Rare B decays and B-$\overline{B}$ mixing in NMFV SUSY

Miguel Arana Catania

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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

Hunting the 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 $\longrightarrow$ Mass basis

Squark sector: Interaction basis $\longrightarrow$ SCKM basis

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

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

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

6 squarks with intergenerational mixing

SUSY scenarios with NMFV

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

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

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

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

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

We consider all possible deltas parameterizing 2 and 3 generation mixing.

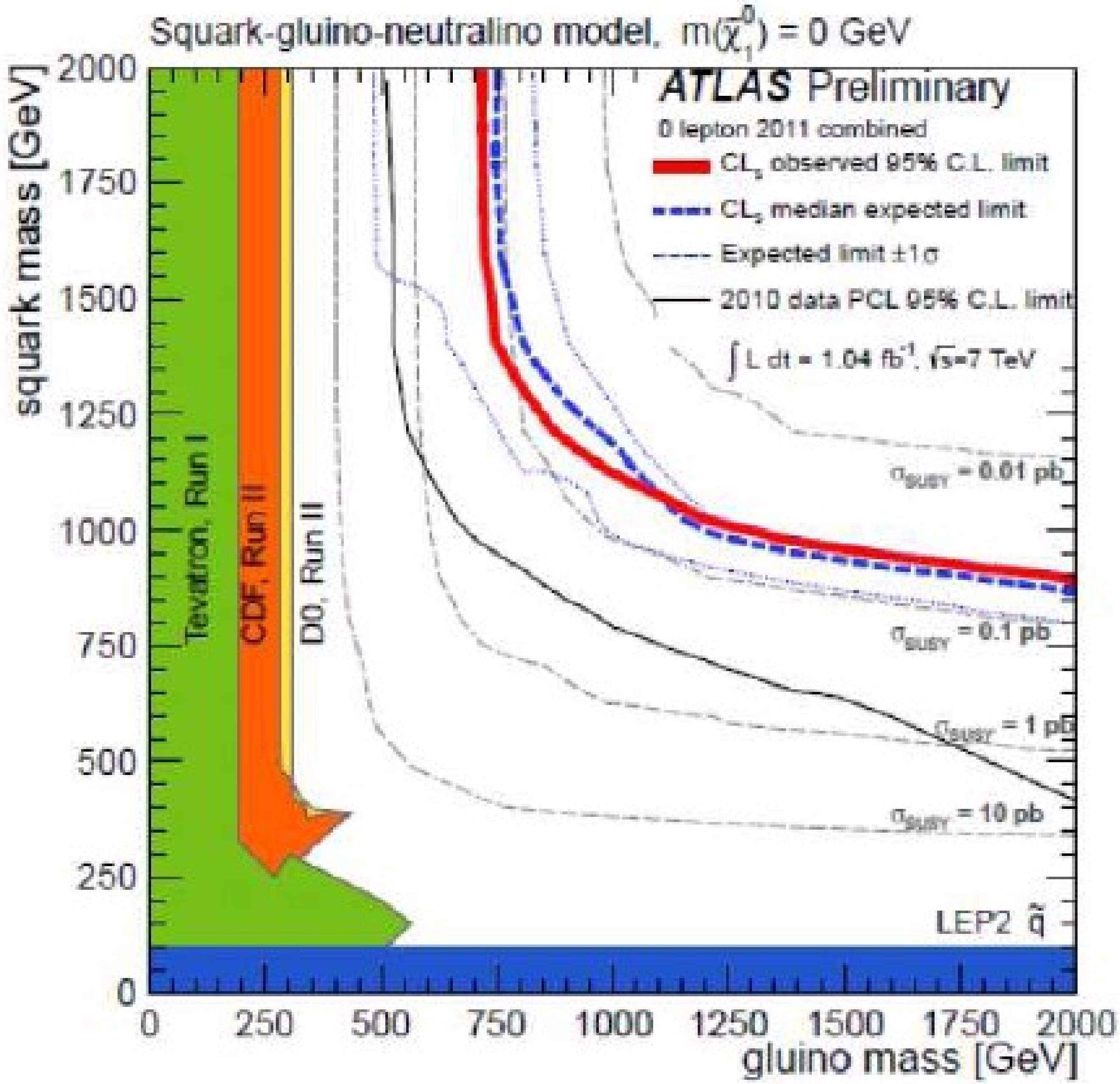
Not using MIA

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

SU(2) imposed

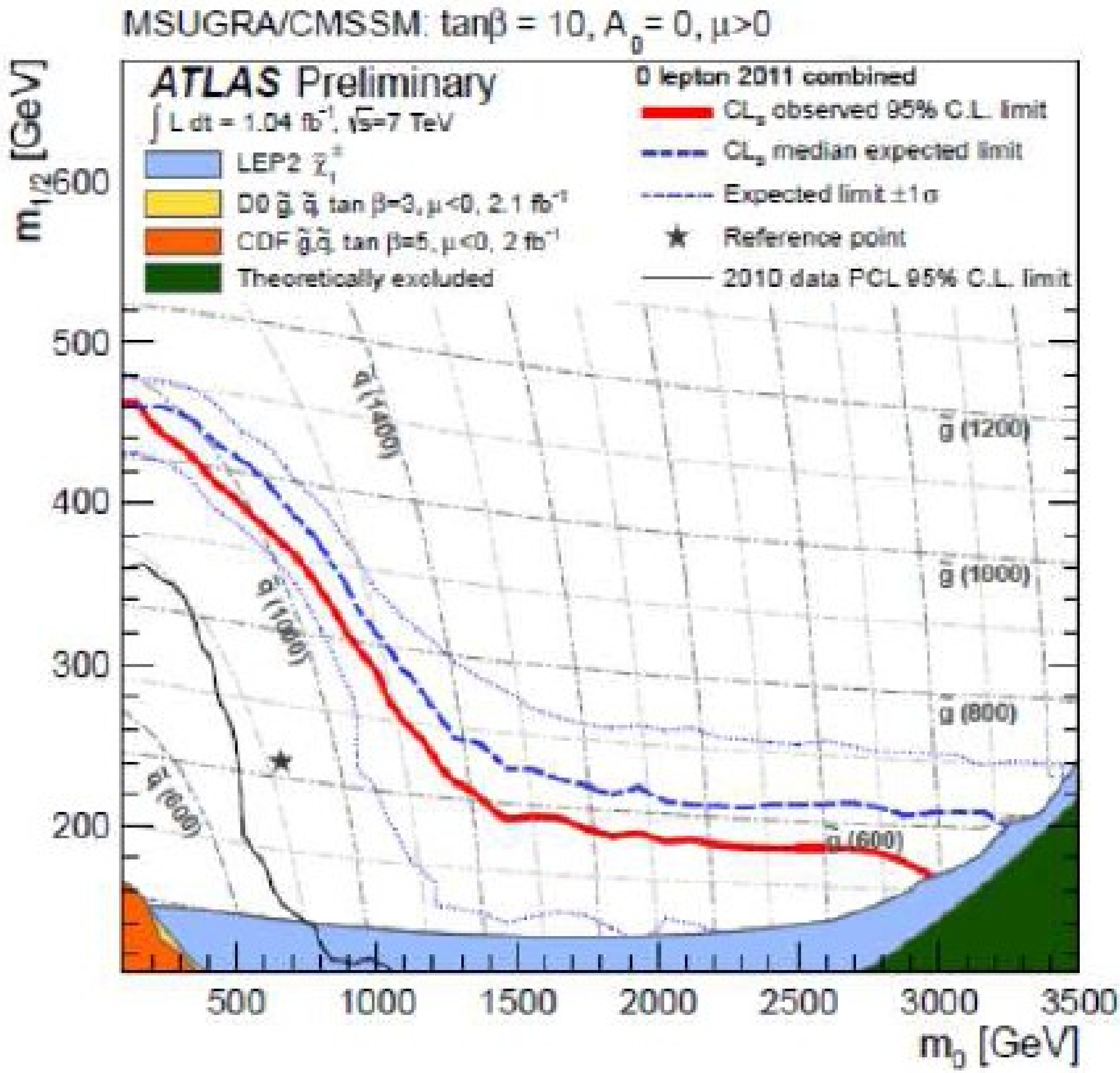
SUSY scenarios with NMFV

LHC constraints



SUSY scenarios with NMFV

LHC constraints



SUSY scenarios with NMFV

$$m^2_{H_{1,2}} = (1 + \delta_{1,2}) m^2_0$$

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H^\pm}$
CMSSM-5	1000	1000	0	5	0	0	117	1747	1746	1749
CMSSM-30	1000	1000	0	30	0	0	122	1416	1416	1418
NUHM-5	600	600	0	5	-1.86	$+1.86$	114	223	219	233
NUHM-30	1000	1000	0	30	-0.6	2.2	122	267	267	281

Other points with μ <0 and A_0 ≠ 0 also considered

Lightests sparticles masses (in GeV):

points	$\widetilde{C}_1^\pm$	$\widetilde{N}_1$	$\widetilde{g}$	$\widetilde{\nu}_\tau$	$\widetilde{\tau}_1$
CMSSM-5	776	427	2174	1189	1061
CMSSM-30	778	428	2175	1145	954
NUHM-5	371	245	1328	737	582
NUHM-30	276	267	2180	1187	908

Heavy SUSY scenarios in order to avoid LHC constraints. All SUSY spectrum very heavy, including lightest squarks (next slide).

Run from GUT to low energy using SPheno

SUSY scenarios with NMFV

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
CMSSM-5	1000	1000	0	5	0	0	117	1747	1746	1749
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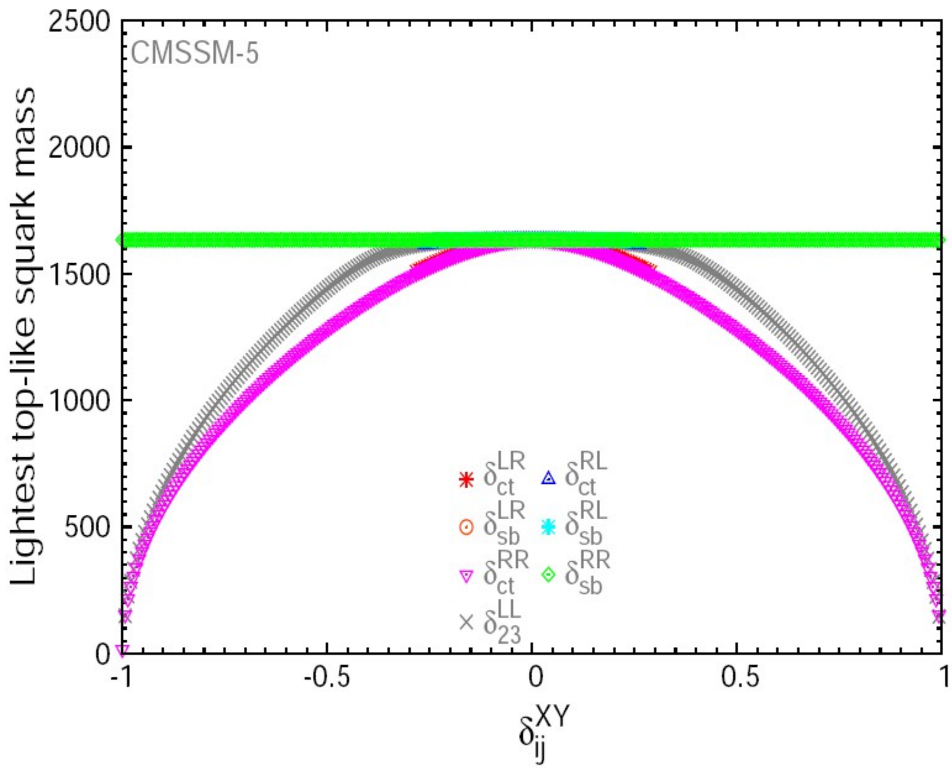

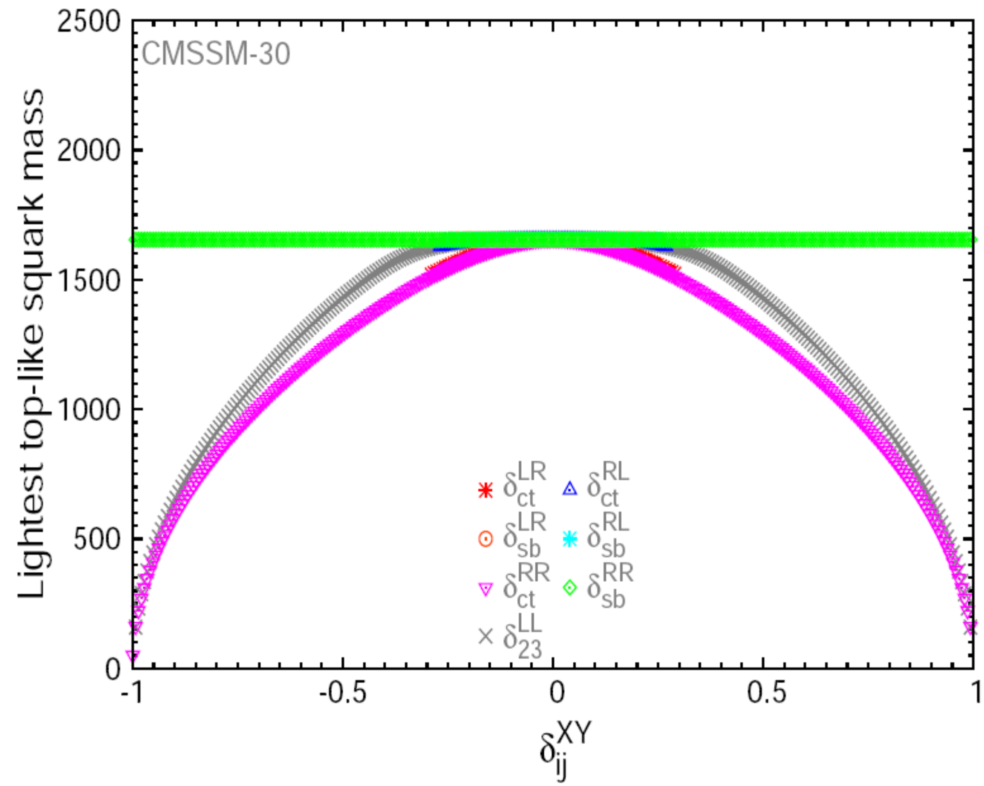

Lightest squarks order 1 TeV or above for the interesting delta regions

SUSY scenarios with NMFV

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H^\pm}$
CMSSM-5	1000	1000	0	5	0	0	117	1747	1746	1749
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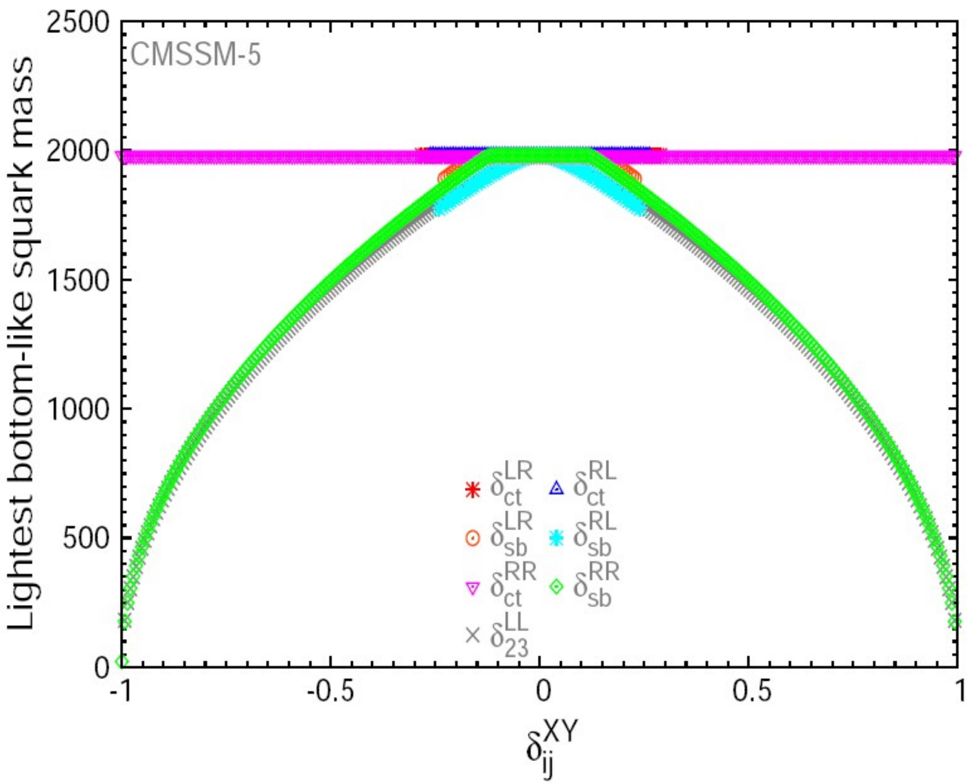

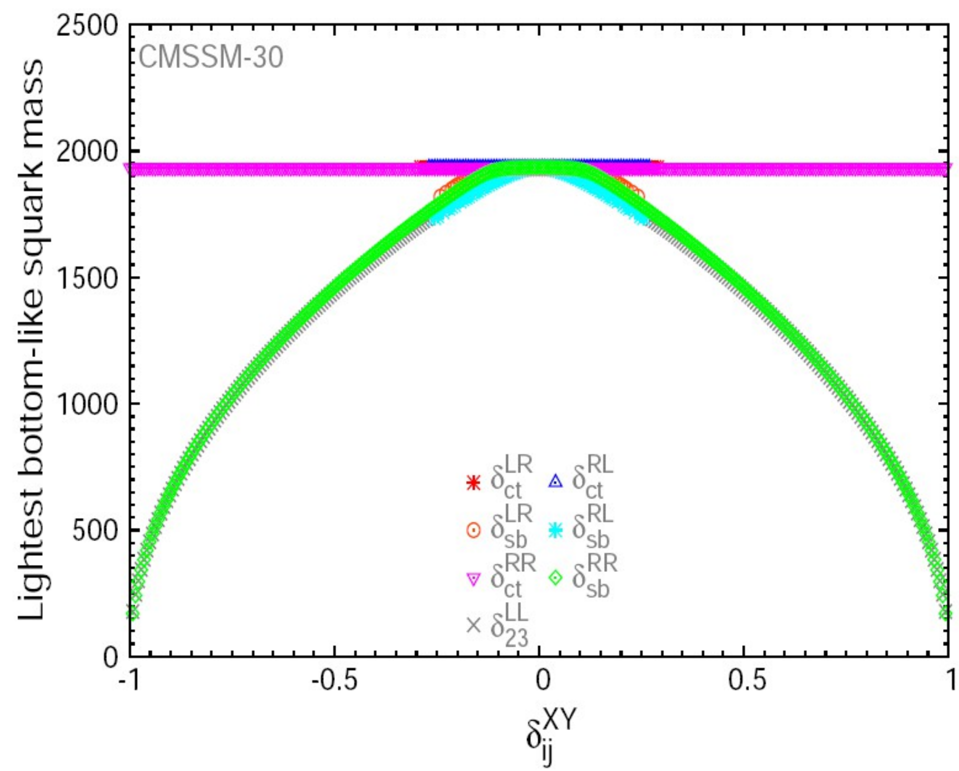

Similarly for sbottom-type squarks

SUSY scenarios with NMFV

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H^\pm}$
CMSSM-5	1000	1000	0	5	0	0	117	1747	1746	1749
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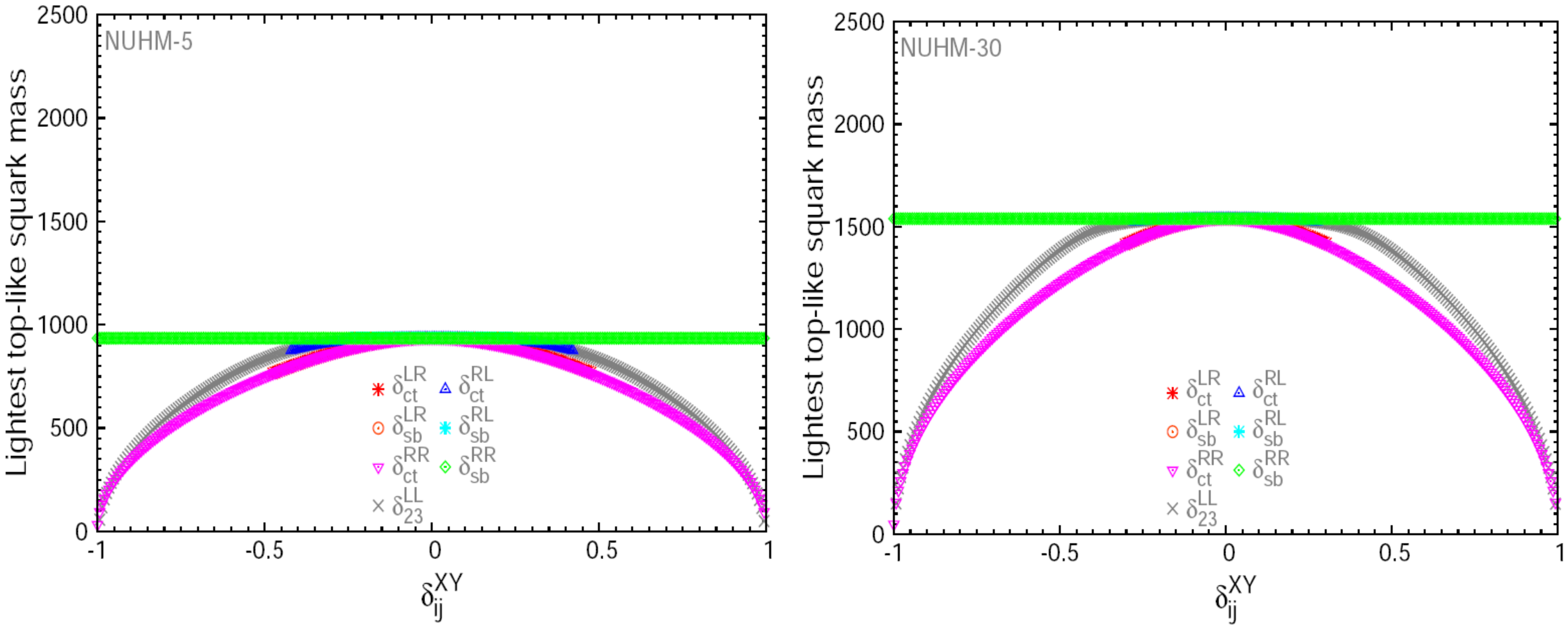

SUSY scenarios with NMFV

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
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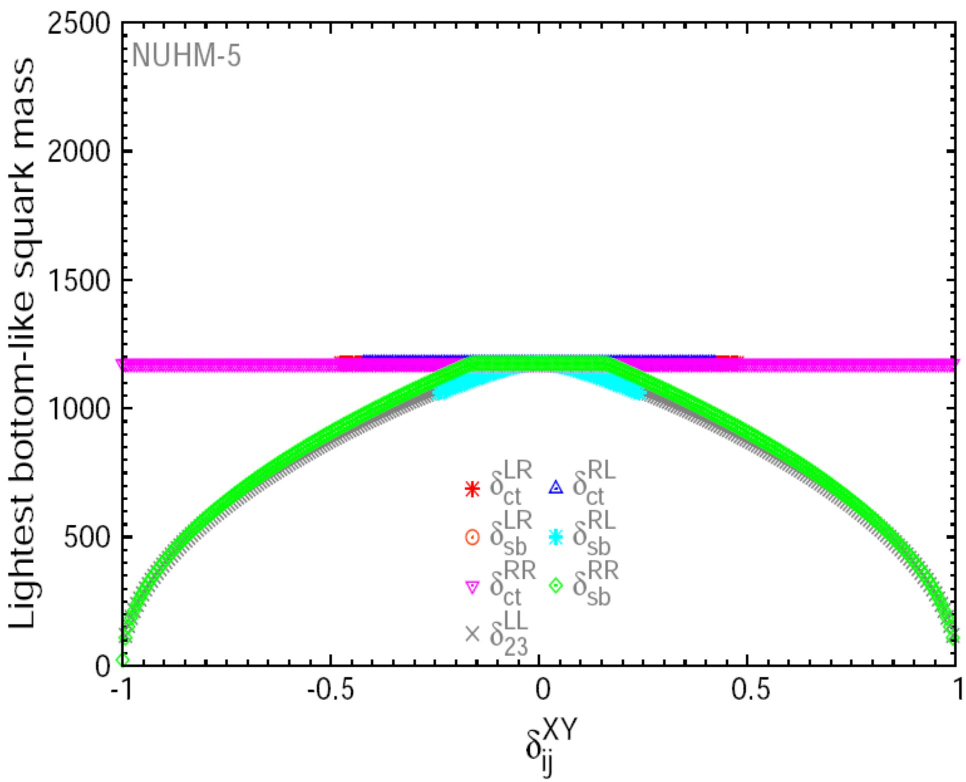
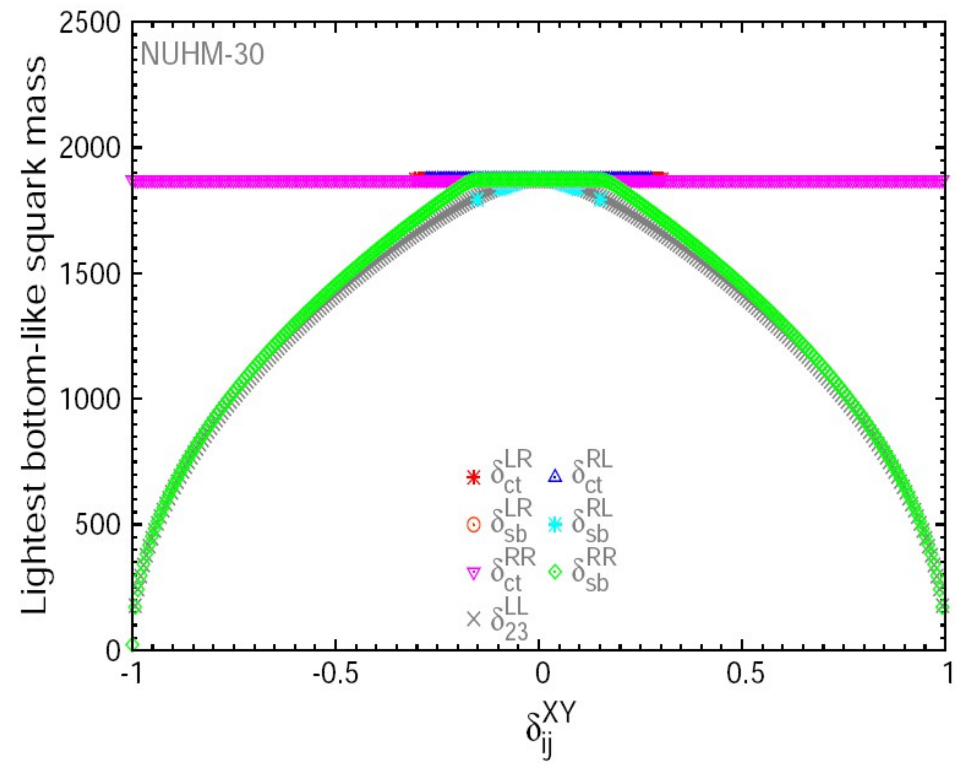




Constraints from B-Physics

We choose the following observables:

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

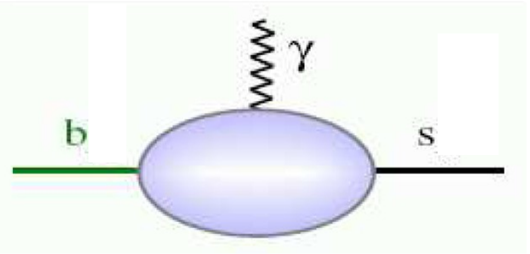
$$\mathrm{BR}(B_s \to \mu^+ \mu^-)$$

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

Constraints from B-Physics

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

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



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

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

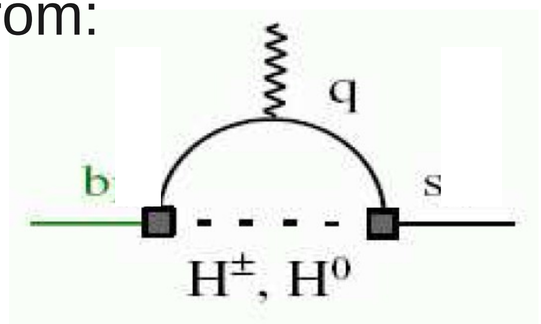
and prime operators exchanging L by R

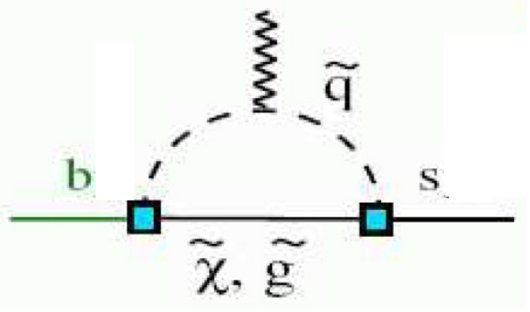
We consider MSSM contributions from:

Loops with Higgs bosons

Loops with charginos

Loops with gluinos





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

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

Constraints from B-Physics

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

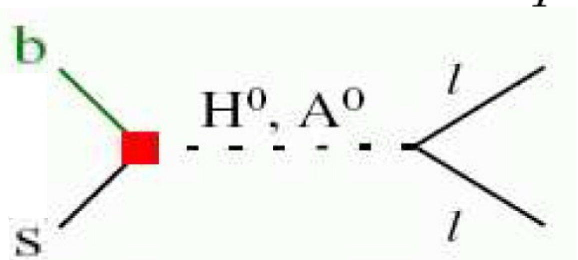
$$\mathcal{H}_{\rm eff} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{\rm CKM}^{ts*} V_{\rm CKM}^{tb} \sum_i (C_i O_i + C_i' O_i')$$

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

$$O_S = m_b\,(\bar{s}P_R b)\,(\bar{\mu}\mu)\,,$$

$$O_P = m_b\,(\bar{s}P_R b)\,(\bar{\mu}\gamma_5\mu)\,,$$

and prime operators exchanging L by R



Box diagrams with charginos

Z-penguin diagrams with charginos

Neutral Higgs penguin diagrams with charginos and gluinos

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm exp} < 4.5 \times 10^{-9} \quad (95\%\ \mathrm{CL})$$

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

Constraints from B-Physics

ΔM_{B_s}

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

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

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

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

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

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

Box diagrams (charginos and gluinos)

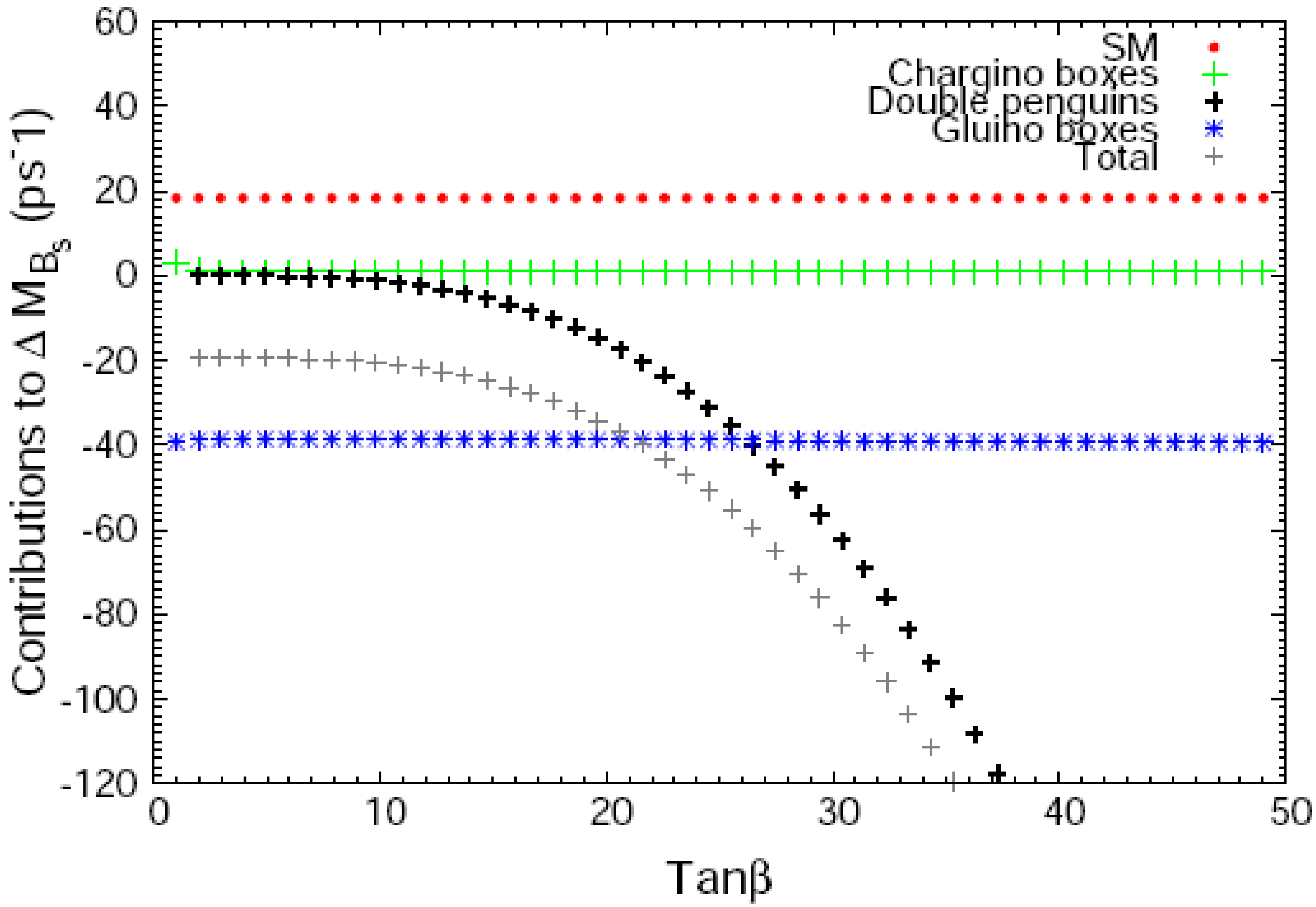
Z-penguin diagrams (charginos)

Neutral Higgs double penguin diagrams (charginos and gluinos)

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

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

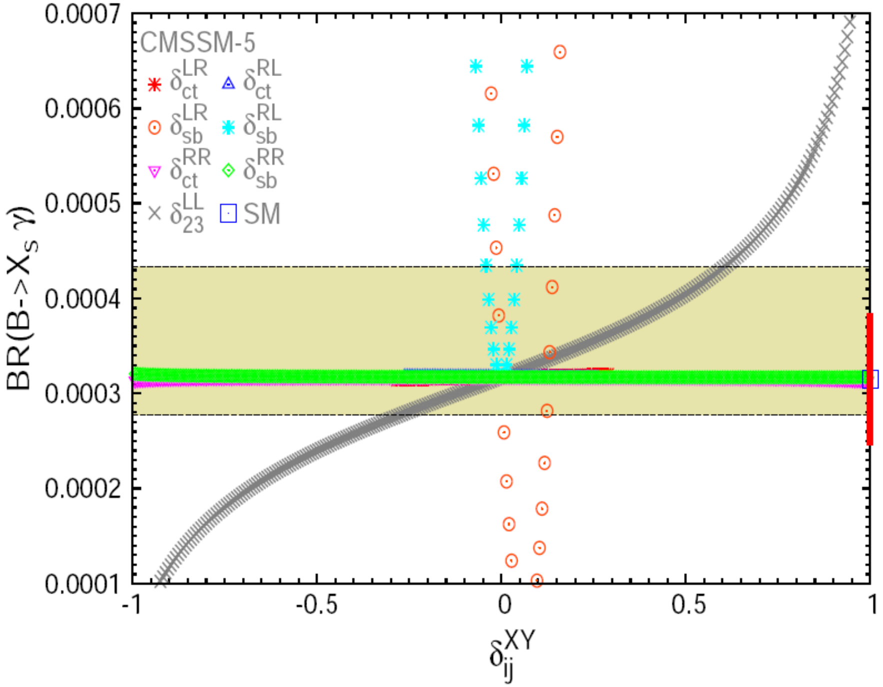
Constraints from B-Physics

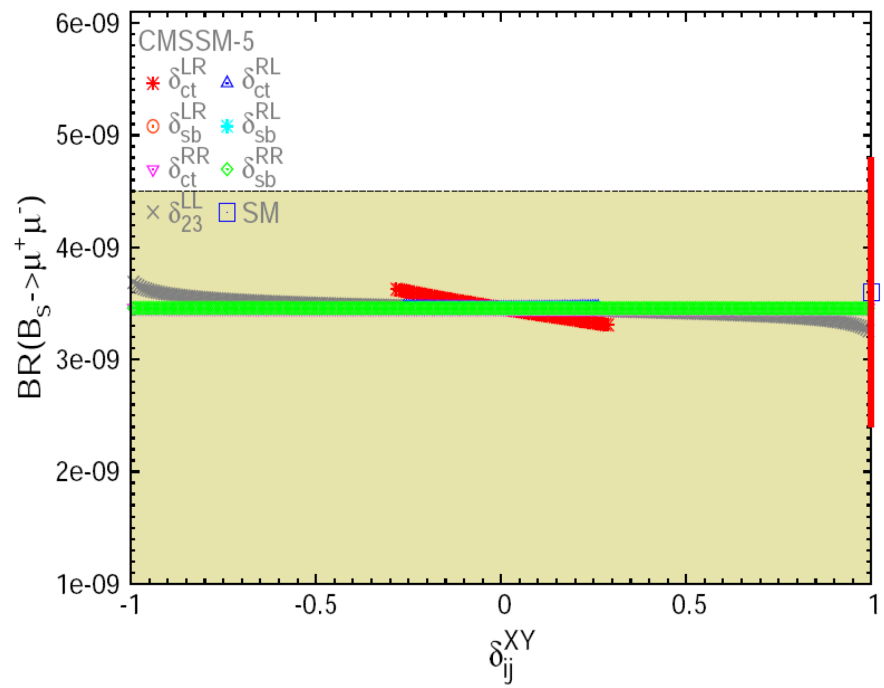


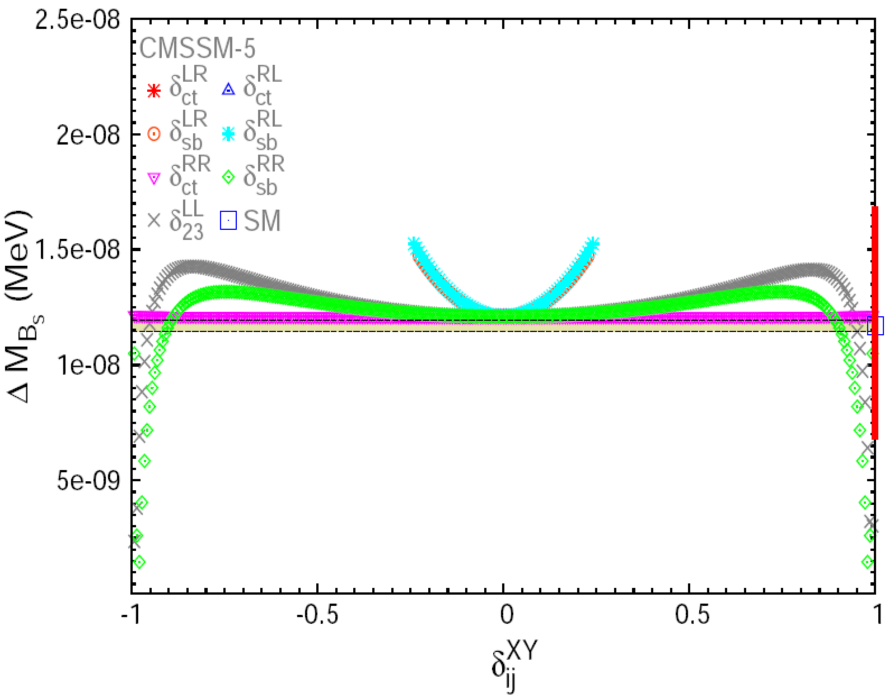
In the literature usually not all contributions are considered.

Gluino boxes are very relevant in NMFV.
Double Higgs penguins important at large $\tan\beta$

Constraints from B-Physics







General larger sensitivity to the sb sector.
ct sector less constrained

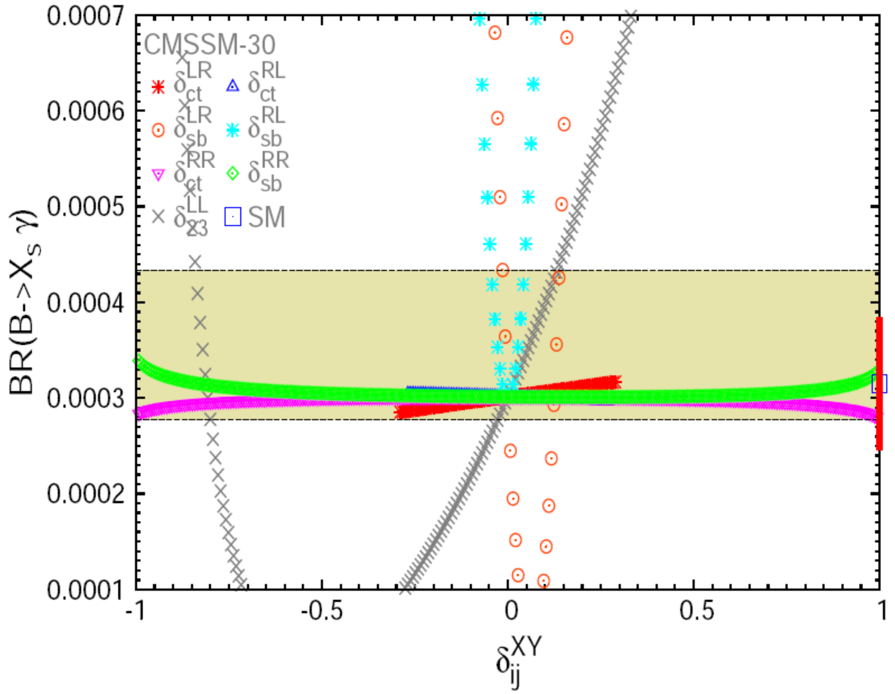
$\mathrm{BR}(B \to X_s\gamma)$ sets strict bounds on δ_{sb}^{LR} δ_{sb}^{RL} δ_{23}^{LL}

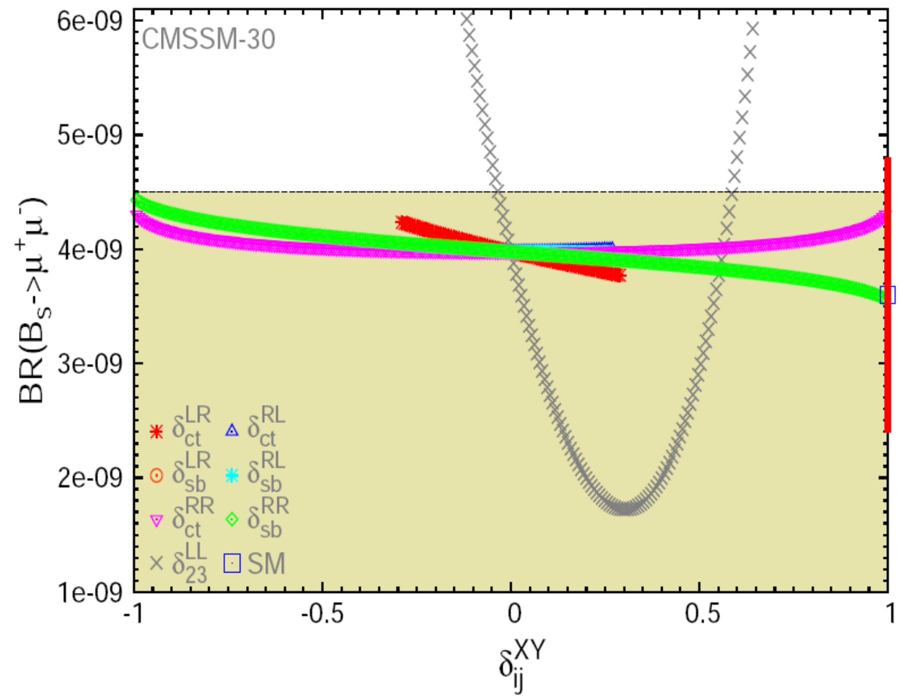
$\mathrm{BR}(B_s \to \mu^+\mu^-)$ sets bounds for large $\tan\beta$ and low m_A

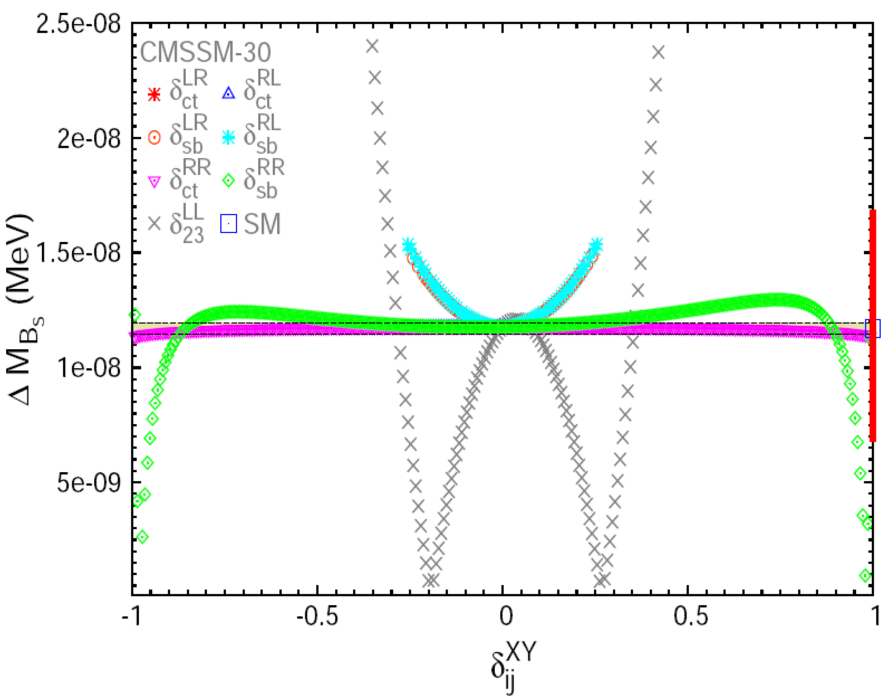
ΔM_{B_s} sets also strong bounds on δ_{sb}^{LR} δ_{sb}^{RL}

points	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM-5	1000	1000	0	5

Constraints from B-Physics





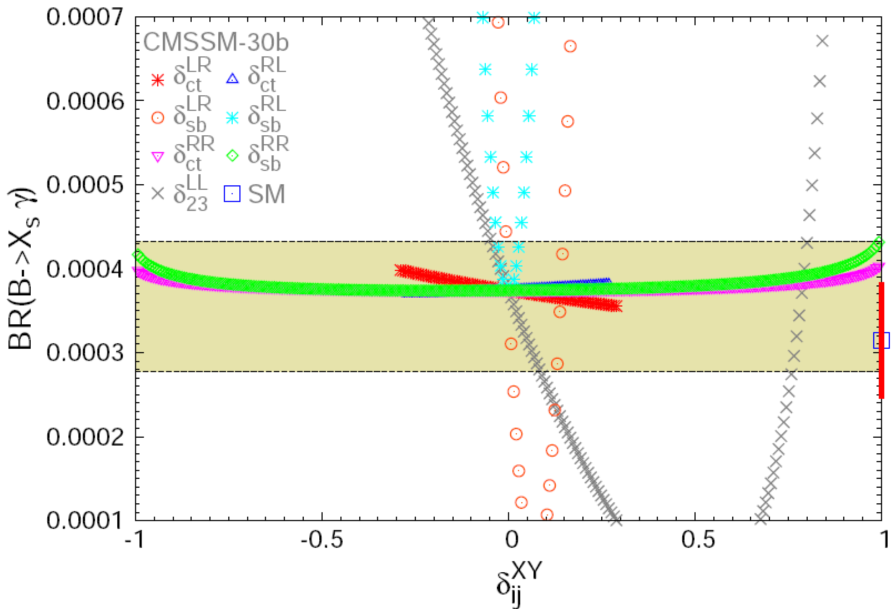


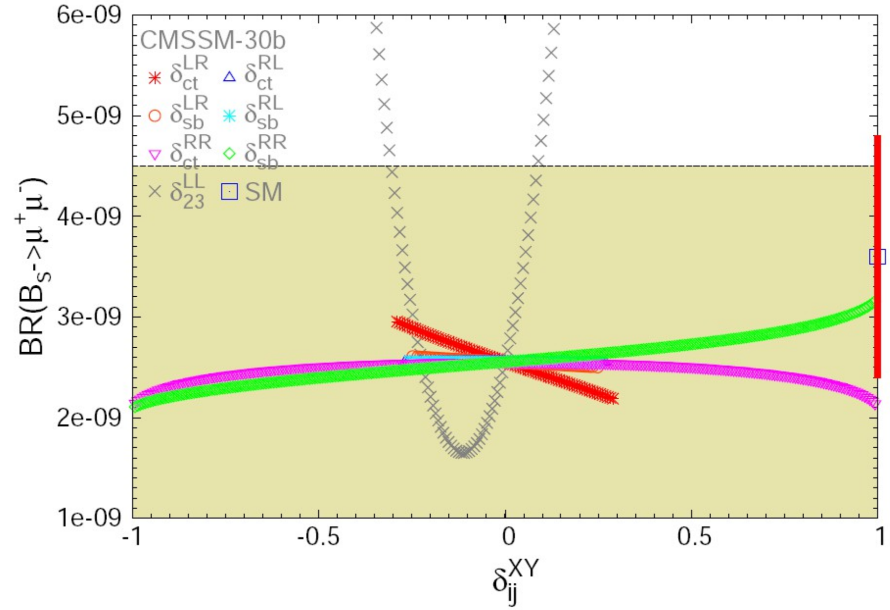
Large $\tan\beta$ allowed if heavy SUSY

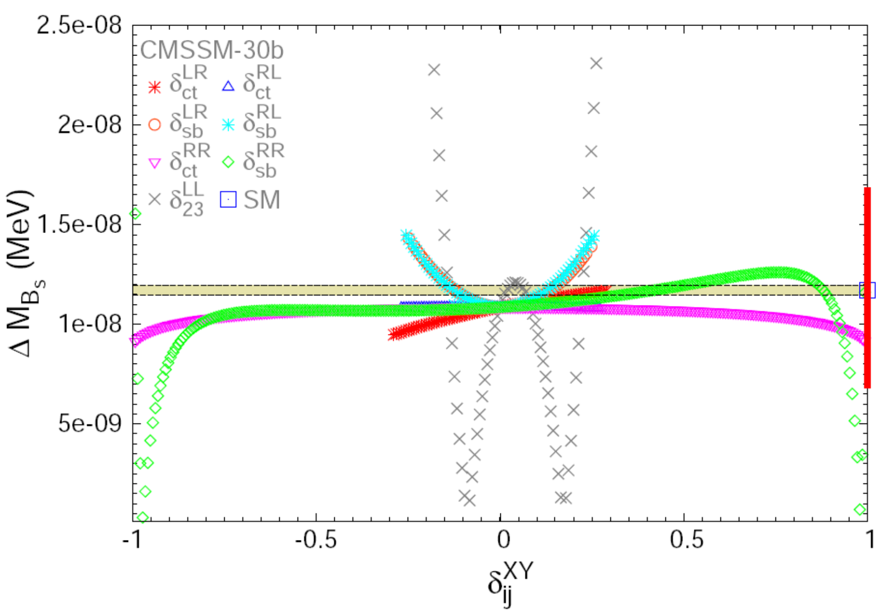
ΔM_{B_s} at large $\tan\beta$ also restricts δ^{LL}_{23}

points	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM-30	1000	1000	0	30

Constraints from B-Physics





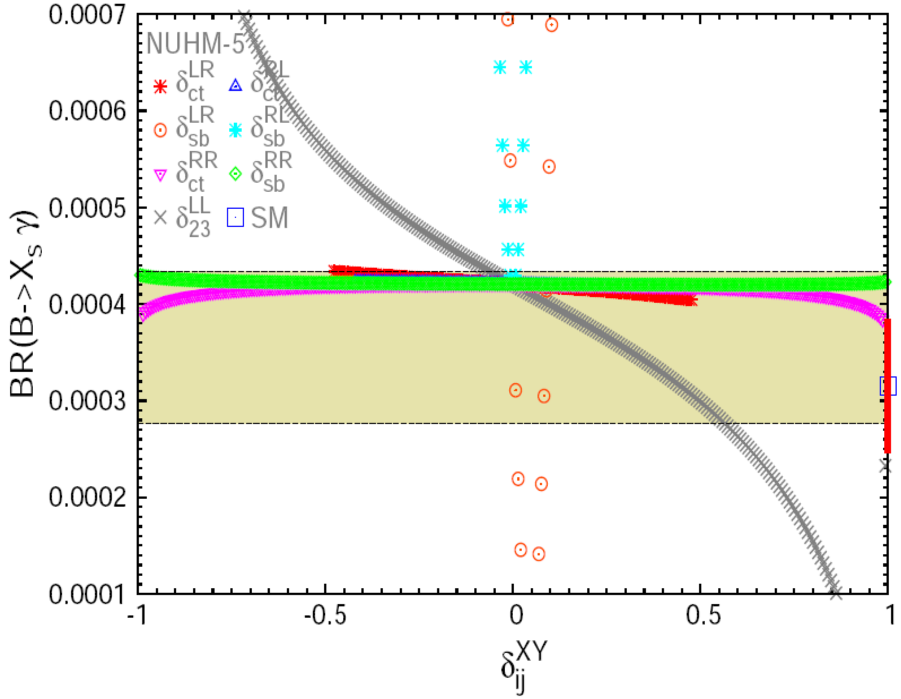


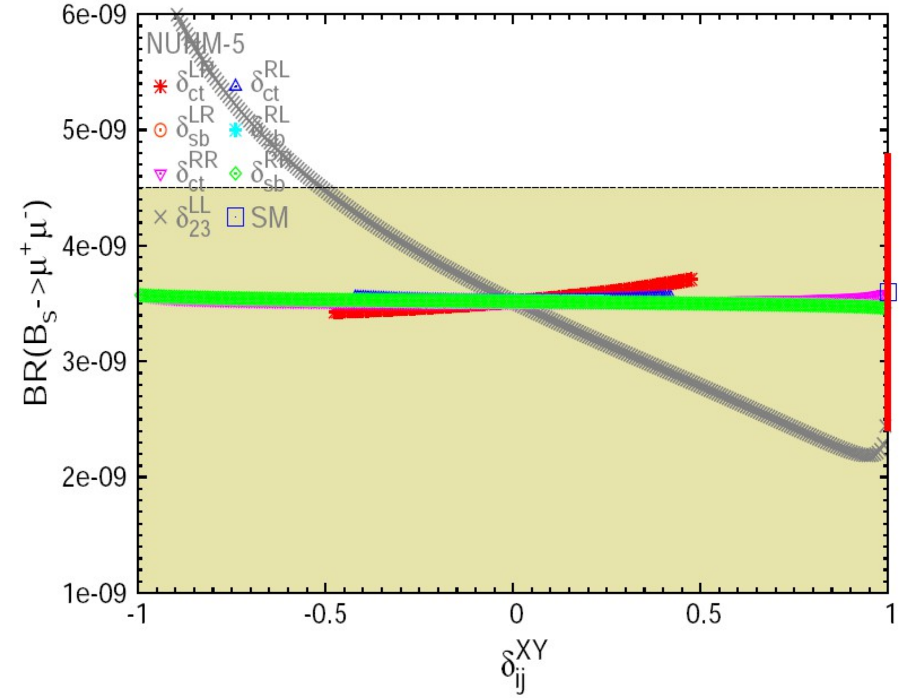
Results changing the sign of μ (μ <0)

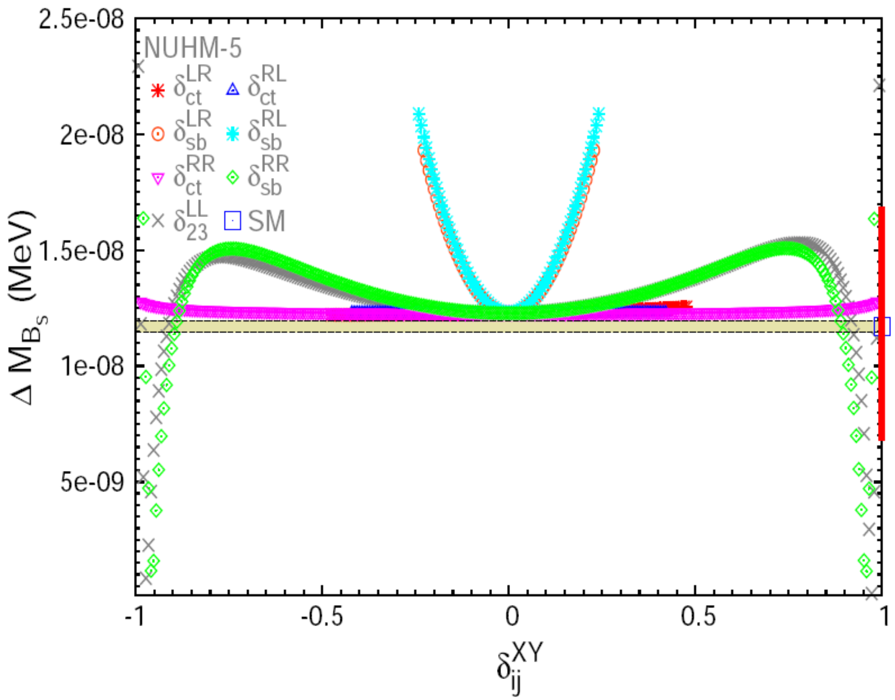
points	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM-30	1000	1000	0	30

Changing A_0 gives similar results.

Constraints from B-Physics



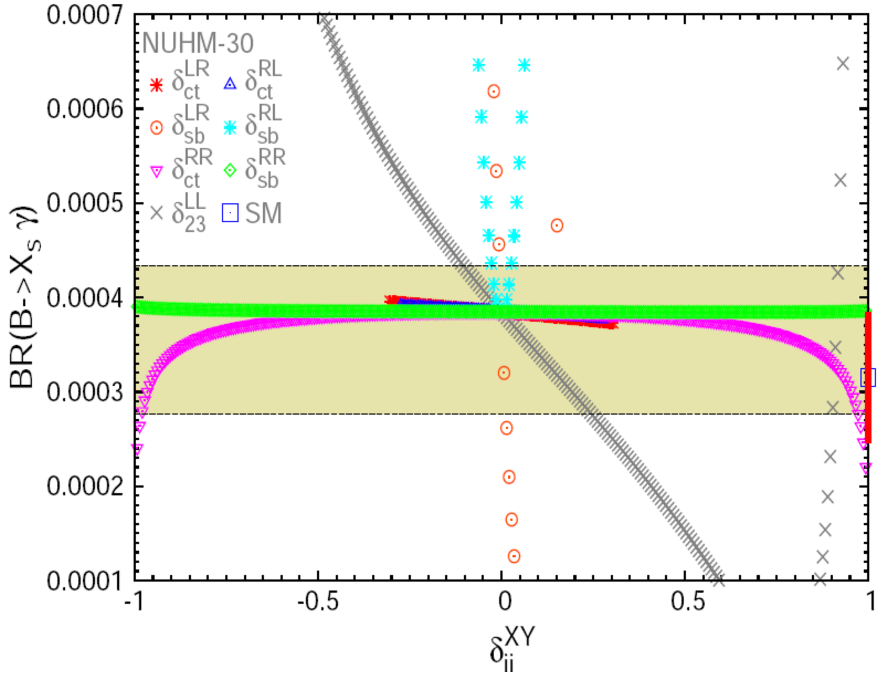


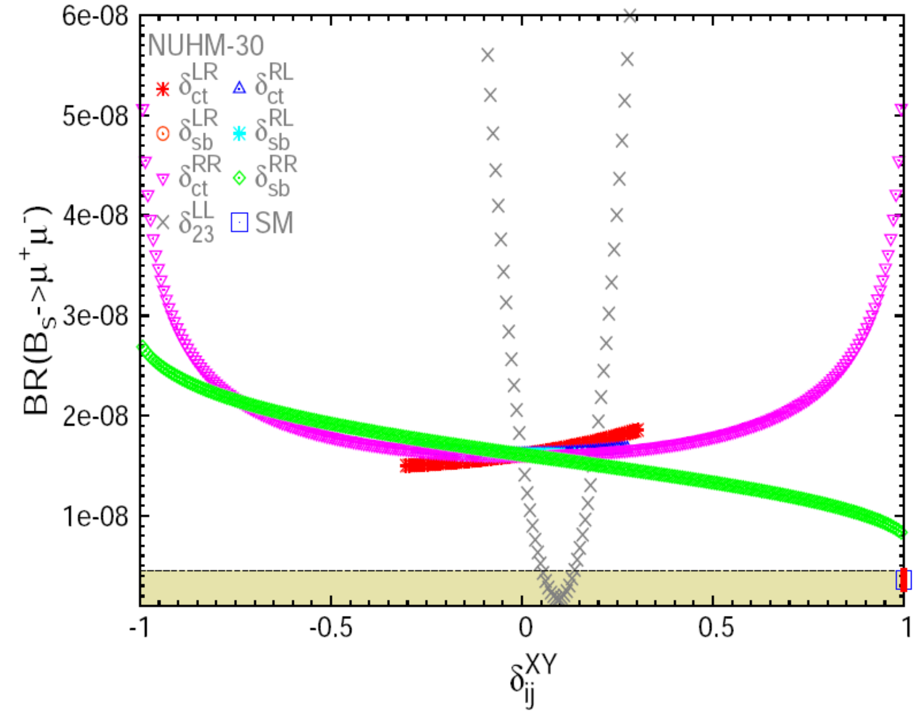


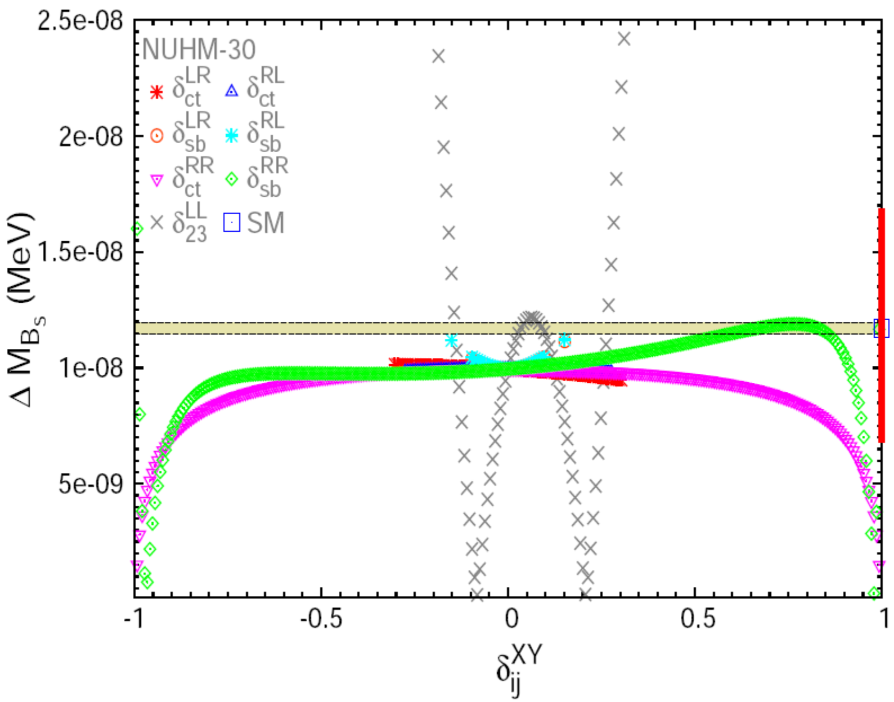
If M_A is low, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ also set restrictions even at low $\tan\beta$=5

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2
NUHM-5	600	600	0	5	-1.86	$+1.86$

Constraints from B-Physics





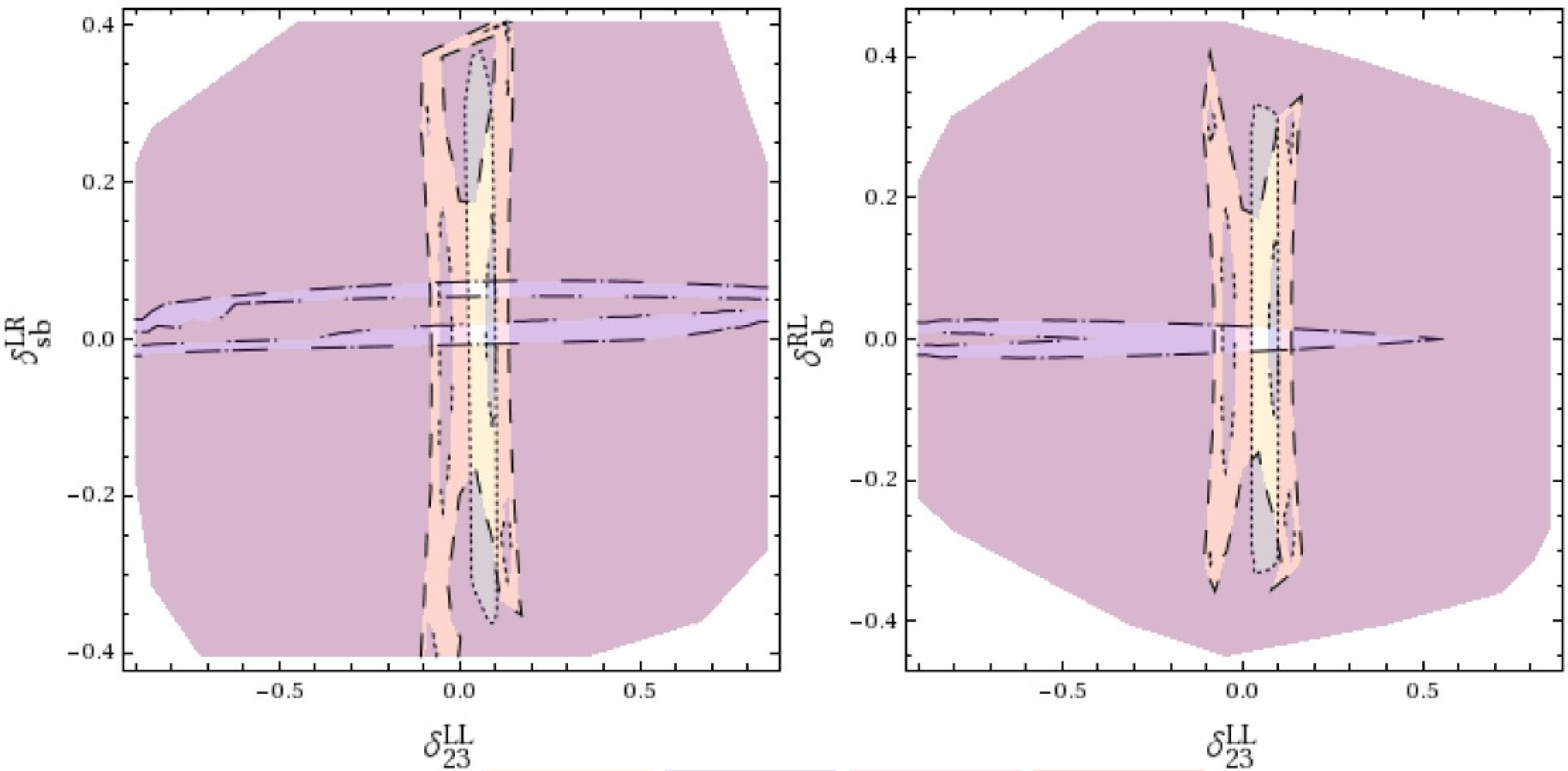


Excluded MFV points can be recovered in NMFV

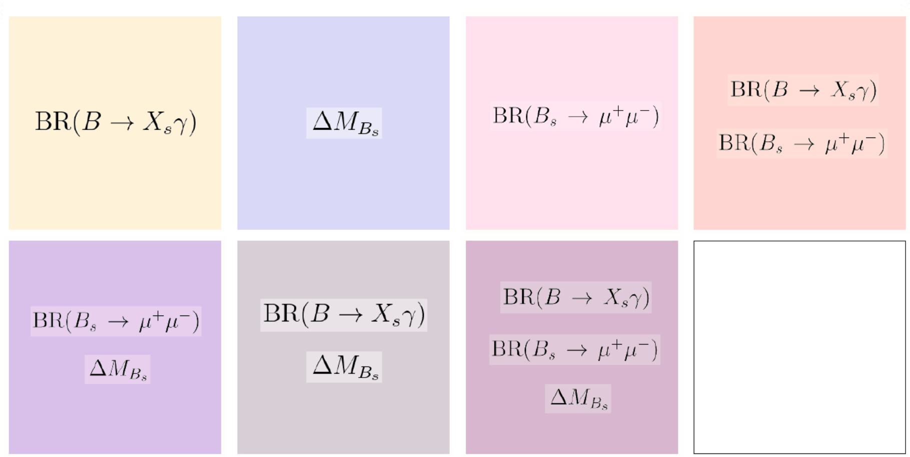
points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2
NUHM-30	1000	1000	0	30	-0.6	2.2

Constraints from B-Physics (two-dimensional constraints)

CMSSM-30

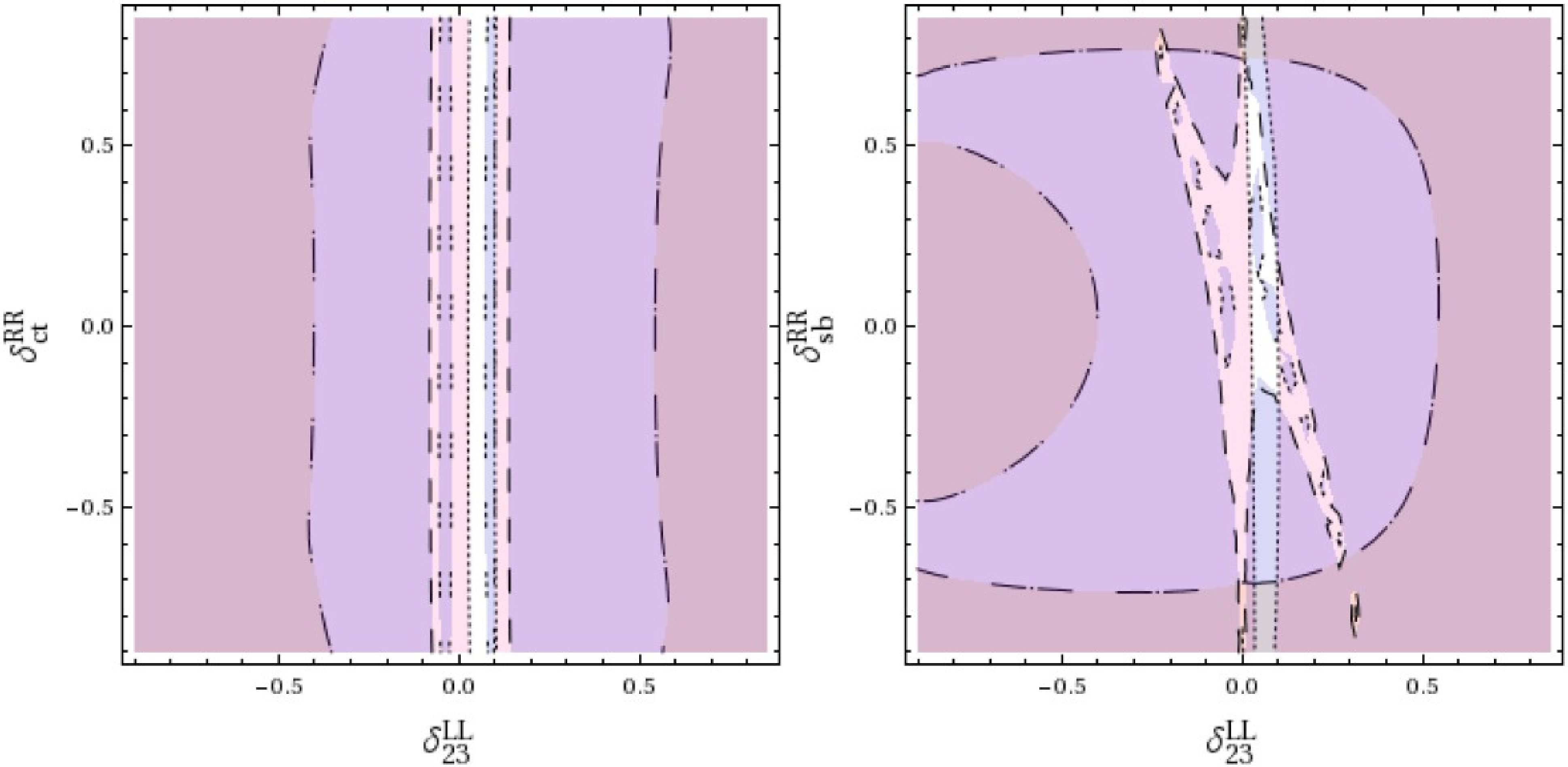


Large $\tan\beta$ scenarios very constrained.
Especially LRsb sector.
Mainly by $\mathrm{BR}(\boldsymbol{B} \to \boldsymbol{X}_s\gamma)$
and $\mathrm{BR}(\boldsymbol{B}_s \to \boldsymbol{\mu}^+\boldsymbol{\mu}^-)$

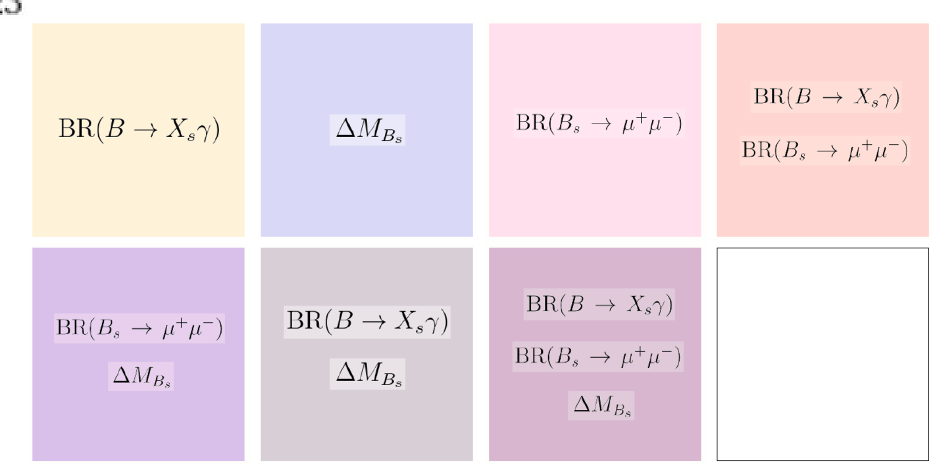


Constraints from B-Physics (two-dimensional constraints)

CMSSM-30

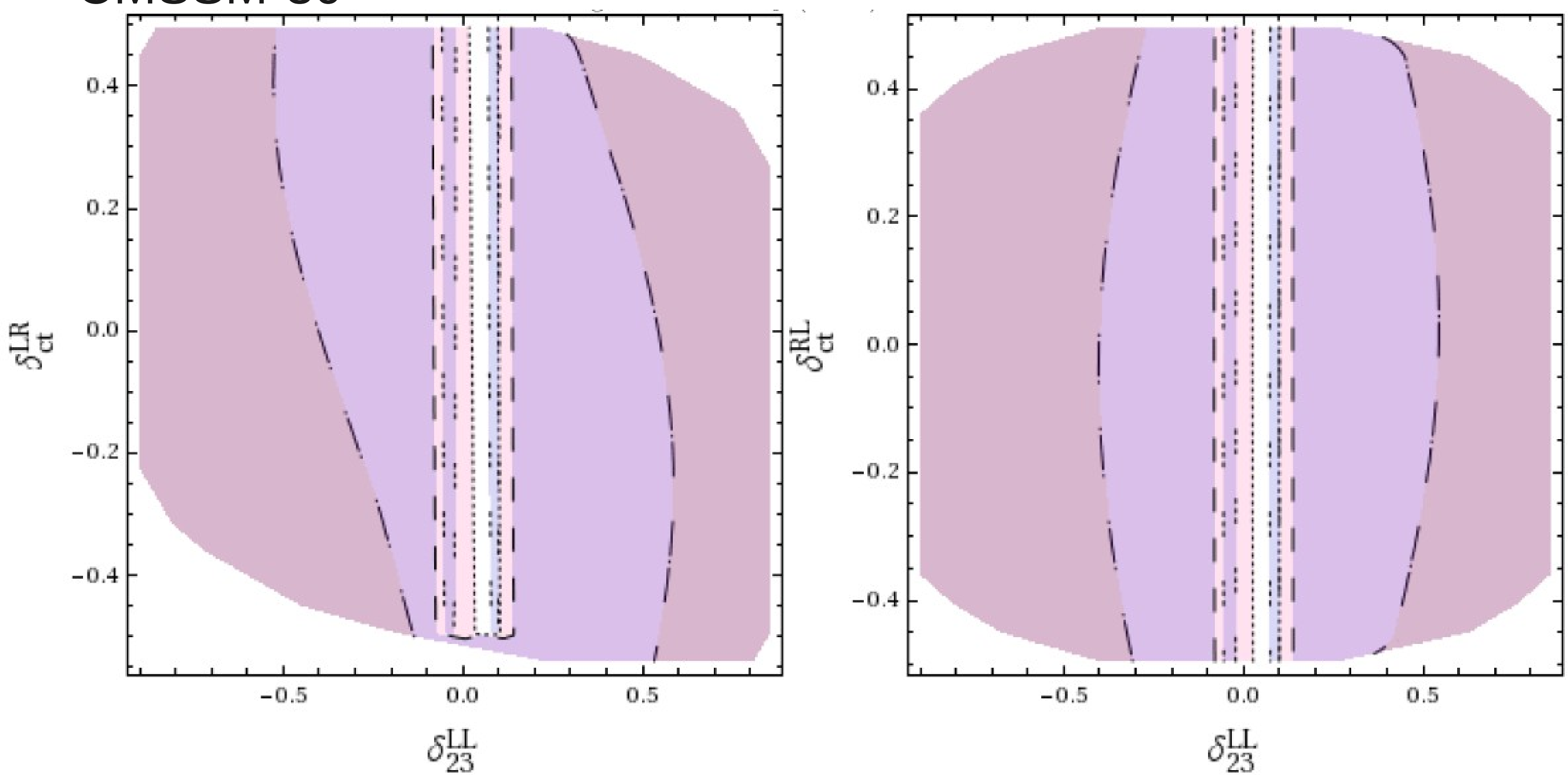


We found large allowed space in the RRct sector.
Main constraints on RRsb by ΔM_{B_s}

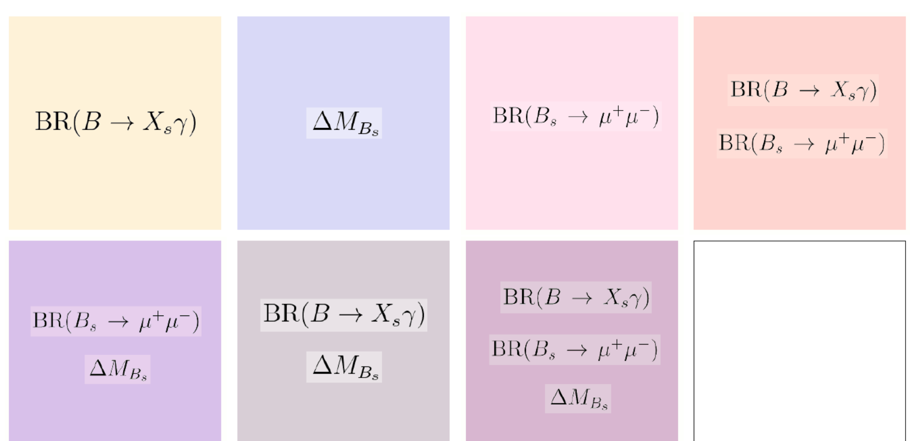


Constraints from B-Physics (two-dimensional constraints)

CMSSM-30

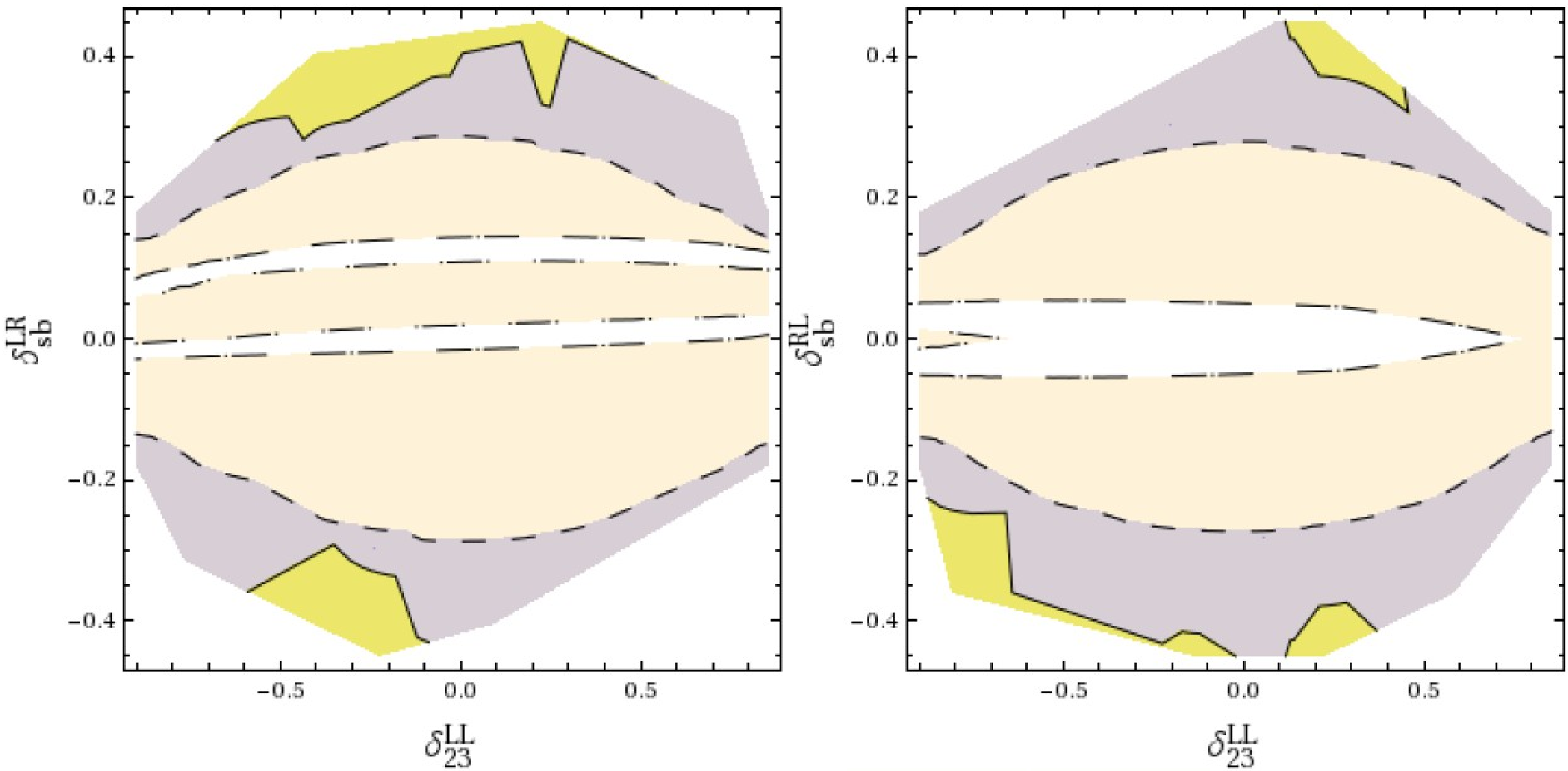


Also the LR/RLct deltas can be very large.



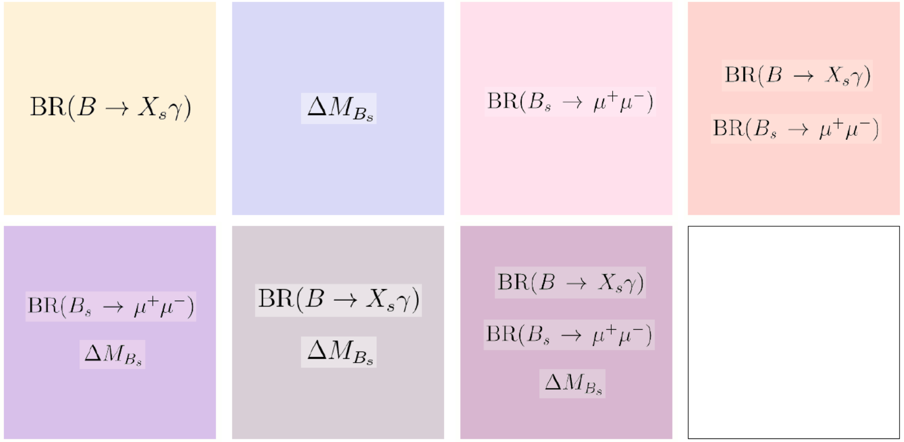
Constraints from B-Physics (two-dimensional constraints)

CMSSM-5



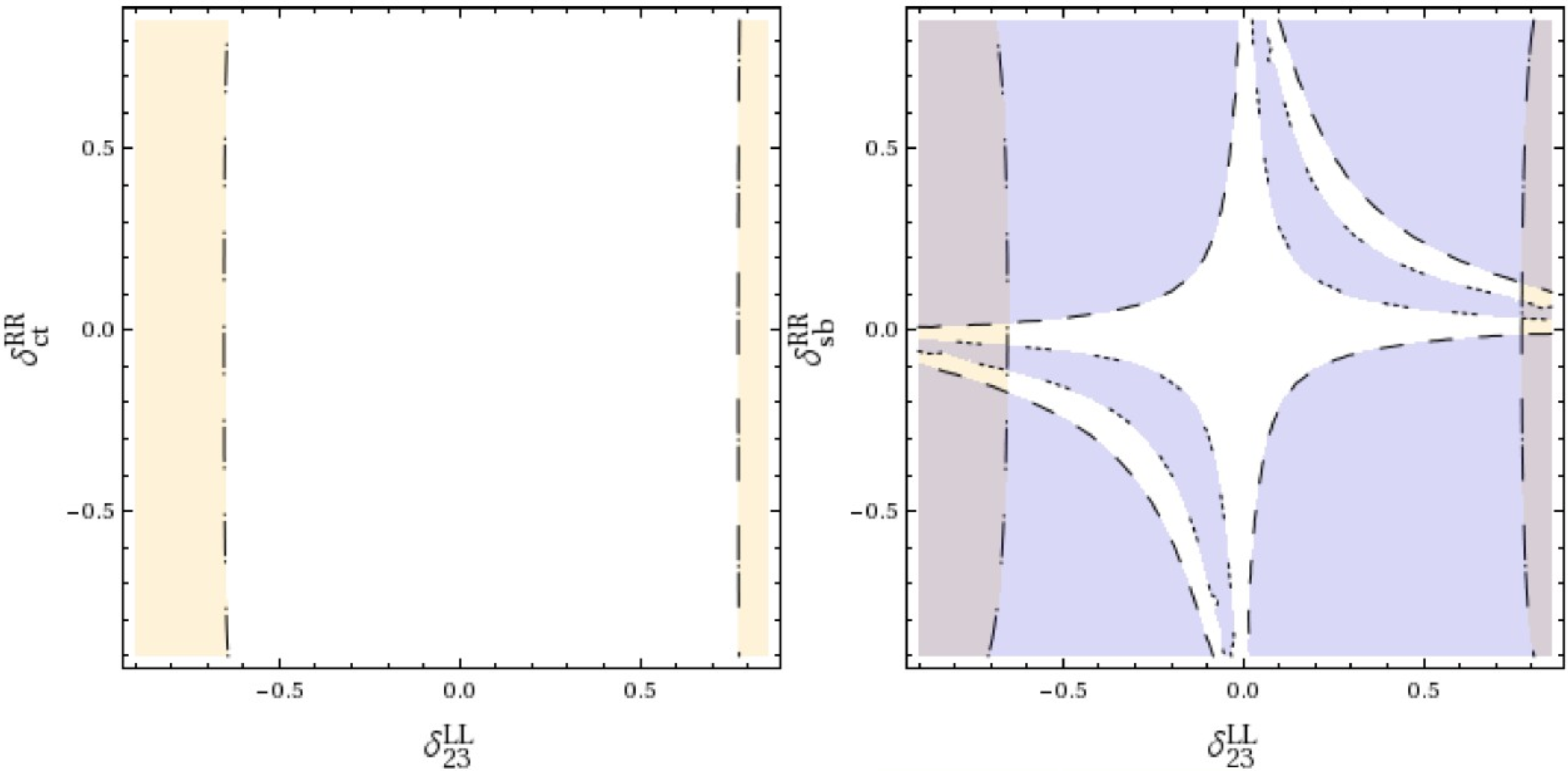
The allowed space grows for low $\tan\beta$

Main constraints in LR by $\mathrm{BR}(B \to X_s\gamma)$

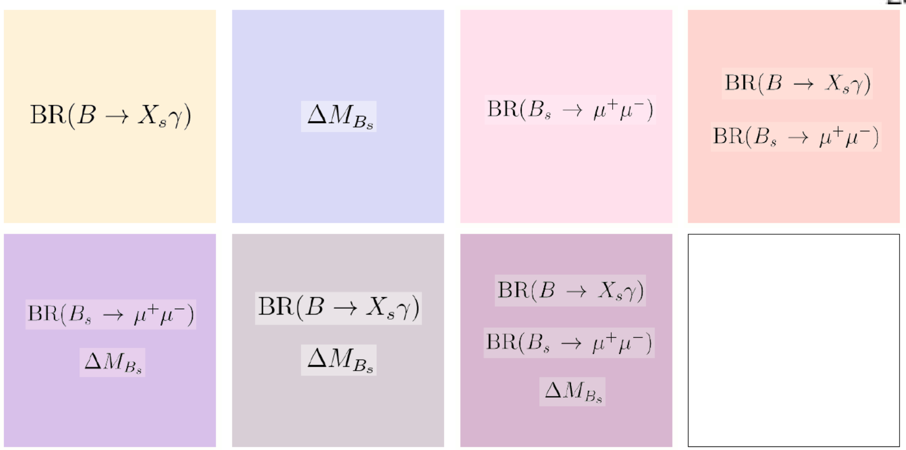


Constraints from B-Physics (two-dimensional constraints)

CMSSM-5

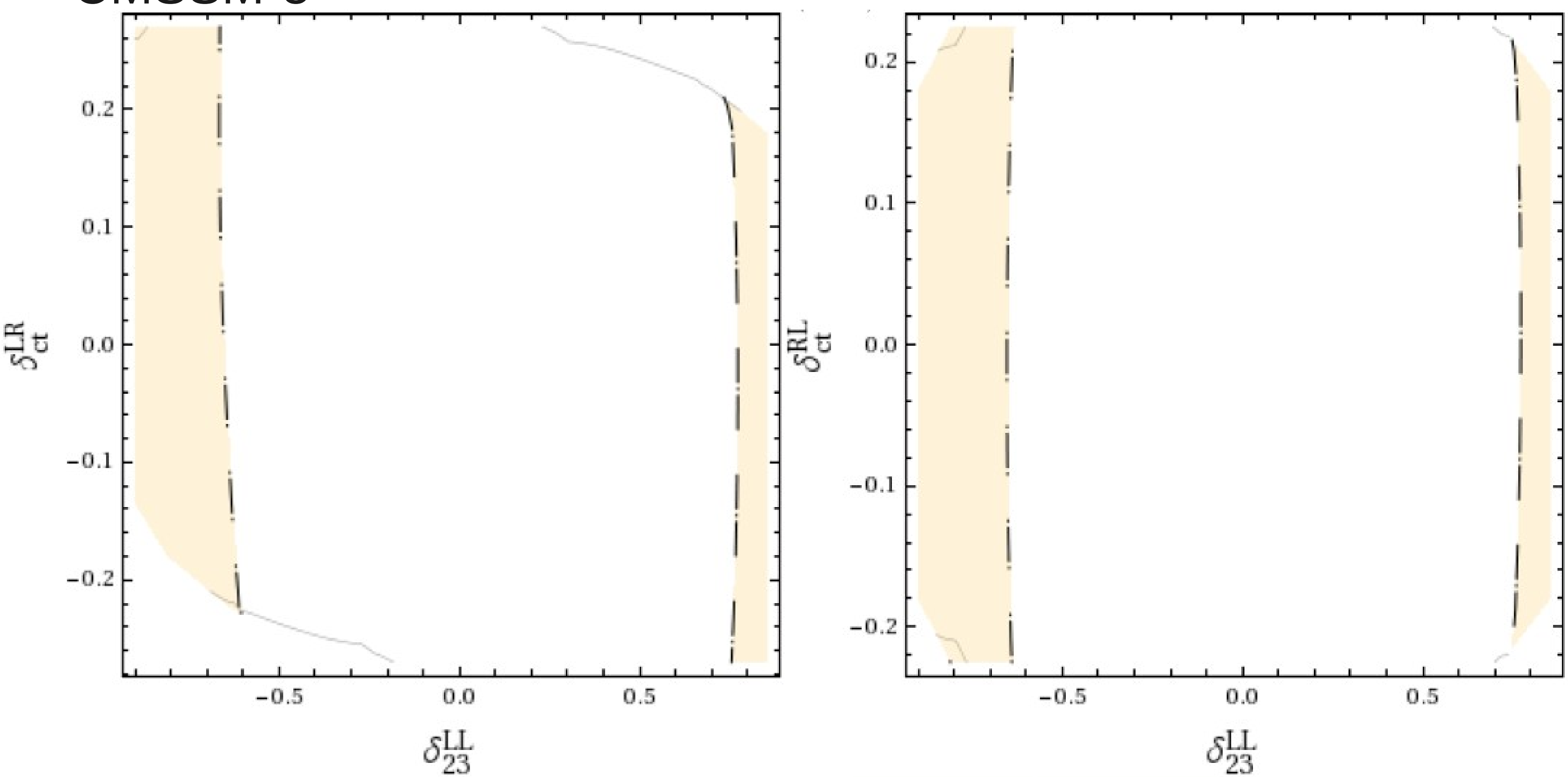


Large deltas RR allowed.

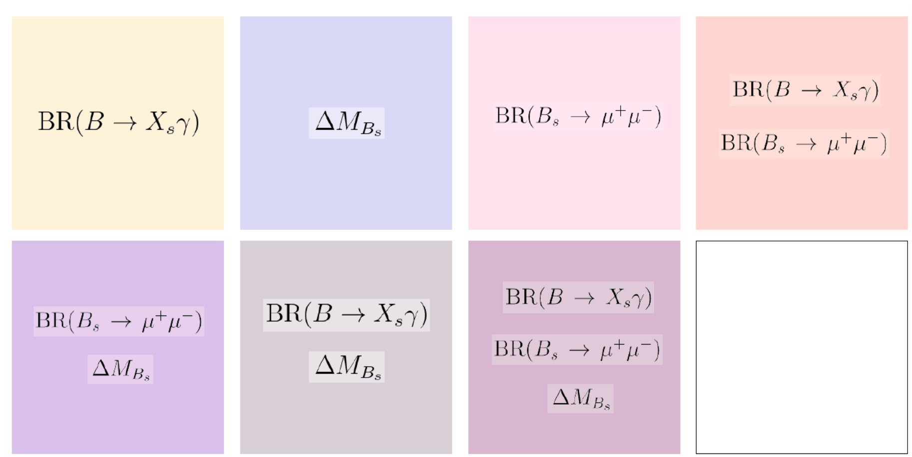


Constraints from B-Physics (two-dimensional constraints)

CMSSM-5

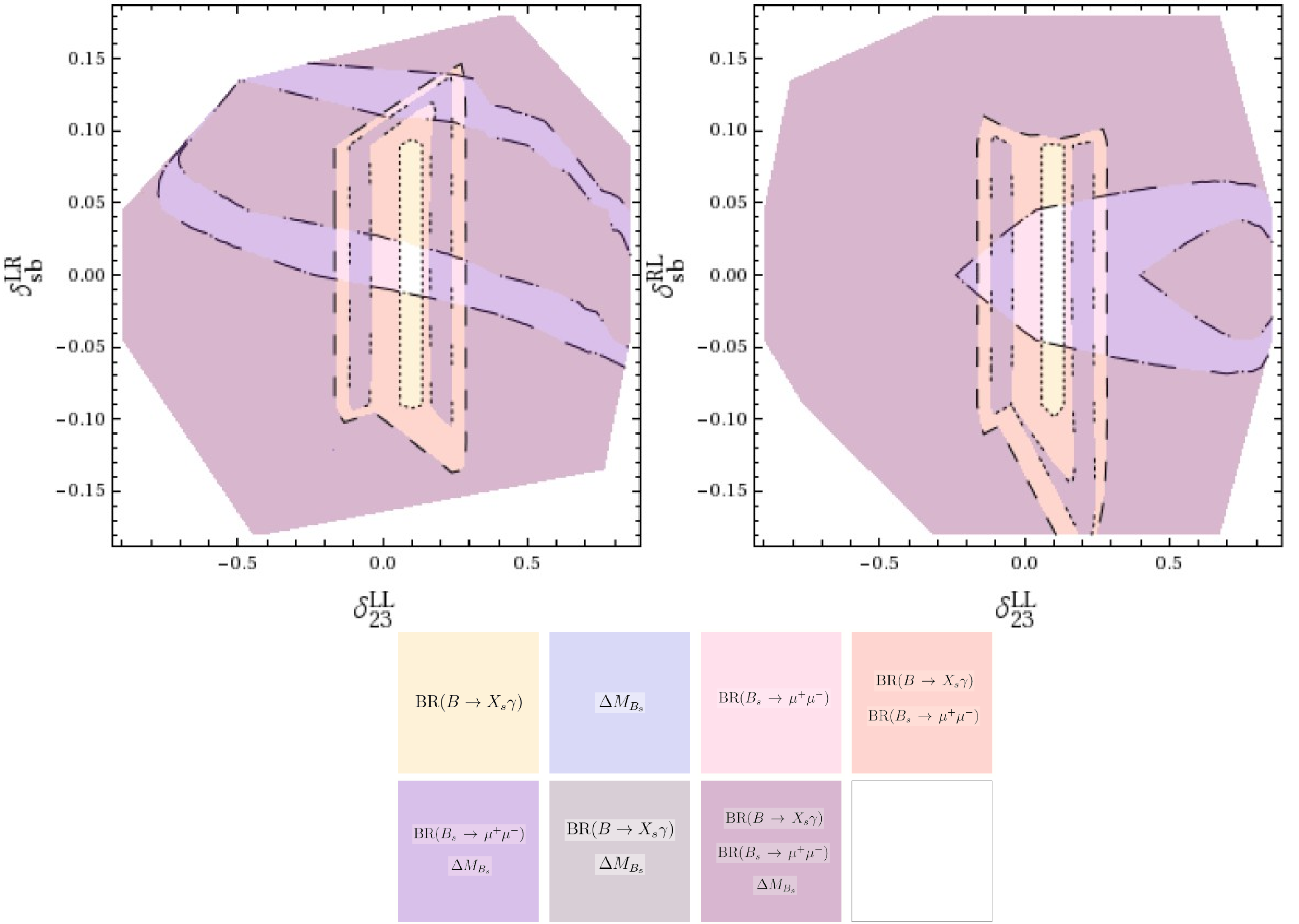


And also large LR/RLct deltas allowed.



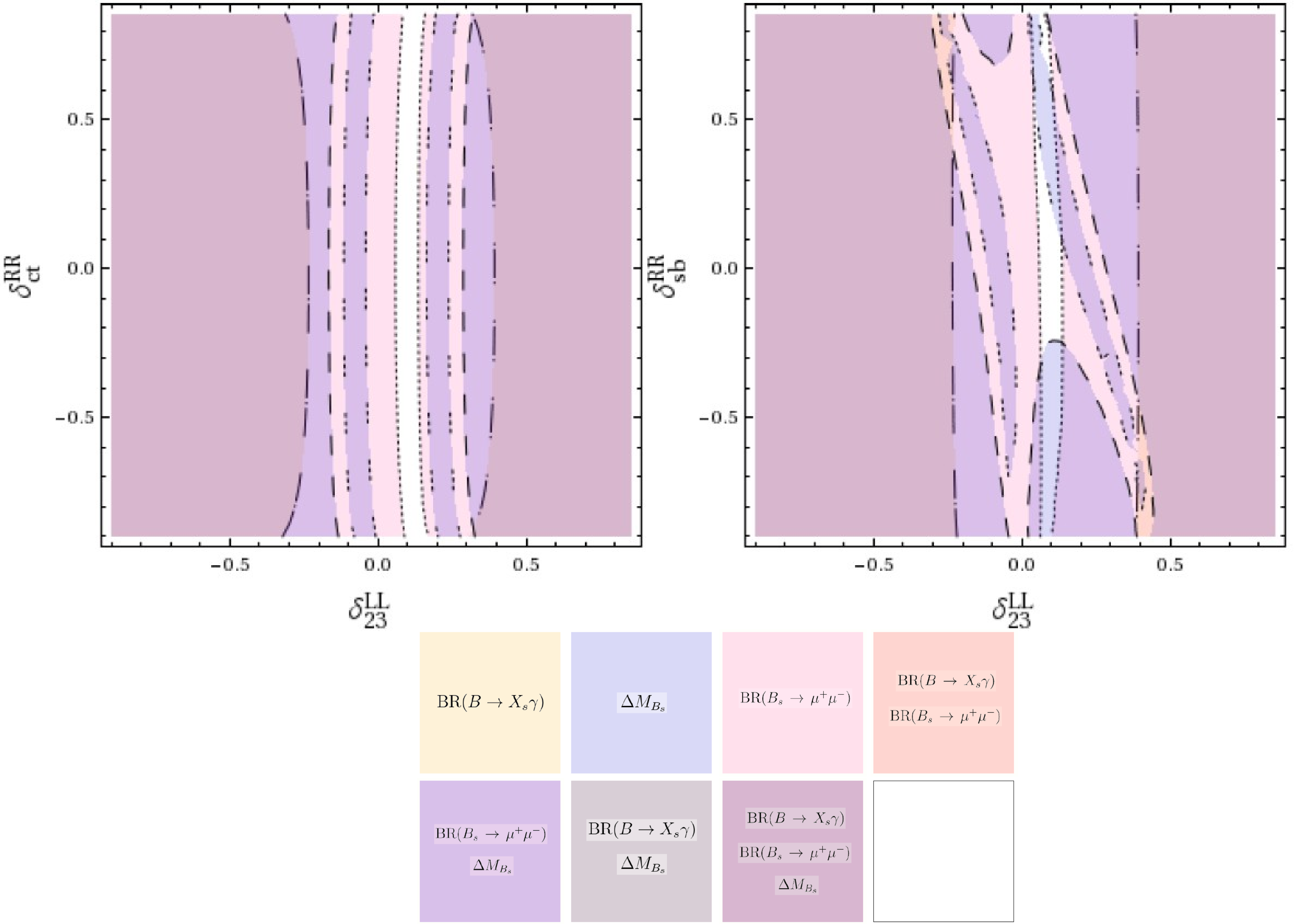
Constraints from B-Physics (two-dimensional constraints)

NUHM-30



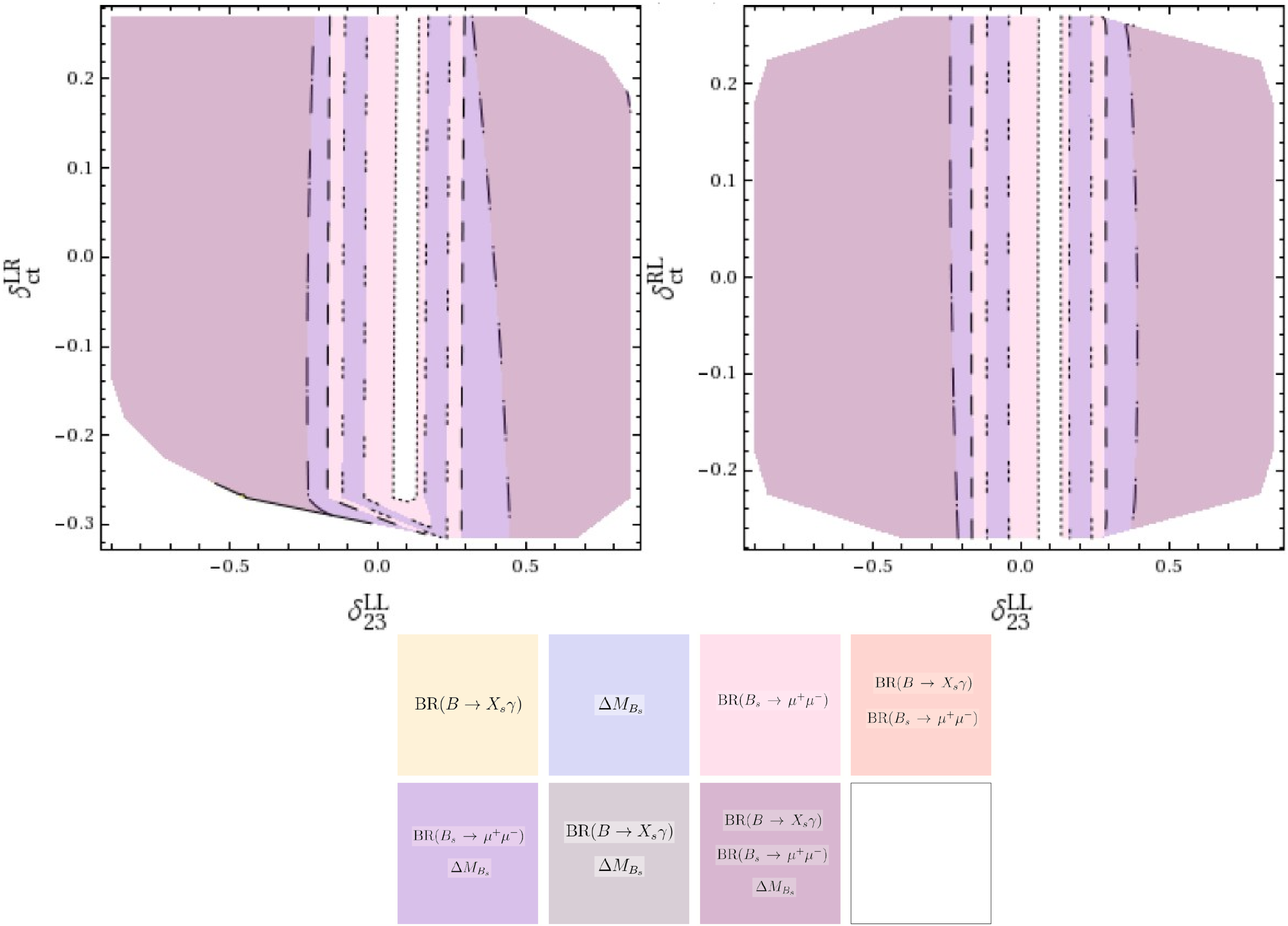
Constraints from B-Physics (two-dimensional constraints)

NUHM-30



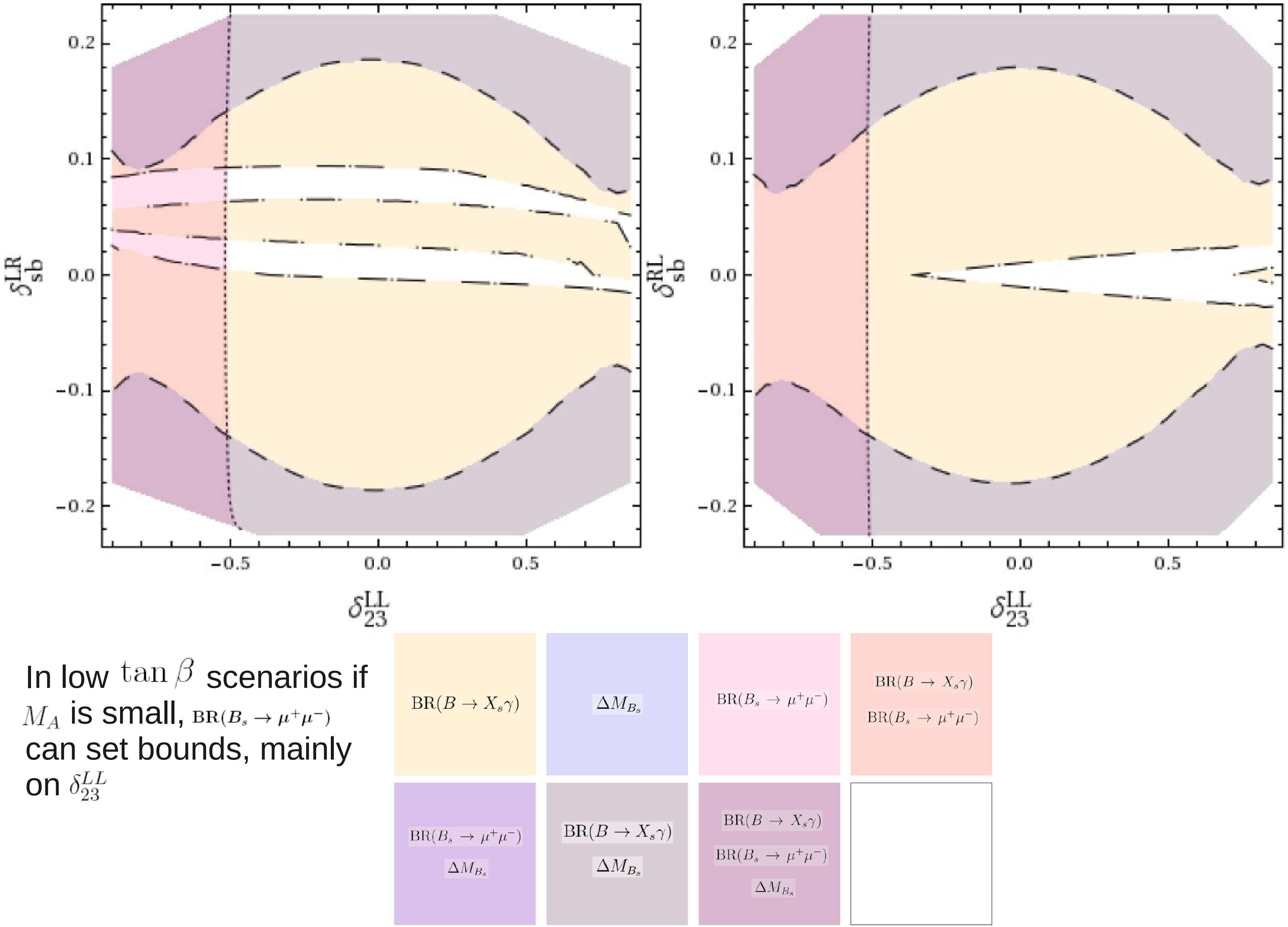
Constraints from B-Physics (two-dimensional constraints)

NUHM-30



Constraints from B-Physics (two-dimensional constraints)

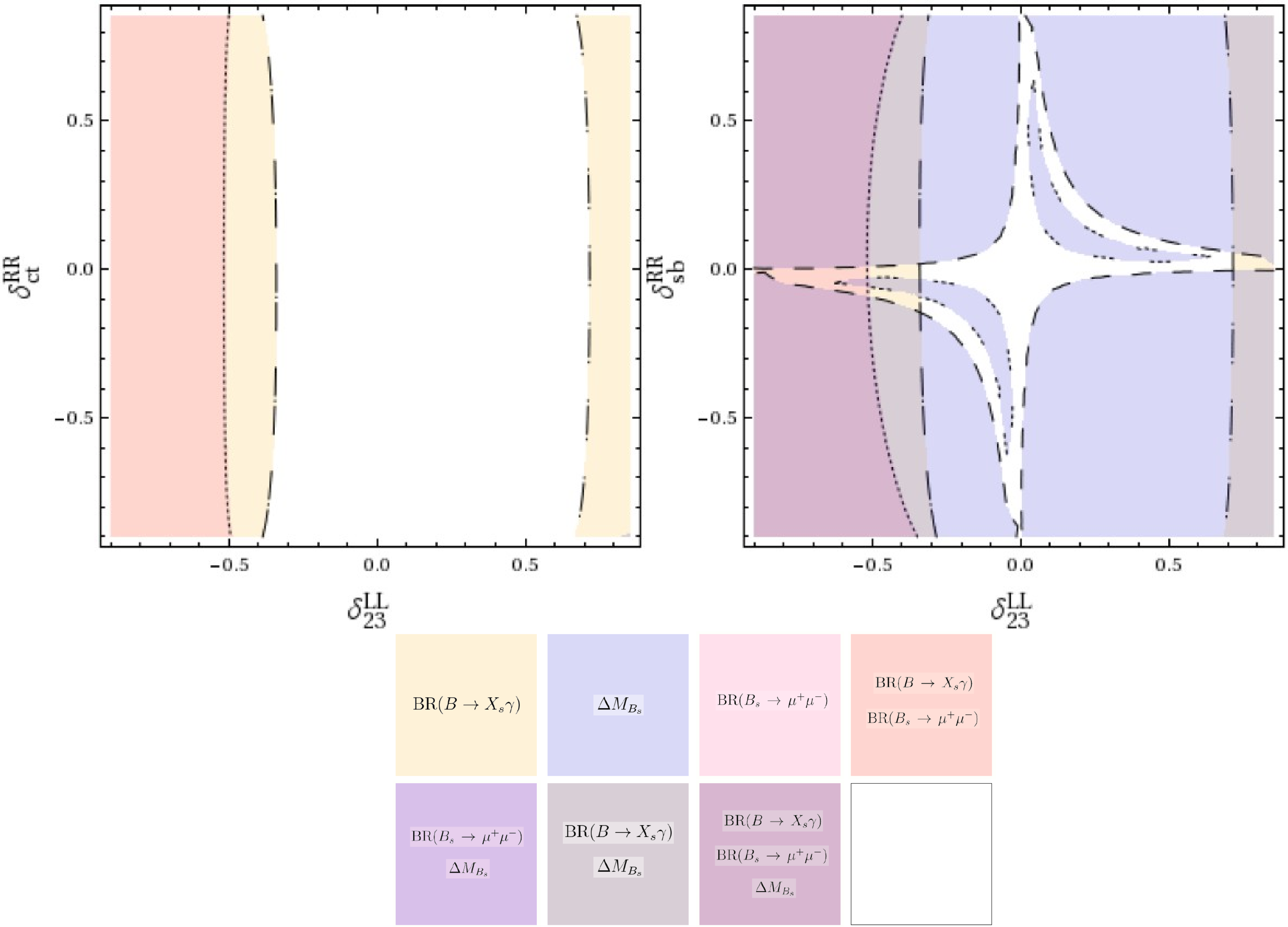
NUHM-5



In low $\tan\beta$ scenarios if M_A is small, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ can set bounds, mainly on δ^{LL}_{23}

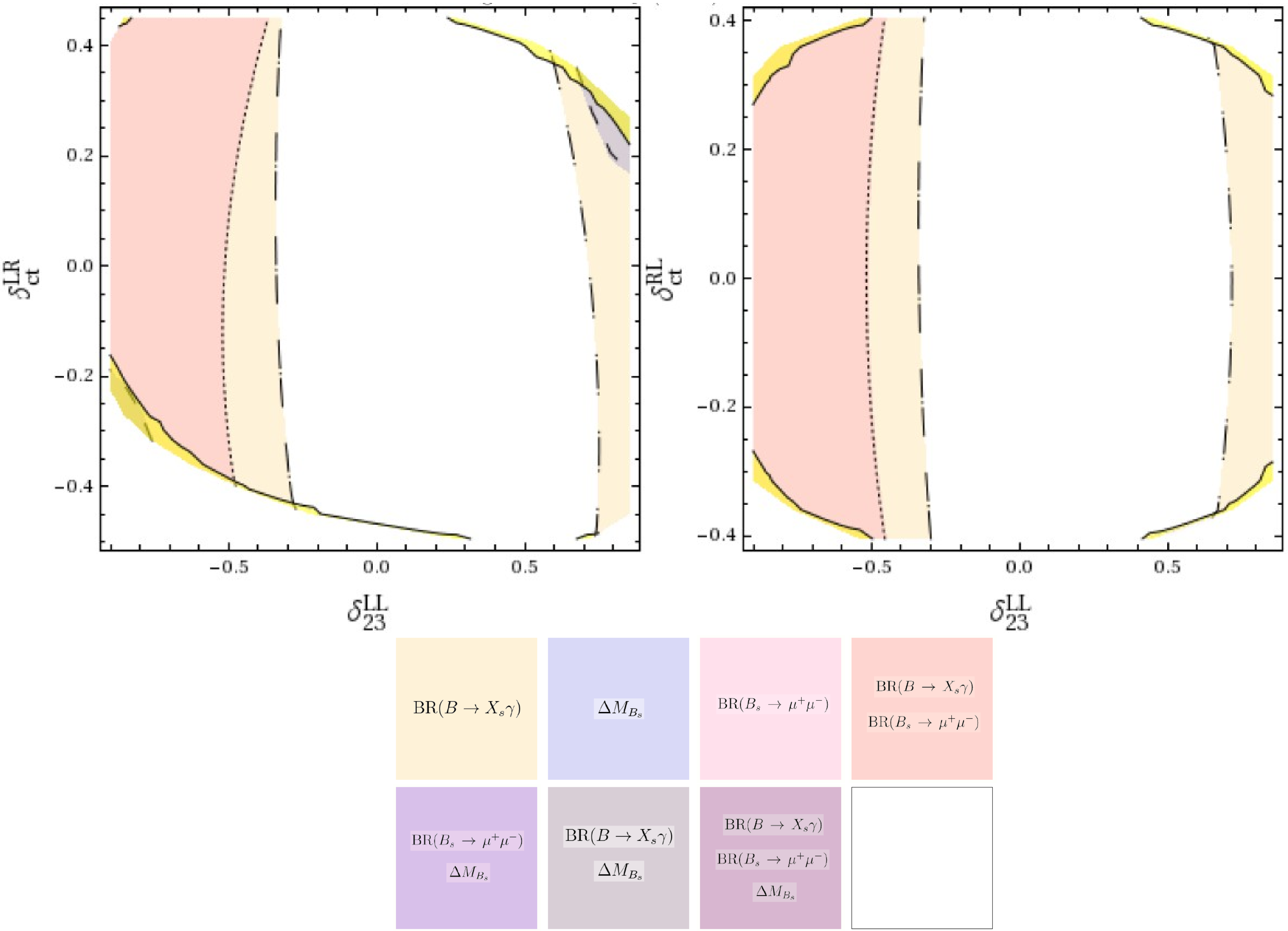
Constraints from B-Physics (two-dimensional constraints)

NUHM-5



Constraints from B-Physics (two-dimensional constraints)

NUHM-5



Radiative corrections to Higgs masses

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

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

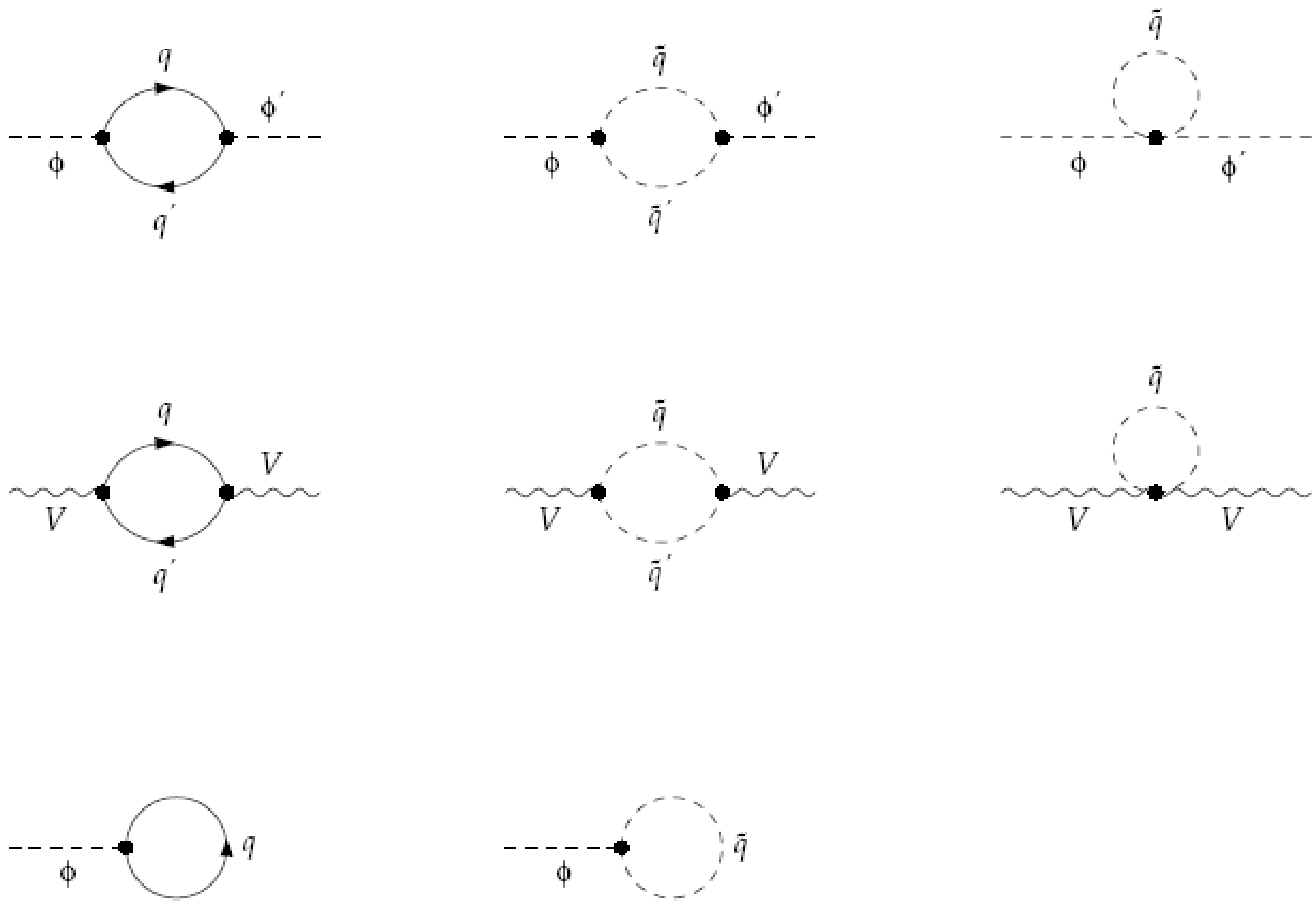
We computed the NMFV contributions to Higgs masses since this contributions could be relevant.

Feynman diagrammatic approach

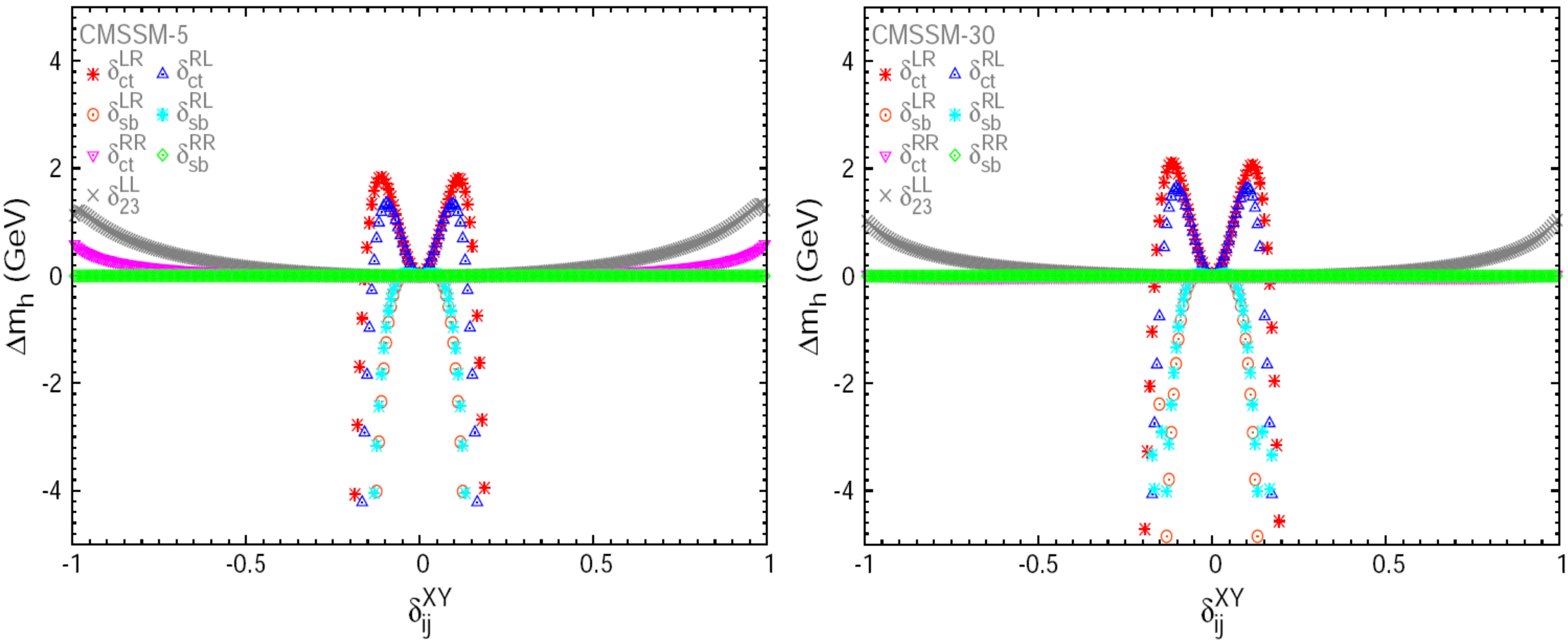
Masses are determined as poles of the propagators (FeynHiggs; self-energies checked with FeynArts/FormCalc)

Radiative corrections to Higgs masses

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



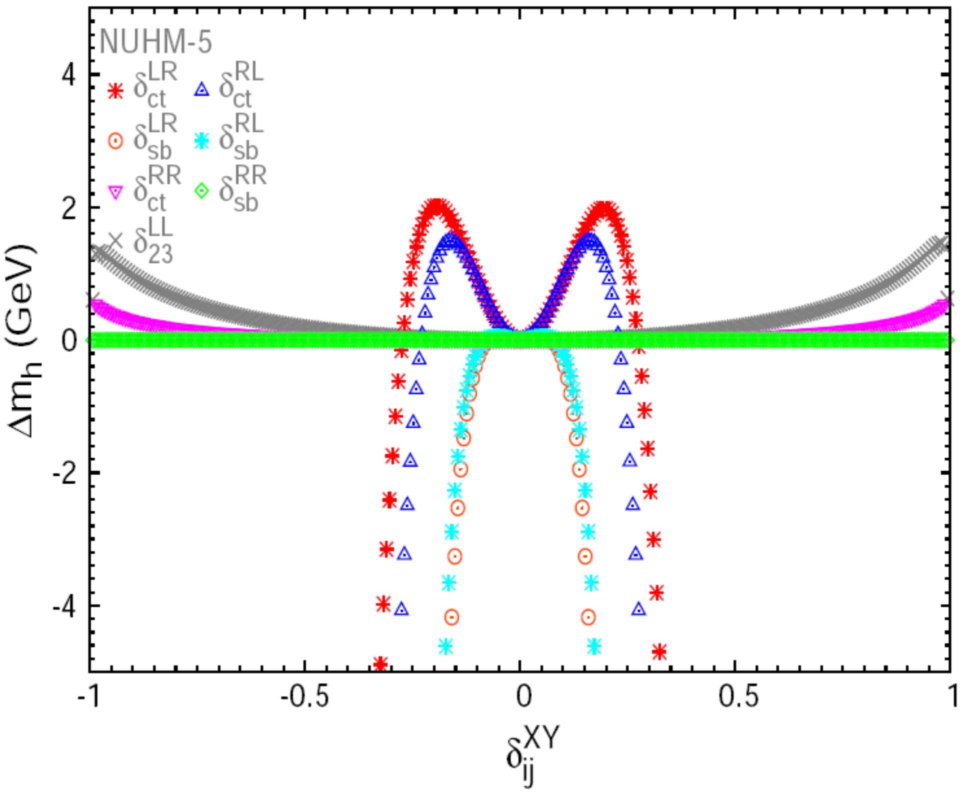
Radiative corrections to Higgs masses

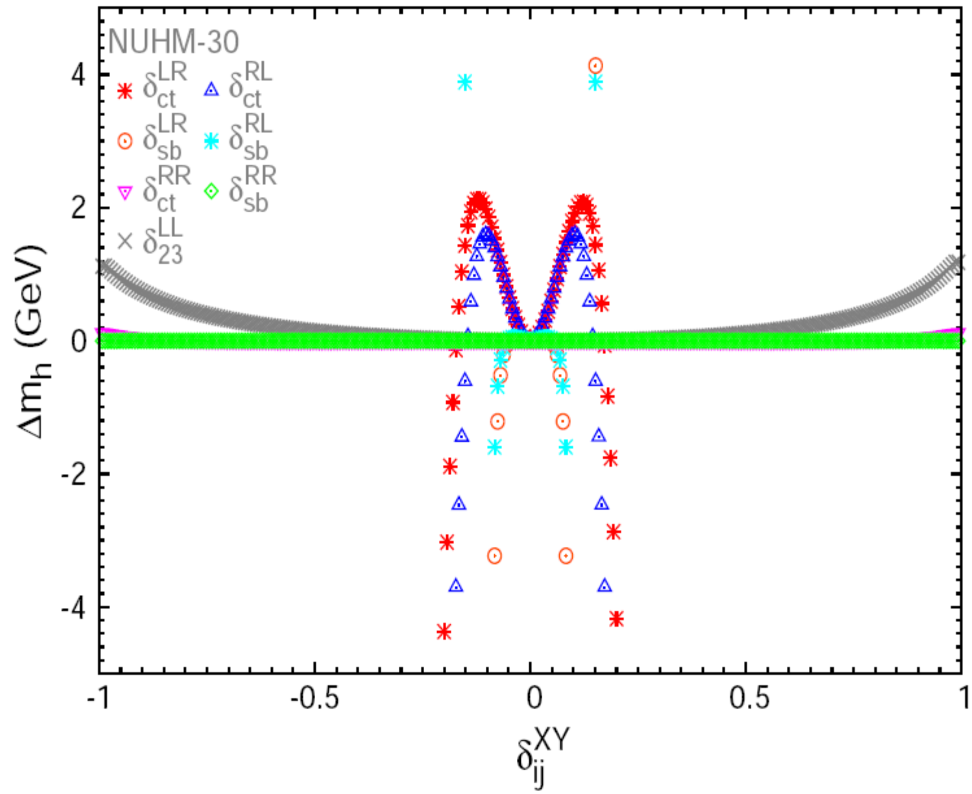


In general, larger corrections for the light Higgs coming from LR/RL sector (ct and sb)

points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
CMSSM-5	1000	1000	0	5	0	0	117	1747	1746	1749
CMSSM-30	1000	1000	0	30	0	0	122	1416	1416	1418
NUHM-5	600	600	0	5	-1.86	$+1.86$	114	223	219	233
NUHM-30	1000	1000	0	30	-0.6	2.2	122	267	267	281

Radiative corrections to Higgs masses





points	$m_{1/2}$	m_0	A_0	$\tan\beta$	δ_1	δ_2	m_h	m_H	M_A	$m_{H\pm}$
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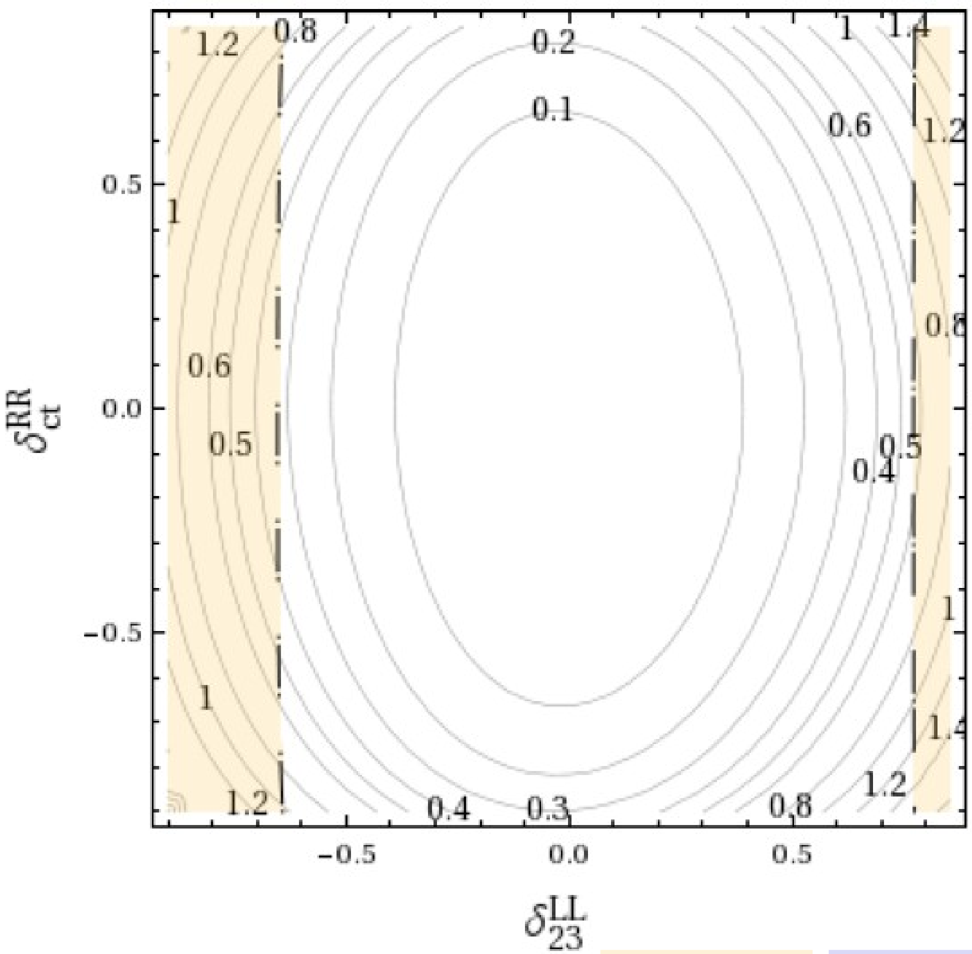
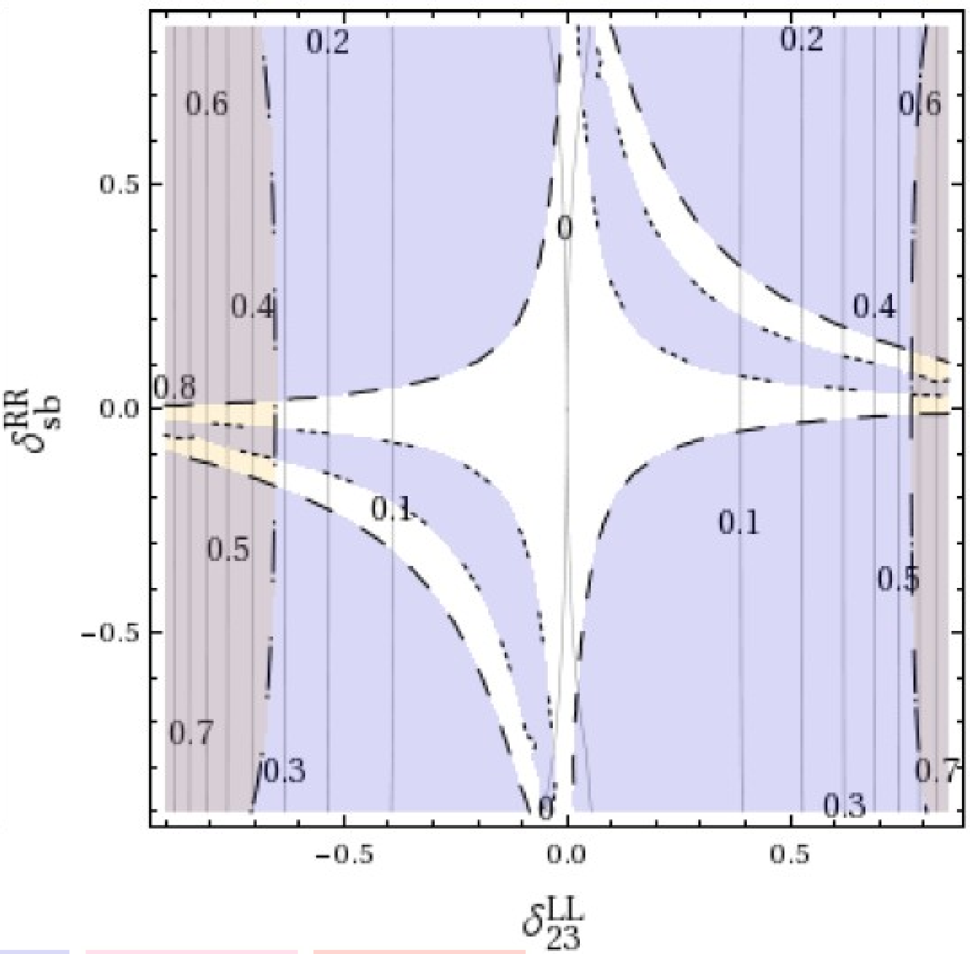
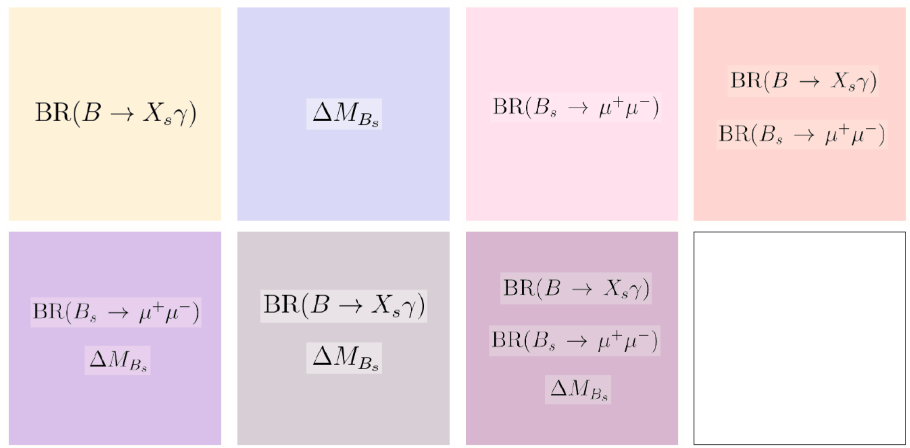
Constraints from B-Physics and radiative corrections to Higgs masses

CMSSM-5



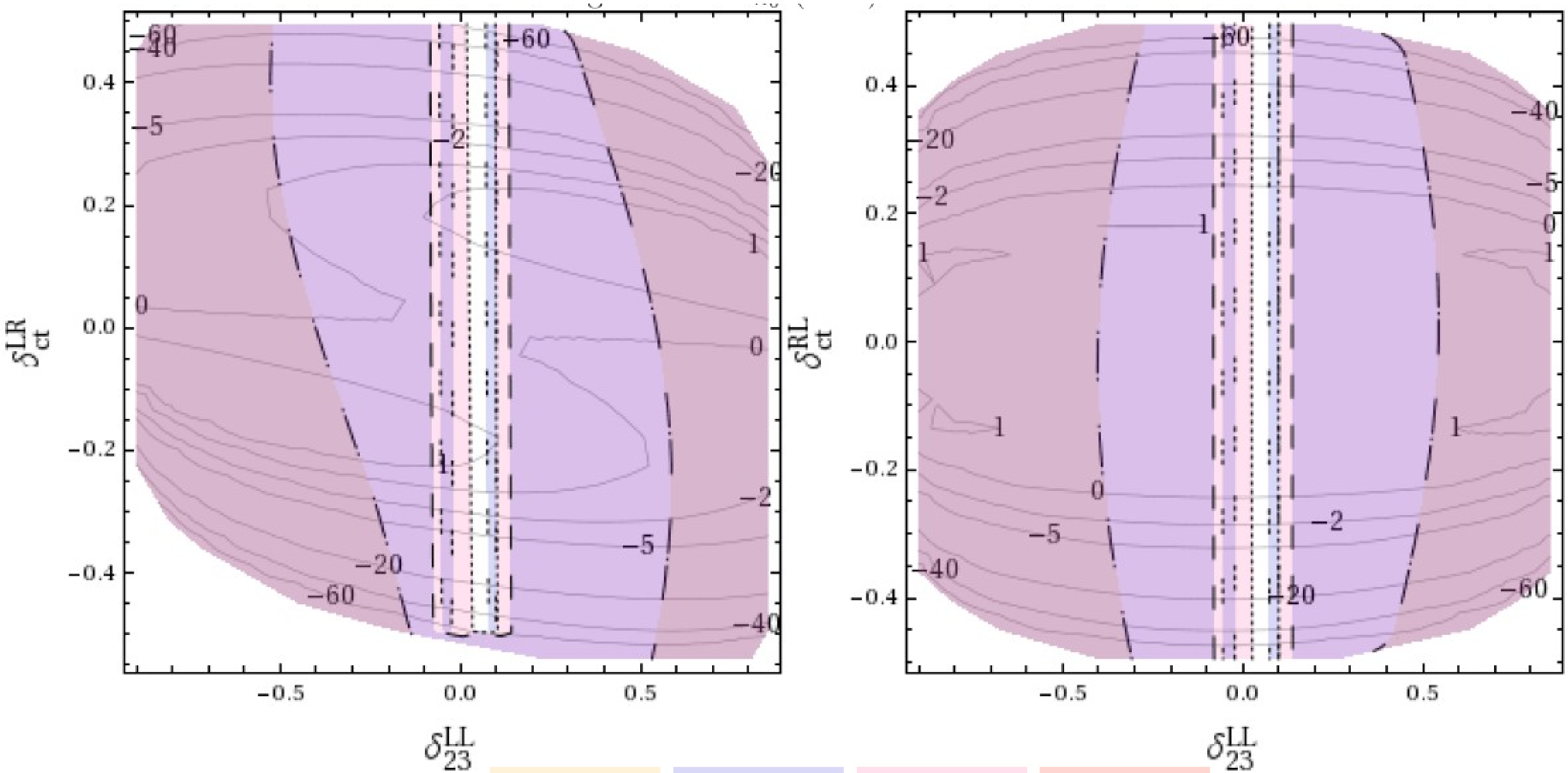


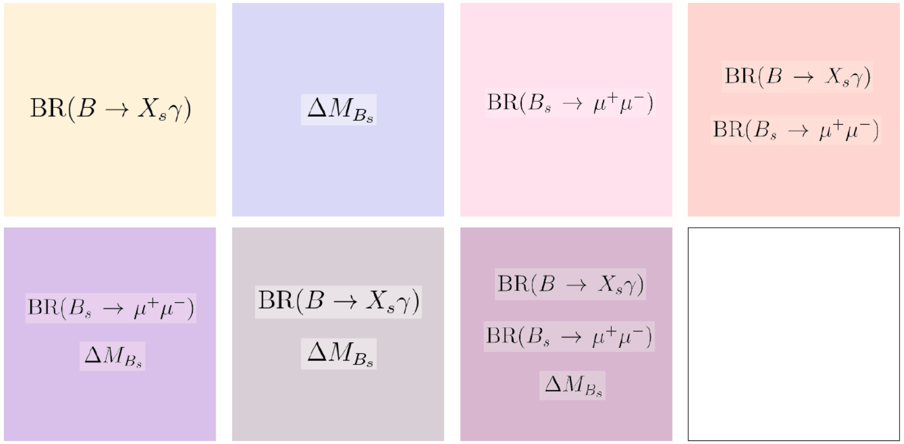
Small Higgs mass corrections coming from the RR sector. And almost no space in the LR/RLsb sector



Constraints from B-Physics and radiative corrections to Higgs masses

CMSSM-30

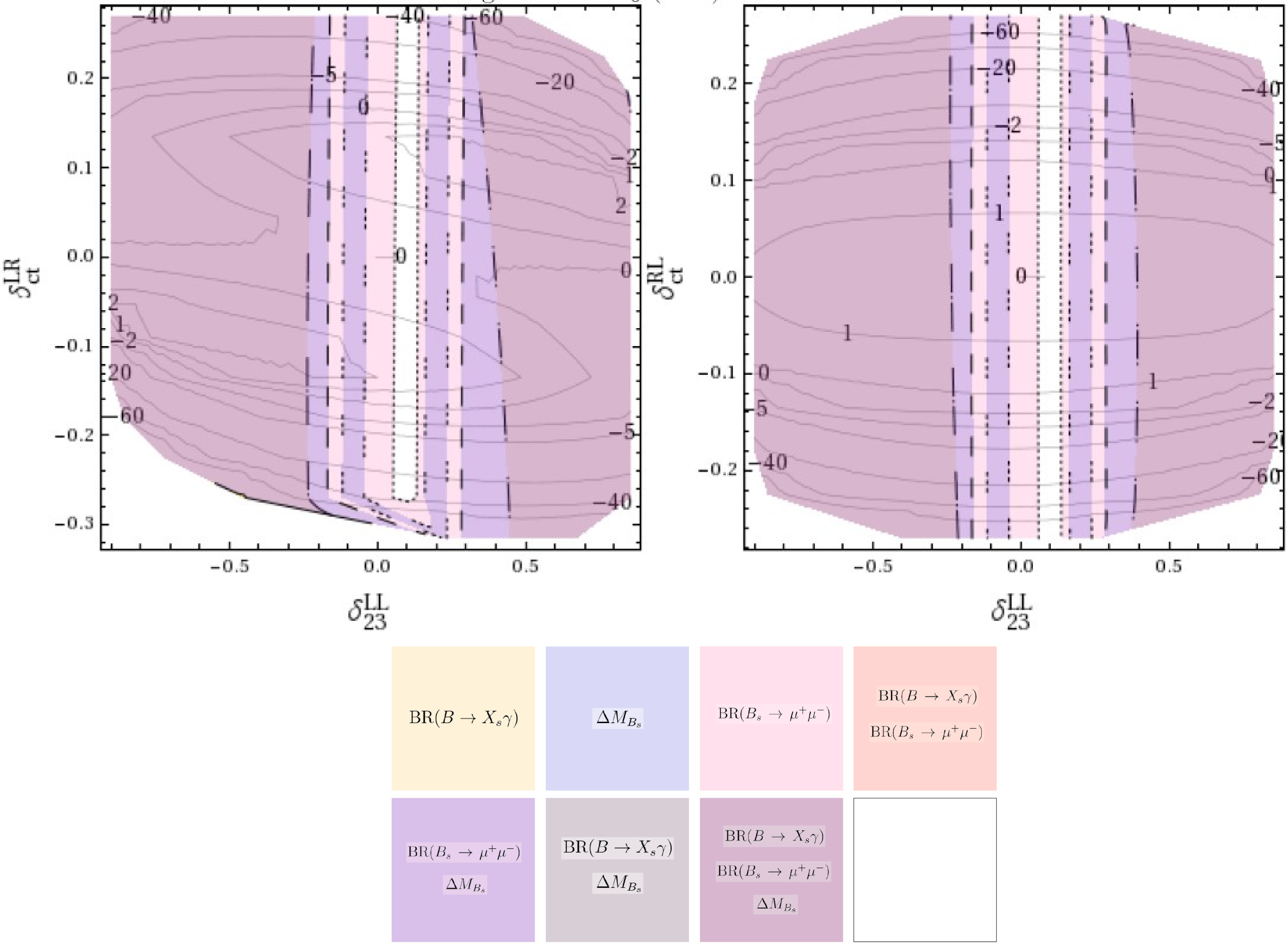




Very large Higgs mass corrections coming from the LR sector, setting bounds on flavor.

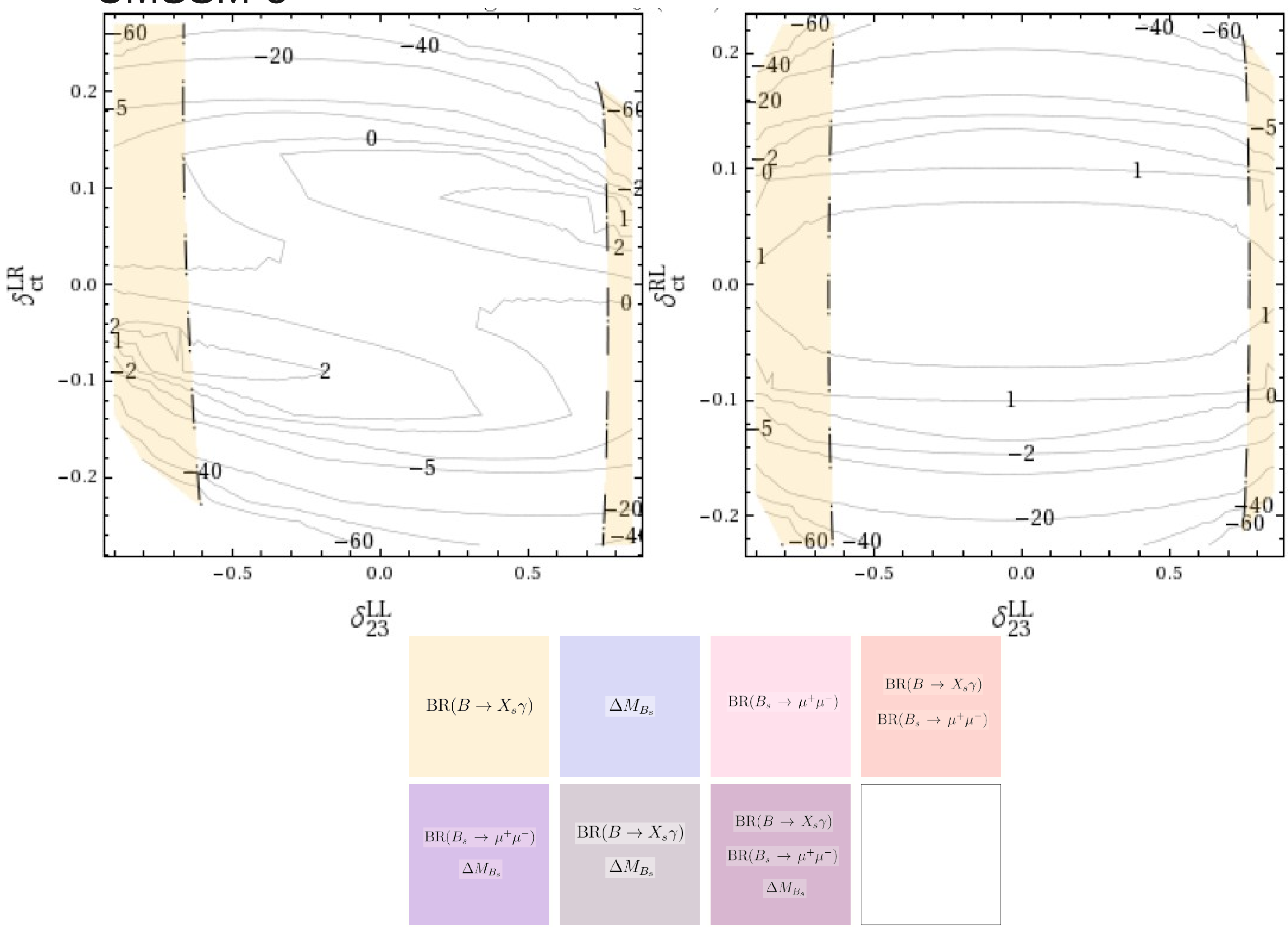
Constraints from B-Physics and radiative corrections to Higgs masses

NUHM-30



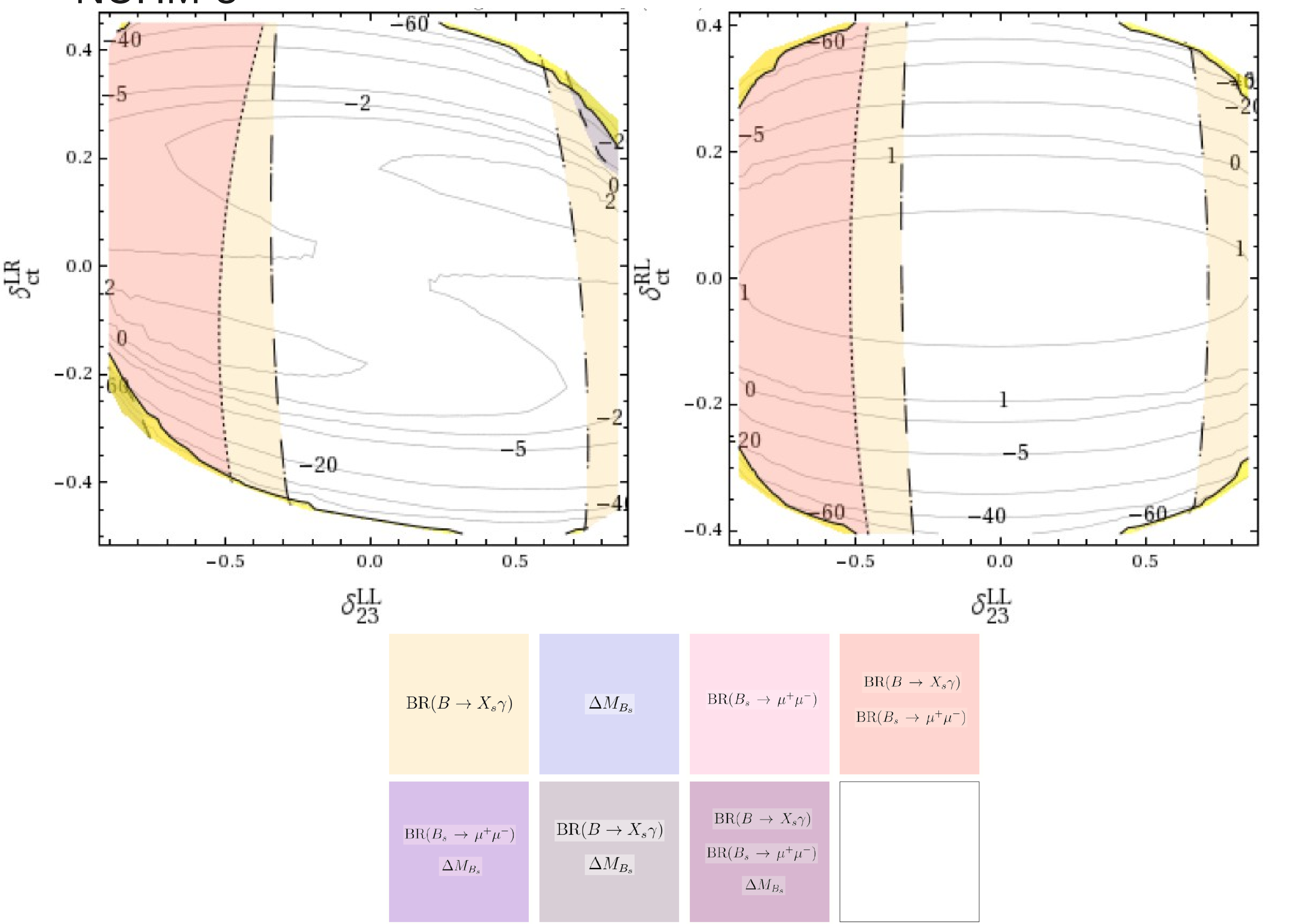
Constraints from B-Physics and radiative corrections to Higgs masses

CMSSM-5



Constraints from B-Physics and radiative corrections to Higgs masses

NUHM-5



Conclusions

We found bounds for flavor from B physics, and large corrections to the Higgs boson masses compatible with these bounds, up to several tens GeV for the lightest boson.

These corrections are two orders of magnitude larger than the 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 $\tan\beta$. Also from high $\tan\beta$ if SUSY is very heavy (order 1 TeV or larger).

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

We are planning to study additional constraints on deltact from rare top decays (t → c gamma, t → c Z, t → c h, ...)