Minimal Flavour Violation with hierarchical squark masses

M. Farina

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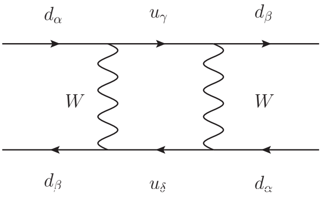
Planck2011, June 01 2011

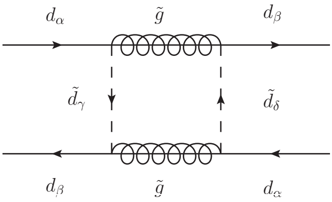
Based on arXiv:1011.0730 [hep-ph] with R. Barbieri, E. Bertuzzo, P. Lodone and D. Zhuridov

What we are talking about

$$\mathcal{L} = \frac{g}{\sqrt{2}} W^+_\mu \bar{u} V \gamma^\mu d + h.c.$$

$$+\mathcal{L}_{SUSY}$$





$$\mathcal{A}^{\Delta F=2}_{\alpha\beta} \propto (V^*_{t\alpha} V_{t\beta})^2 \ \langle \overline{M} | (\bar{d}_{L\alpha} \gamma_\mu d_{L\beta})^2 | M \rangle$$

+ ?

The NP Flavour Problem

New Physics flavour effects via a generic effective-theory approach

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
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G. Isidori, Y. Nir and G. Perez; '10

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Minimal Flavour Violation in a slide

- With no Yukawa the global flavour symmetry in the quarks sector is

$$U(3)_Q \otimes U(3)_{u_R} \otimes U(3)_{d_R}$$

- Minimal Flavour Violation $\Rightarrow$ flavour violation completely determined by the structure of the ordinary Yukawa couplings.
- SM like CKM suppression in leading $\Delta F = 2$ and $\Delta F = 1$ FCNC amplitudes:

$$\mathcal{A}^{\Delta F=2}_{\alpha\beta}|_{MFV} = (V^*_{t\alpha} V_{t\beta})^2 \mathcal{A}^{(\Delta F=2)}_{\text{SM}} (1 + \epsilon^{\Delta F=2}) \, .$$

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Flavour and SUSY

In principle SUSY suffers the NP flavour problem.
There are three main solutions:

- Degeneracy
- Alignment
- Hierarchy

Naive heavy squark masses limits

- Hierarchy only

$$m_{1,2} \gtrsim 500\ TeV$$

- Invoking mild assumptions on degeneracy and alignment

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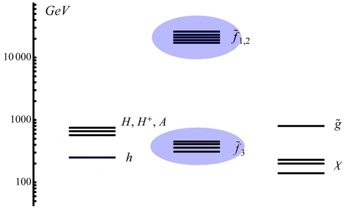

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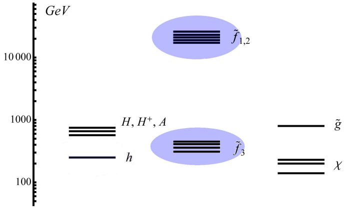

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Our Assumptions

Special role of the top Yukawa coupling

Blending of the three approaches

- Among the squarks, only those that interact with the Higgs system via the top Yukawa coupling are significantly lighter than the others.

- With only the up-Yukawa couplings, Y_u, turned on, but not the down-Yukawa couplings, Y_d, there is no flavour transition between the different families.

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Symmetries and consequences

- If $Y_d = 0$ then the largest flavour global symmetry is

$$U(1)_{\tilde{B}_1} \times U(1)_{\tilde{B}_2} \times U(1)_{\tilde{B}_3} \times U(3)_{d_R}$$

- Y_d is promoted to a non-dynamical spurion field
- $m^2_{\tilde{Q}}, m^2_{\tilde{u}}$ and the A-terms for the charge 2/3 squarks are flavour diagonal (cause of large separation corrections are negligible).
- On the other hand

$$m^2_{\tilde{d}_R} = m^2(\mathbf{1} + aY_d^+ Y_d)$$

- The only other mass matrix that needs to be diagonalized is the d-quark mass matrix,
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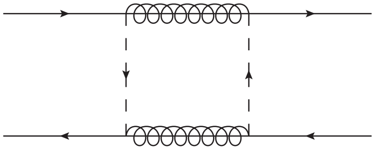
The effective lagrangian

- General structure of the $\Delta F = 2$ effective Lagrangian

$$\mathcal{L}^{\Delta F=2} \propto \xi_k^{\alpha\beta} \xi_j^{\alpha\beta} f_{j,k} \, (\bar{d}_{L\alpha} \gamma_\mu d_{L\beta})^2 + h.c.,$$

where $\xi_j^{\alpha\beta} = V_{j\alpha} V_{j\beta}^*$



Effective MFV

- Using $\Sigma_i \xi_i^{\alpha\beta} = 0$

$$\mathcal{L}^{\Delta F=2} = \mathcal{L}_{33}^{\Delta F=2} + \mathcal{L}_{12}^{\Delta F=2} + \mathcal{L}_{12,3}^{\Delta F=2}$$

- Recalling what happens in MFV, if all FCNC have the form we call this effective Minimal Flavour Violation.

- This turns to

$$\begin{array}{lll} \mathcal{L}_{33}^{\Delta F=2} \leftrightarrow \xi_3^2 & \Rightarrow & \text{Effective MFV} \\ \mathcal{L}_{12}^{\Delta F=2} \leftrightarrow \xi_2^2 & \Rightarrow & \Lambda_{Re} > 9.8 \cdot 10^2 \text{ TeV} \\ \mathcal{L}_{12,3}^{\Delta F=2} \leftrightarrow \xi_2\xi_3 & \Rightarrow & \Lambda_{Im} > 1.6 \cdot 10^4 \text{ TeV} \end{array}$$

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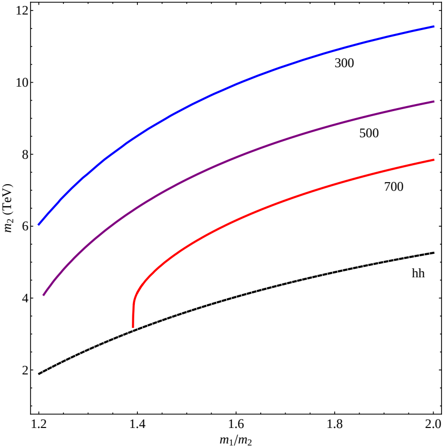
Results: Lower Bounds



QCD Running

- The $\mathcal{L}_{12,3}^{\Delta F=2}$ has a peculiar feature. Being sensitive to two mass scales large logs arise

$$\propto \log \frac{m_h^2}{m_\ell^2}$$

- QCD running and integrating out properly carried in two steps
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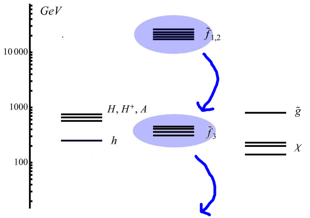

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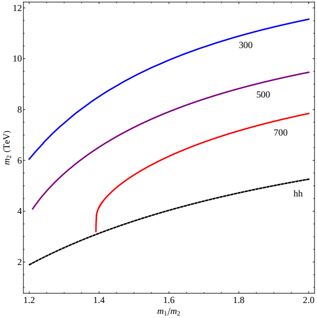
Summary

- Minimal Flavour Violation can be compatible with hierarchical sfermions
- Reasonable bounds on heavy squark masses in the case of interest
- Proper QCD effects calculation including a previously neglected effect. Order 20% change from naive calculation.



QCD 1

Usual treatment

- Integrating out one obtains an effective lagrangian

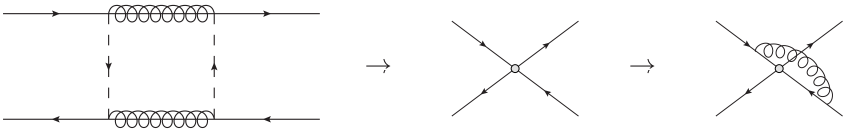
$$\mathcal{L}^{\Delta F=2} = C_1(m_h)Q_1 + h.c.$$

with $Q1 = Q_1 = (\overline{d}^{\alpha}\gamma^{\mu}P_L s^{\alpha})\,(\overline{d}^{\beta}\gamma_{\mu}P_L s^{\beta})$

- QCD corrections taken into account corrections using ADM formalism

$$\frac{dC_1}{d\log\mu} = \Gamma C_1,$$

$$C_1(\mu) = U(\mu, m_h)C_1(m_h)$$



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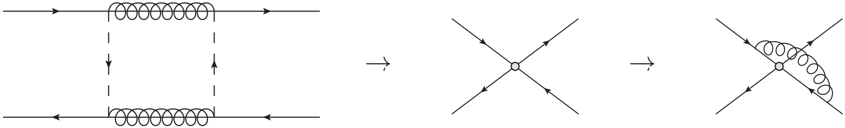


QCD 2

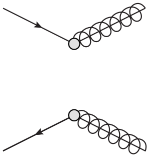
Large Logs and $\Delta F = 1$ operators

- The $\mathcal{L}_{12,3}^{\Delta F=2}$ has a peculiar feature. Being sensitive to two mass scales large logs arise

$$C_1 \propto \log \frac{m_h^2}{m_\ell^2}$$

- The new ingredient is the mixing between $\Delta F = 2$ and new $\Delta F = 1$ operators

$$\hat{C}_g =$$

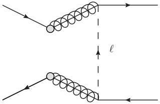


QCD 3

Improved running

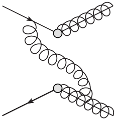
- The RGE for C_1 now has the form

$$\frac{dC_1}{d\log\mu} = \frac{\alpha_s}{2\pi}\left(\gamma_1 C_1 + \xi_3^{ds}\hat{\gamma}_{g1}\hat{C}_g\right),$$



- In conclusion

$$C_1(m_l) = \left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_1/b_0} C_1(m_h) + \xi_3^{ds}\hat{\gamma}_{g1} A B_D A^{-1}\hat{C}_g(m_h)\,,$$



$$(B_D)_{kk} = \frac{1}{\gamma_k - \gamma_1}\left[\left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_k/b_0} - \left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_1/b_0}\right]$$

$$,\ \gamma_k = (\hat{\gamma}^D_{gg})_{kk}.$$

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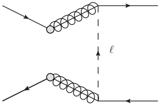
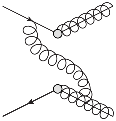
- The RGE for C_1 now has the form

$$\frac{dC_1}{d\log\mu} = \frac{\alpha_s}{2\pi}\left(\gamma_1 C_1 + \xi_3^{ds}\hat{\gamma}_{g1}\hat{C}_g\right),$$



- In conclusion

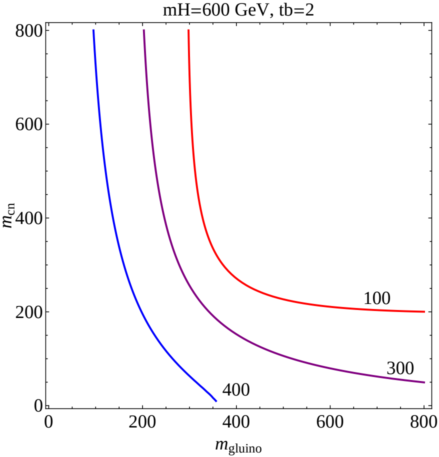
$$C_1(m_l) = \left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_1/b_0} C_1(m_h) + \xi_3^{ds}\hat{\gamma}_{g1} A B_D A^{-1}\hat{C}_g(m_h)\ ,$$



$$(B_D)_{kk} = \frac{1}{\gamma_k - \gamma_1}\left[\left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_k/b_0} - \left(\frac{\alpha_s(m_l)}{\alpha_s(m_h)}\right)^{\gamma_1/b_0}\right]$$

$$,\ \gamma_k = (\hat{\gamma}_{gg}^{D})_{kk}.$$

Light-Light Case



CKM Matrix

Wolfenstein parametrization

$$V \simeq$$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\lambda = 0.2257 \pm 0.0010, \quad A = 0.814 \pm 0.022,$$

$$\rho = +0.135^{+0.031}_{-0.016}, \quad \eta = +0.349 \pm 0.017.$$

Effective MFV $\Delta F = 2$

- Recalling what happens in MFV, if all FCNC have the form

$$\mathcal{A}_{\alpha\beta}^{\Delta F=2}|_{MFV} = (V_{t\alpha}^* V_{t\beta})^2 \mathcal{A}_{\alpha\beta}^{\Delta F=2}|_{SM}(1+\epsilon^{\Delta F=2})$$

  we call this effective Minimal Flavour Violation.

- Using $\Sigma_i \xi_i^{\alpha\beta} = 0$

$$\mathcal{L}^{\Delta F=2} = \mathcal{L}_{33}^{\Delta F=2} + \mathcal{L}_{12}^{\Delta F=2} + \mathcal{L}_{12,3}^{\Delta F=2}$$

$$\mathcal{L}_{33}^{\Delta F=2} = (\xi_3^{\alpha\beta})^2 (f_{3,3} - 2f_{3,1} + f_{1,1}) Q_1^{\alpha\beta} + h.c.,$$

$$(\xi_3^{ds})^2 \sim \lambda^{10} + i\lambda^{10}$$

$$\mathcal{L}_{12}^{\Delta F=2} = (\xi_2^{\alpha\beta})^2 (f_{2,2} - 2f_{2,1} + f_{1,1}) Q_1^{\alpha\beta} + h.c.,$$

$$(\xi_2^{ds})^2 \sim \lambda^2 + i\lambda^6$$

$$\mathcal{L}_{12,3}^{\Delta F=2} = 2(\xi_2^{\alpha\beta}\xi_3^{\alpha\beta})(f_{3,2} - f_{3,1} + f_{1,1} - f_{1,2}) Q_1^{\alpha\beta} + h.c.$$

$$\xi_2^{ds}\xi_3^{ds} \sim \lambda^6 + i\lambda^6$$

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$$\xi_2^{ds}\xi_3^{ds} \sim \lambda^6 + i\lambda^6$$

Effective MFV $\Delta F = 2$

- Recalling what happens in MFV, if all FCNC have the form

$$\mathcal{A}^{\Delta F=2}_{\alpha\beta}|_{MFV} = (\xi_3^{\alpha\beta})^2 \mathcal{A}^{\Delta F=2}_{\alpha\beta}|_{SM}(1+\epsilon^{\Delta F=2})$$

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$$(\xi_3^{ds})^2 \sim \lambda^{10} + \imath\lambda^{10}$$

$$(\xi_2^{ds})^2 \sim \lambda^2 + \imath\lambda^6$$

$$\xi_2^{ds}\xi_3^{ds} \sim \lambda^6 + \imath\lambda^6$$

Effective MFV

$\Delta F = 1$ case

- Recalling what happens in MFV, if all FCNC have the form

$$\mathcal{A}_{\alpha\beta}^{\Delta F=1,s}|_{MFV} = (V_{t\alpha}^* V_{t\beta})\ \mathcal{A}_{\alpha\beta}^{\Delta F=1,s}|_{SM}(1+\epsilon^{\Delta F=1,s})$$

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$$\mathcal{L}^{\Delta F=1} = \mathcal{L}_{31}^{\Delta F=1} + \mathcal{L}_{21}^{\Delta F=1}$$

  where

$$\mathcal{L}_{31}^{\Delta F=1} = \Sigma_s \Sigma_{\alpha\neq\beta} \xi_3^{\alpha\beta}(f_3^{(s)} - f_1^{(s)}) Q_{(s)}^{\alpha\beta} + h.c.,$$

$$\xi_3^{bs} \sim \lambda^2 + i\lambda^4$$

$$\mathcal{L}_{21}^{\Delta F=1} = \Sigma_s \Sigma_{\alpha\neq\beta} \xi_2^{\alpha\beta}(f_2^{(s)} - f_1^{(s)}) Q_{(s)}^{\alpha\beta} + h.c.$$

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Effective MFV

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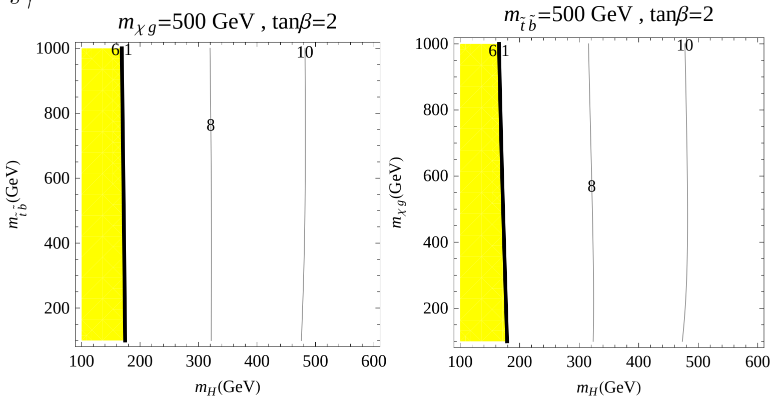
$$\xi_3^{bs} \sim \lambda^2 + \imath\lambda^4$$

$$\mathcal{L}^{\Delta F=1}_{21} = \Sigma_s \Sigma_{\alpha\neq\beta} \xi_2^{\alpha\beta} (f_2^{(s)} - f_1^{(s)}) Q^{\alpha\beta}_{(s)} + h.c.$$

$$\xi_2^{bs} \sim \lambda^2$$

$\Delta F = 1$

$b \to s\gamma$



- Process dominated by charged Higgses exchanges. So that for

$$m_{H^+} \gtrsim 200\ GeV$$

only a very weak constraint on the squarks masses is present.

Less Restrictive 1

- What about less restrictive flavour symmetries?

$$U(1)_{\tilde{B}_1} \times U(1)_{\tilde{B}_2} \times U(1)_{\tilde{B}_3} \times U(1)_{d_{R_3}} \times U(2)_{d_R}$$

$$\Pi_{i=1}^{3} U(1)_{\tilde{B}_i} \times U(1)_{d_{R_i}}$$

- Now U cannot be transformed away

$$m^2_{\tilde{d}_R} = m^2(\mathbf{1} + aY_d^+ Y_d),$$

- The flavour Lagrangian gets extra terms

$$\Delta\mathcal{L}_{FC} = -\sqrt{2}\frac{g'}{3}\tilde{d}^*_R\, U\, \overline{\widetilde{B}}\, d_R + \sqrt{2}\, g_3\, \tilde{d}^*_R\, \lambda^b\, U\, \overline{\widetilde{g}^b}\, d_R + h.c.$$

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Less Restrictive 2

- We define $\eta_j^{\alpha\beta} = U_{j\alpha} U_{j\beta}^*$ and we consider

$$\eta_j^{\alpha\beta} = \xi_j^{\alpha\beta} e^{i\phi_j^{\alpha\beta}}$$

- Dominance of left right operators due to stronger bounds

$$Q_{4,5} = (\bar{d}_R s_L)(\bar{d}_L s_R)$$

- So that in a generic form

$$\Delta\mathcal{L}_{(123,12)}^{\Delta S=2,LR} \approx (\xi_2\eta_3, \xi_2\eta_2)\frac{\alpha_s^2}{m_h^2} Q_{4,5}$$

Less Restrictive 3

- For the symmetry $U(1)_{\tilde{B}_1} \times U(1)_{\tilde{B}_2} \times U(1)_{\tilde{B}_3} \times U(1)_{d_{R_3}} \times U(2)_{d_R}$

$$m_h \gtrsim 450\ TeV \left(\left| \frac{\eta_3}{\xi_3} \right| \sin \phi_3 \right)^{1/2}$$

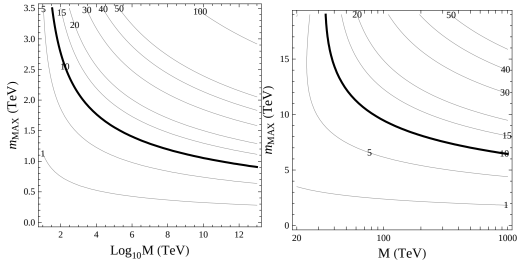
- For the symmetry $\Pi_{i=1}^{3} U(1)_{\tilde{B}_i} \times U(1)_{d_{R_i}}$

$$m_h \gtrsim 10^4\ TeV \left(\left| \frac{\eta_2}{\xi_2} \right| \sin \phi_2 \right)^{1/2}$$

Non Standard Susy Spectrum

- *λSUSY.* This is the NMSSM case with an extra chiral singlet S coupled in the superpotential to the usual Higgs doublets by $\Delta f = \lambda S H_1 H_2$, where the upper bound on the lightest scalar is:

$$m_h^2 \leq m_Z^2(\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)\,. \qquad (1)$$



Left: MSSM, Right:λ SUSY

QCD 2

Large Logs and $\Delta F = 1$ operators

- The $\mathcal{L}^{\Delta F=2}_{12,3}$ has a peculiar feature. Being sensitive to two mass scales large logs arise

$$C_1 \propto \log \frac{m_h^2}{m_\ell^2}$$

- The new ingredient is the mixing between $\Delta F = 2$ and new $\Delta F = 1$ operators

$$\begin{aligned} Q_1^g &= \delta^{ab}\delta_{\beta\alpha}(\overline{d}^\beta P_R \widetilde{g}^b)(\overline{\widetilde{g}^a} P_L s^\alpha) \\ Q_2^g &= d^{bac} t^c_{\beta\alpha}(\overline{d}^\beta P_R \widetilde{g}^b)(\overline{\widetilde{g}^a} P_L s^\alpha) \\ Q_3^g &= i f^{bac} t^c_{\beta\alpha}(\overline{d}^\beta P_R \widetilde{g}^b)(\overline{\widetilde{g}^a} P_L s^\alpha)\ . \end{aligned}$$

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\end{aligned}$$