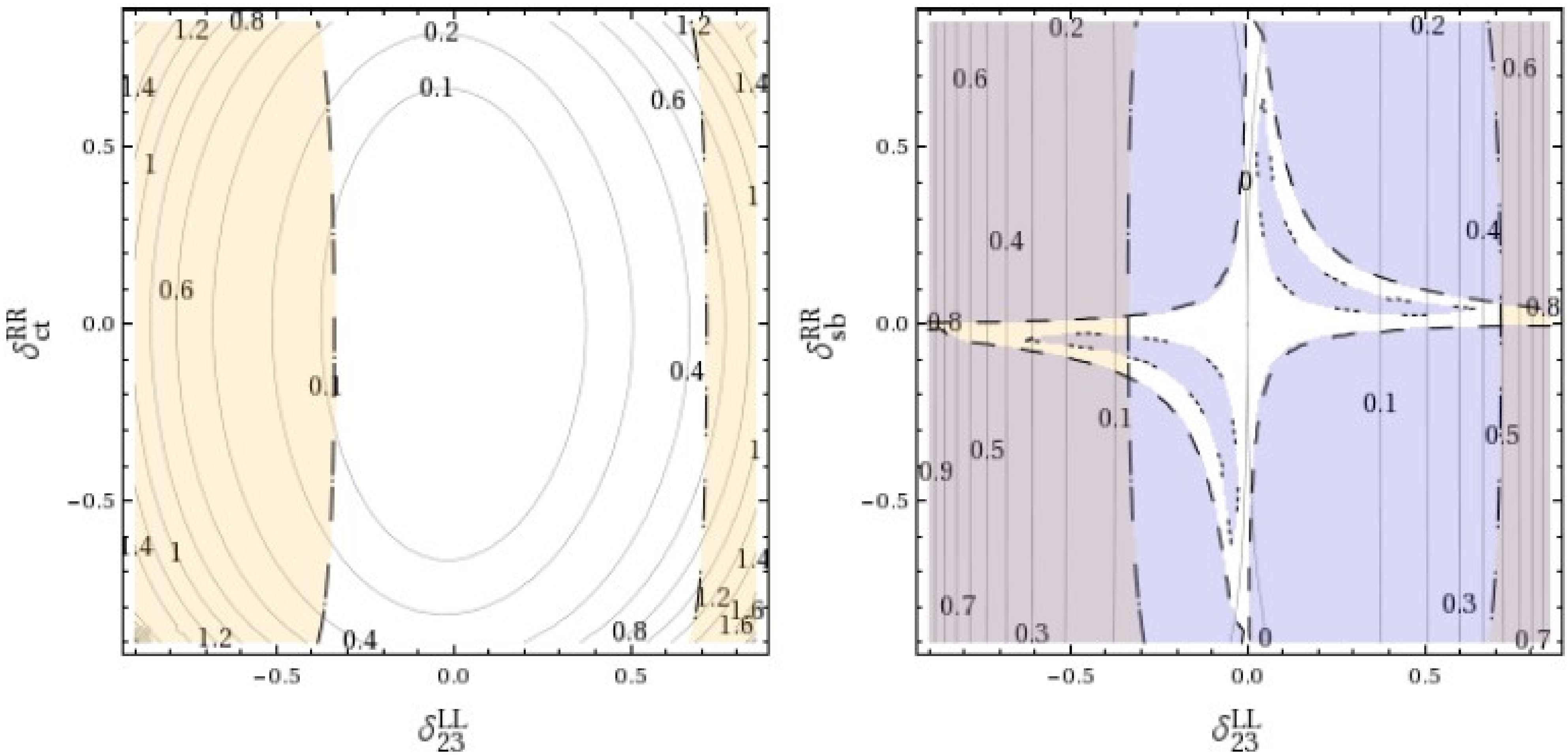
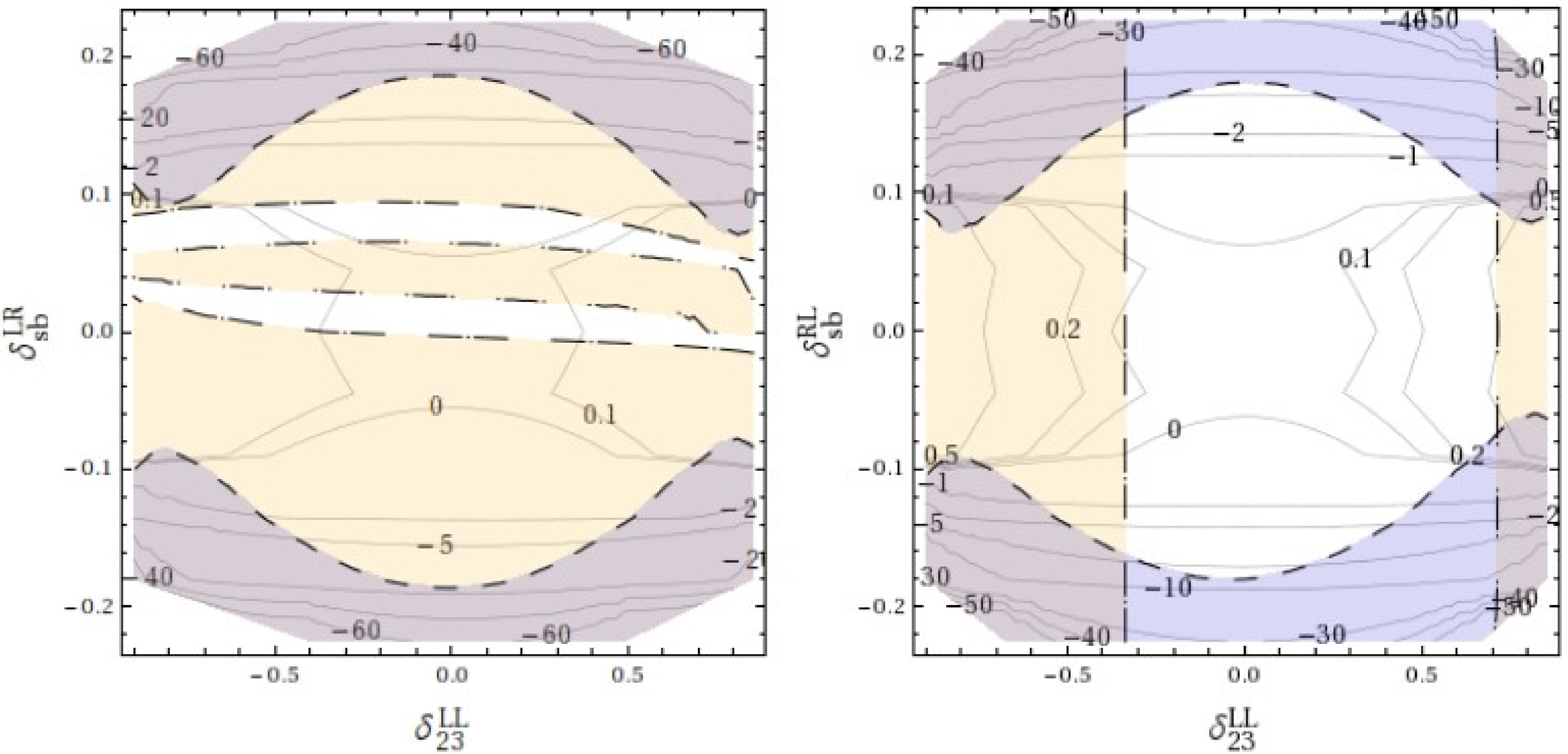
Higgs mases and B-Physics constraints



points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
HeavySLightH	600	600	0	5	−1.86	+1.86	114	223	219	233

Higgs masses and B-Physics constraints



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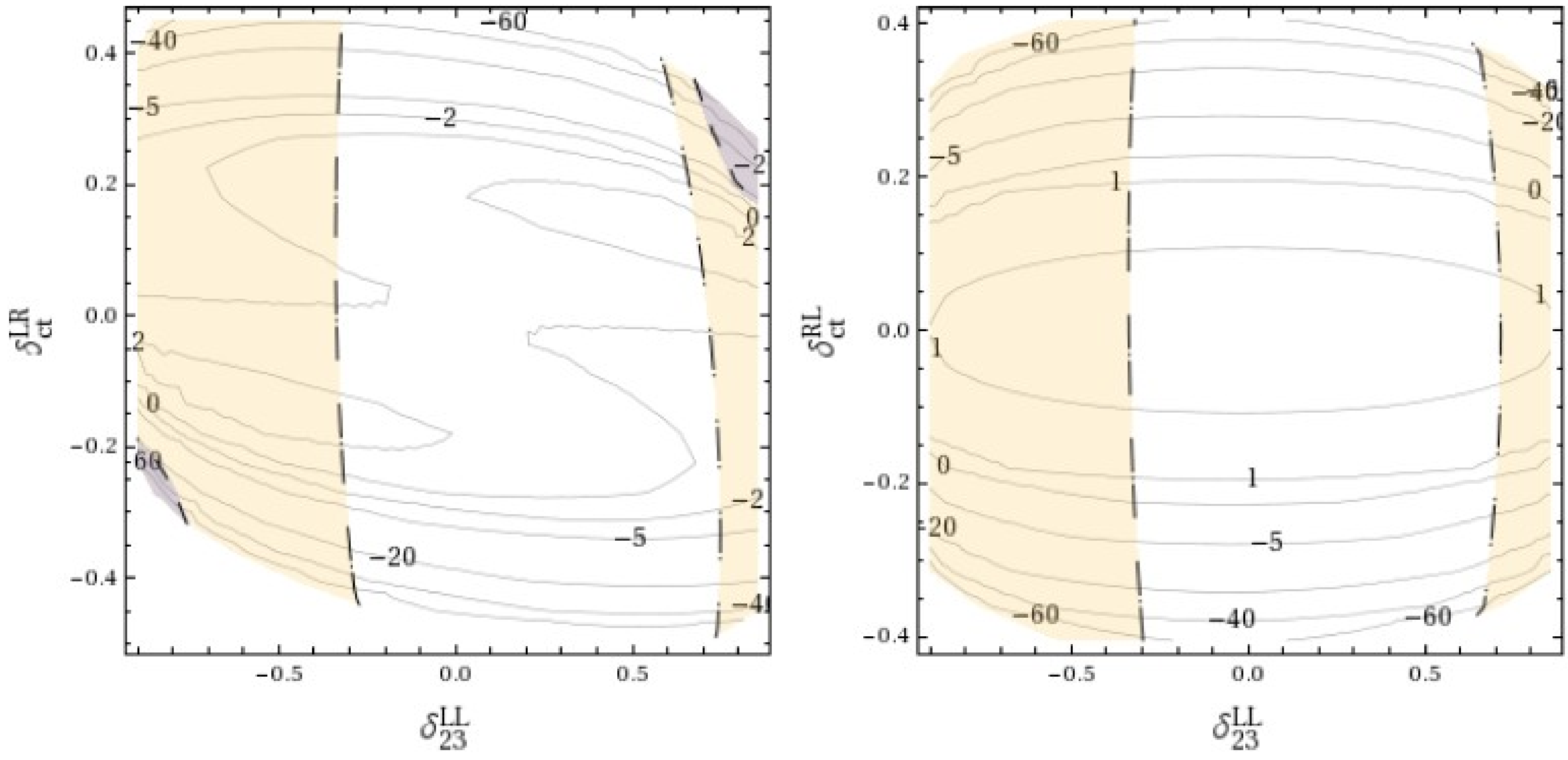
Higgs masses and B-Physics constraints



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Conclusions

We found large corrections to the Higgs boson masses, up to several tens GeV for the lightest boson.

These corrections are two orders of magnitude larger than the anticipated LHC precission, and three orders than the ILC.

Mainly coming from the ct sector (which is less constrained by B-Physics) and from scenarios with low $\tan\beta$

These corrections can be used to set further bounds on flavour violation

Everything is included in FeynHiggs (www.feynhiggs.de)

Beyond...

SUSY scenarios with NMFV

Quark sector: Interaction basis ⟶ Mass basis

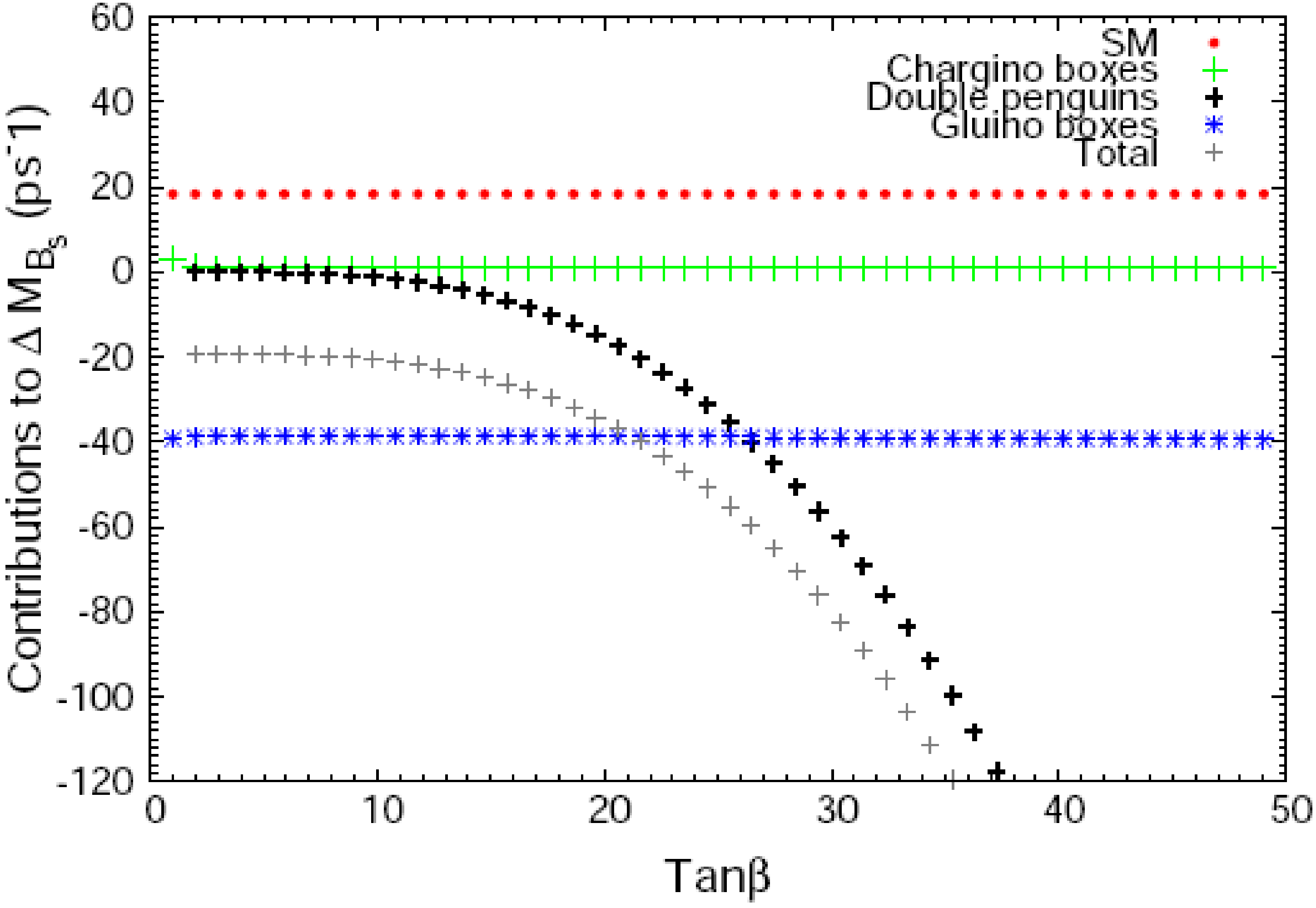
$$\begin{pmatrix} u^{\rm phys}_{L,R} \\ c^{\rm phys}_{L,R} \\ t^{\rm phys}_{L,R} \end{pmatrix} = V^u_{L,R} \begin{pmatrix} u^{\rm int}_{L,R} \\ c^{\rm int}_{L,R} \\ t^{\rm int}_{L,R} \end{pmatrix} \;, \qquad \begin{pmatrix} d^{\rm phys}_{L,R} \\ s^{\rm phys}_{L,R} \\ b^{\rm phys}_{L,R} \end{pmatrix} = V^d_{L,R} \begin{pmatrix} d^{\rm int}_{L,R} \\ s^{\rm int}_{L,R} \\ b^{\rm int}_{L,R} \end{pmatrix}$$

$$V^u_L Y^{u*} V^{u\dagger}_R = {\rm diag}(y_u, y_c, y_t)$$

$$V^d_L Y^{d*} V^{d\dagger}_R = {\rm diag}(y_d, y_s, y_b)$$

$$V_{\rm CKM} = V^u_L V^{d\dagger}_L \,.$$

Constraints from B-Physics



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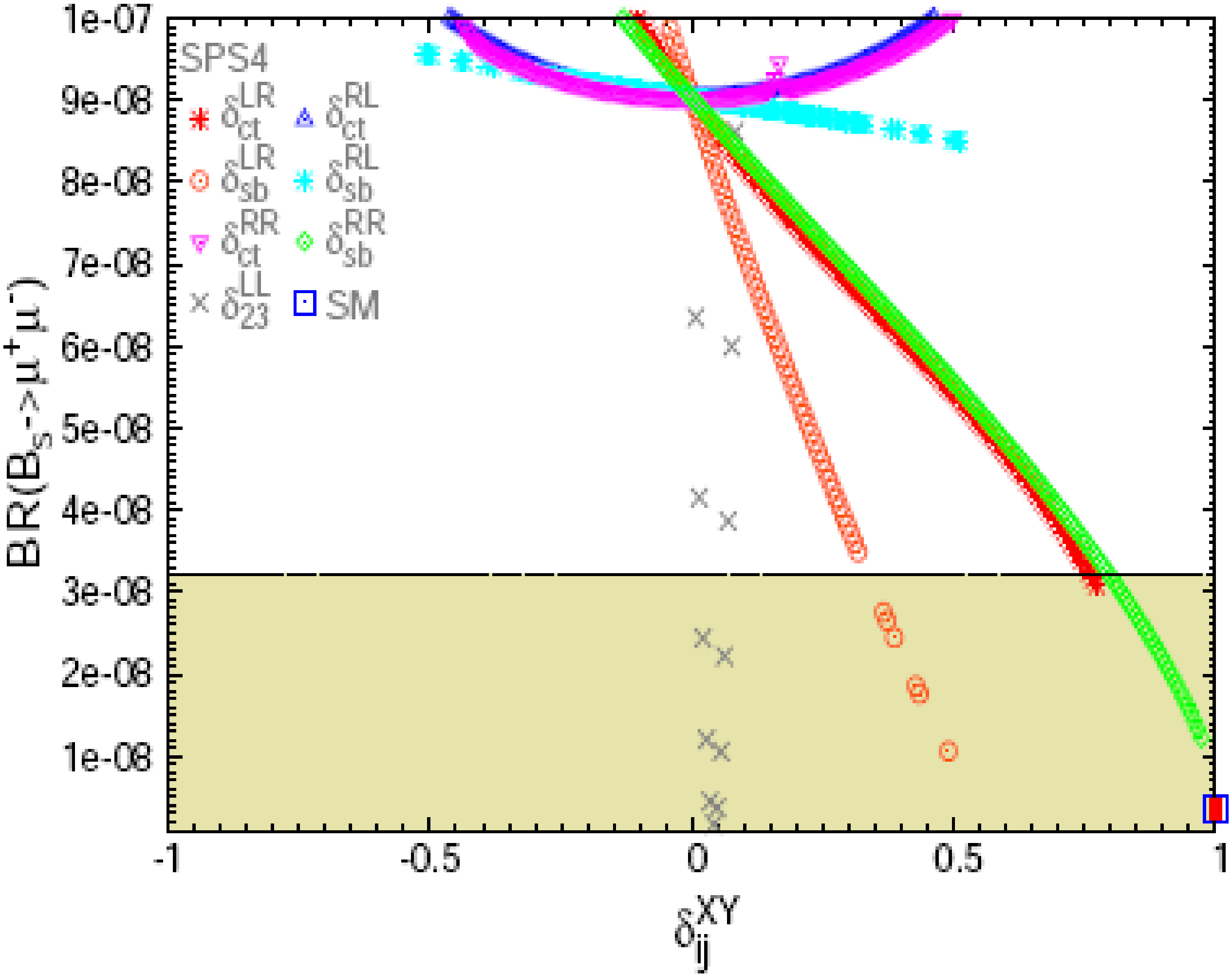

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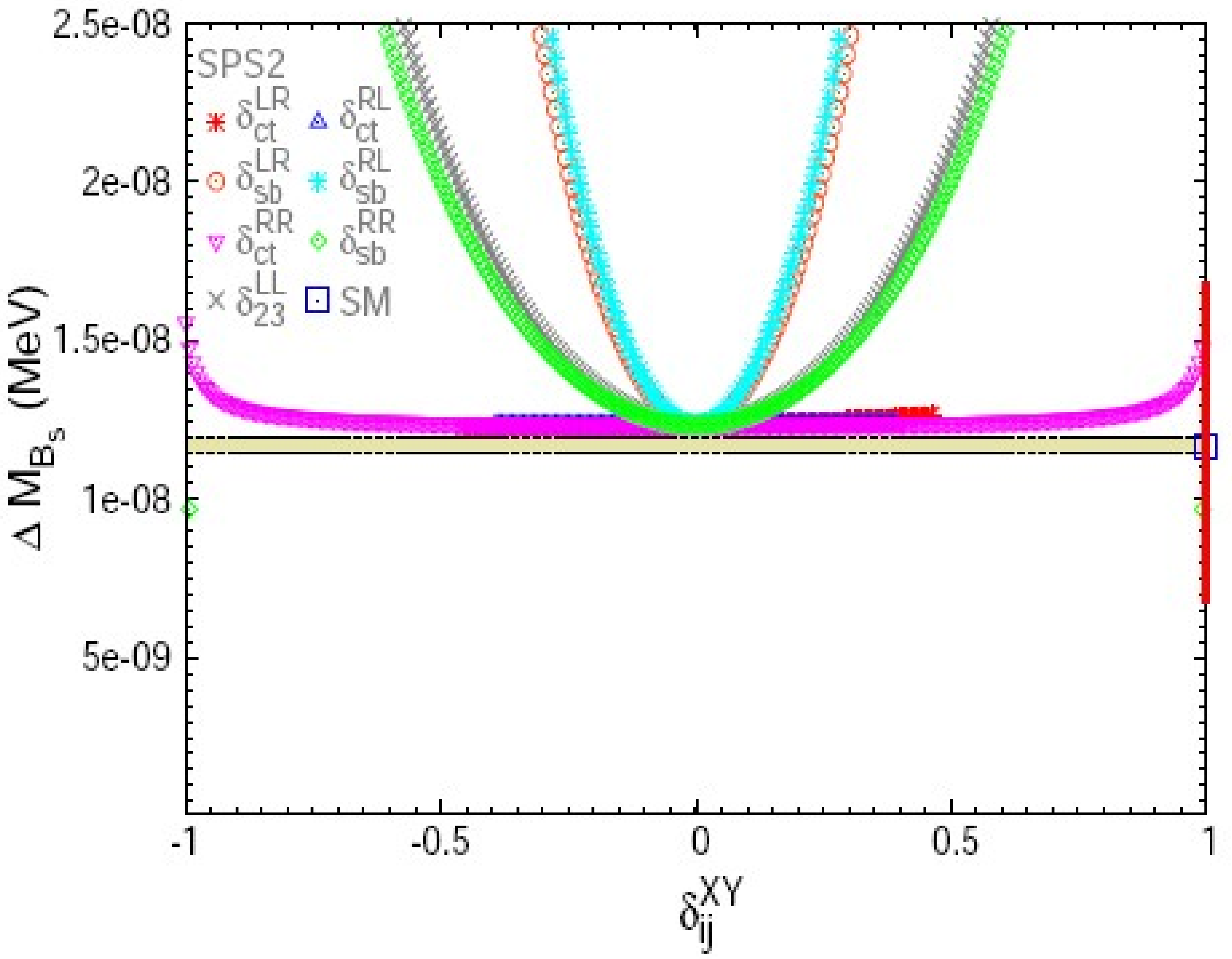
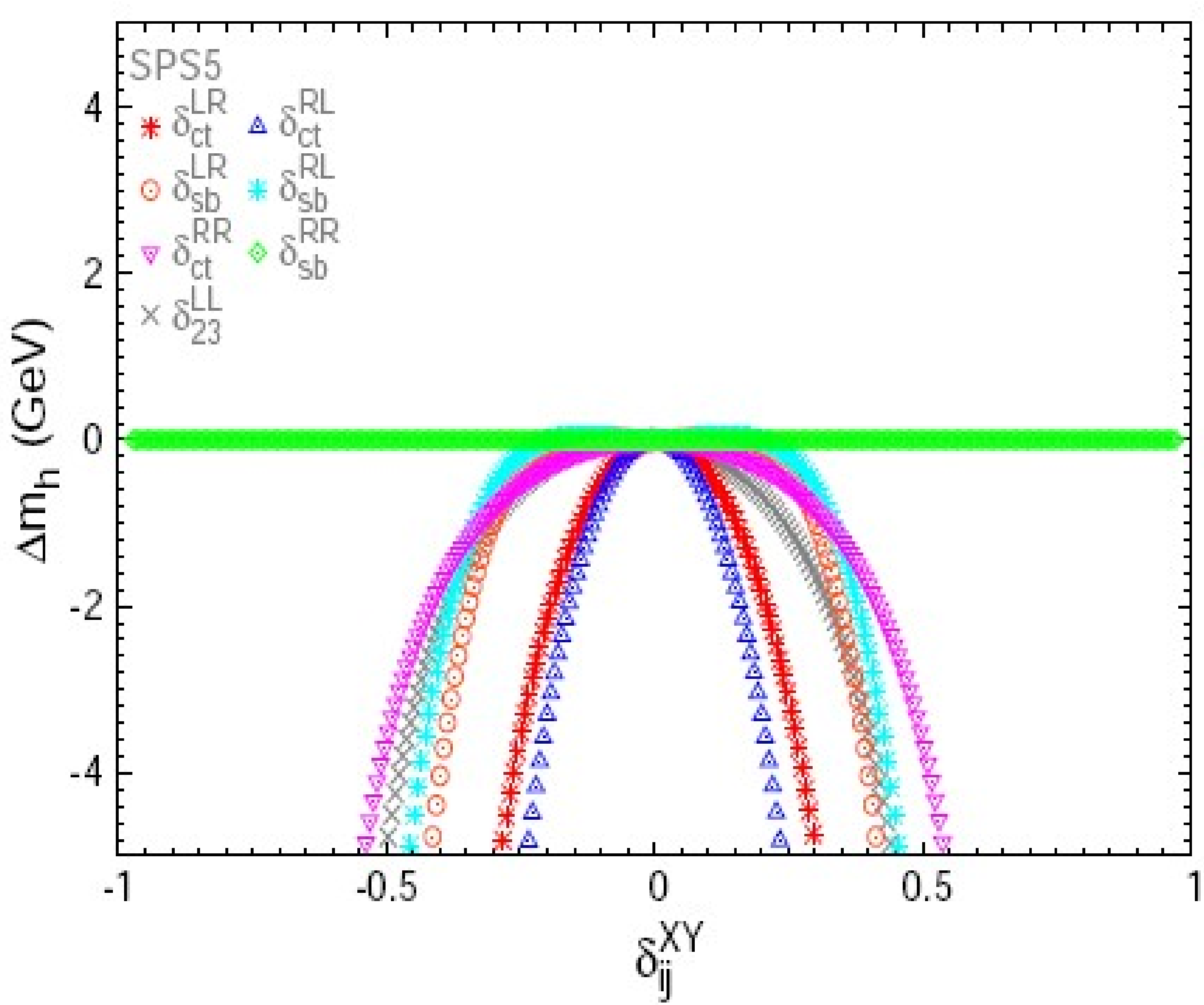


Radiative corrections to Higgs masses



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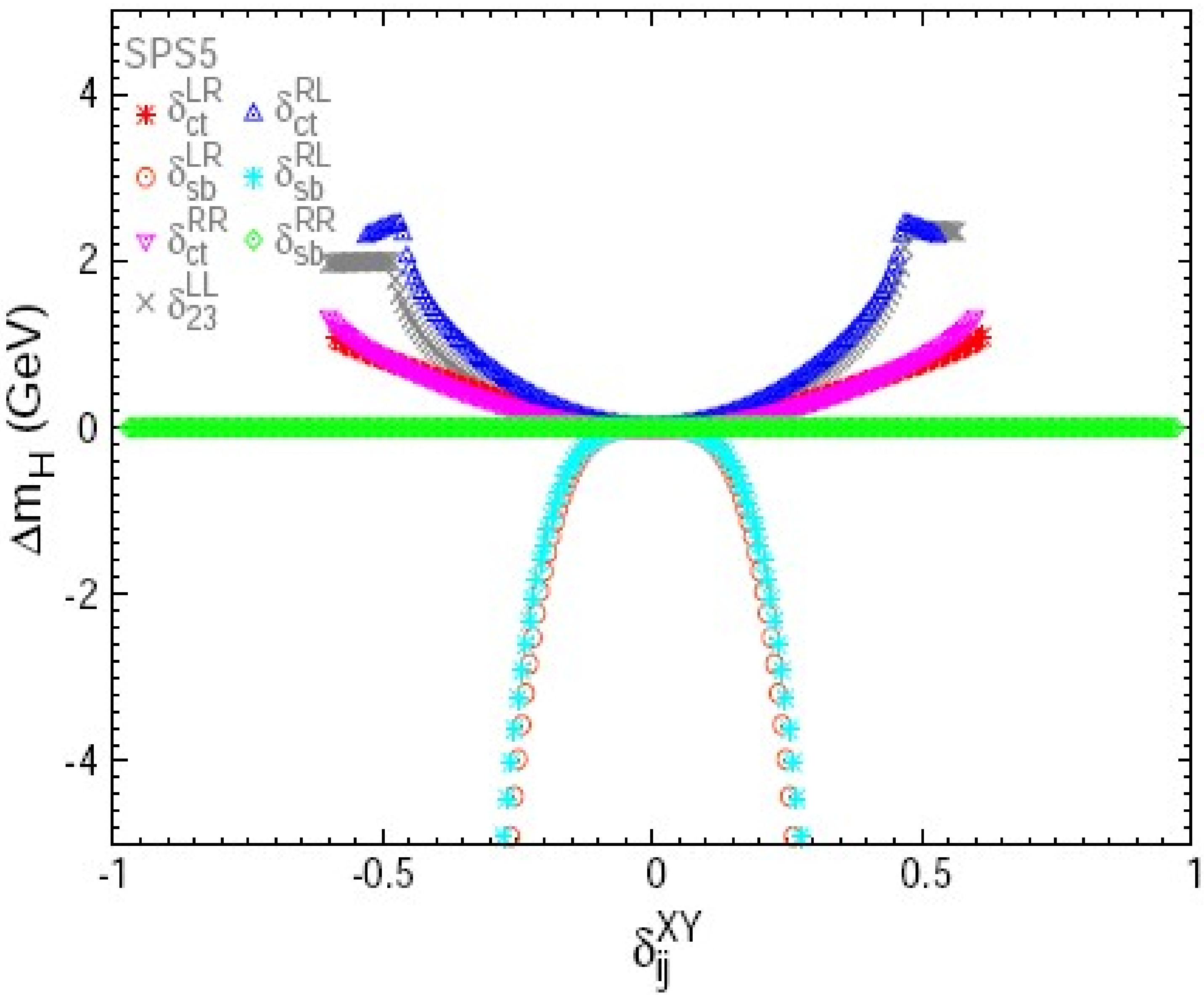

Radiative corrections to Higgs masses