Is light pseudoscalar Higgs still possible in $\mathbb{SO}(10)$ motivated MSSM with large $\tan\beta$?

Peter Maták, Tomáš Blažek

Comenius University in Bratislava

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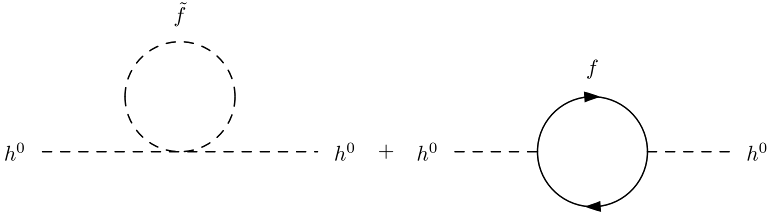
Why supersymmetry?

Protect the higgs self-energy from quadratic divergent terms.



$$\delta m^2 = \frac{\lambda_{\tilde{f}}}{16\pi^2}\Lambda_{UV}^2 - \frac{\lambda_f^2}{16\pi^2}\Lambda_{UV}^2 + \dots \lesssim 1\mathrm{TeV} \quad (1)$$

MSSM - second Higgs doublet

SUSY does not allow complex conjugation of scalar fields in Yukawa terms. This forces us to introduce second higgs doublet. Second higgs doublet is also welcome due to the gauge anomaly cancelation.

$$\mathcal{L}^{SM}_{Yukawa} = -\delta_{ij} u^c Y_u Q^j H^{i*} - \ldots \longrightarrow \mathcal{L}^{MSSM}_{Yukawa} = -\epsilon_{ij} u^c Y_u Q^j H^i_u - \ldots \qquad (2)$$

$$H_d = \begin{pmatrix} H^0_d \\ H^-_d \end{pmatrix} = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(H^0 c_\alpha - h^0 s_\alpha + iA^0 s_\beta - iG^0 c_\beta) \\ H^- s_\beta - G^- c_\beta \end{pmatrix} \qquad (3)$$

$$H_u = \begin{pmatrix} H^+_u \\ H^0_u \end{pmatrix} = \begin{pmatrix} H^+ c_\beta + G^+ s_\beta \\ v_u + \frac{1}{\sqrt{2}}(H^0 s_\alpha + h^0 c_\alpha + iA^0 c_\beta + iG^0 s_\beta) \end{pmatrix} \qquad (4)$$

$$\tan\beta \stackrel{\mathrm{def}}{=} \frac{v_u}{v_d} \qquad \mathrm{GUT} : y_b \approx y_t \Rightarrow \tan\beta \approx 50$$

Why $B_s^0 \to \mu^+\mu^-$?

- In the SM, the flavour changing amplitudes are small. In the SM exensions, their values can be enlarged up to several orders due to extended Higgs sector (large values of $\tan\beta$). The branching ratio of the $B_s^0 \to \mu^+\mu^-$ process is proportional to the $\tan^6\beta$.
- SM gives branching ratio $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.1 \pm 1.4) \times 10^{-9}$ (C.Bobeth, T.Ewerth, F.Krüger, J.Urban *Phys. Rev.* D64 (2001)). Experimental bound is $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.1 \times 10^{-8}$ at 95% CL (LHCb-CONF-2011-047, CMS PAS BPH-11-019).
- In the $B_s^0 \to \mu^+\mu^-$ process, the renormalization effects (running of the Wilson coefficients from the electroweak scale to 5 GeV) do not play significant role. (A.J.Buras, 1998)
- No sign of squarks and gluinos in hadronic jets at LHC...
- ...but plenty of B_s^0's produced.
- $B_s^0 \to \mu^+\mu^-$ can be one of the first signals of the beyond Standard Model physics.

Sources of the flavour violation

- Cabibbo - Kobayashi - Maskawa mixing matrix (Minimal Flavour Violation)
- Off-diagonal elements of the squark mass matrix

$$\mathcal{L}_{mass} = \ldots - \begin{pmatrix} \tilde{q}_L^\dagger & \tilde{q}_R^\dagger \end{pmatrix} \begin{pmatrix} \mathcal{M}^2_{\tilde{q},LL} & \mathcal{M}^2_{\tilde{q},LR} \\ \mathcal{M}^2_{\tilde{q},RL} & \mathcal{M}^2_{\tilde{q},RR} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} \ldots \tag{5}$$

$$\tilde{u}_\alpha = Z_u^\dagger \begin{pmatrix} \tilde{u}_L \\ \tilde{u}_R \end{pmatrix}, \tilde{d}_\alpha = Z_d^* \begin{pmatrix} \tilde{d}_L \\ \tilde{d}_R \end{pmatrix} \tag{6}$$

Relevant mass insertions

- Possible off-diagonal elements are often parametrized as

$$(\delta_{\tilde{q},XY})^{JI} = \frac{(\Delta\mathcal{M}^2_{\tilde{q},XY})^{JI}}{\bar{m}^2_{\tilde{q}}}. \tag{7}$$

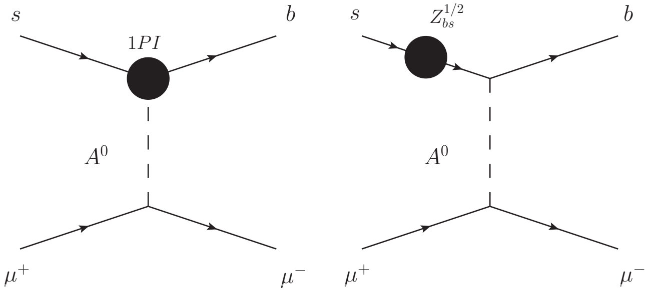
- Left-handed squarks $\tilde{u}_L, \tilde{d}_L$ are members of the same $SU(2)$-doublet, hence

$$\mathcal{M}^2_{\tilde{u},LL} = V_{CKM}\mathcal{M}^2_{\tilde{d},LL}V^\dagger_{CKM}. \tag{8}$$

- Mass matrix has to be unitary: $\mathcal{M}^2_{\tilde{q}} = (\mathcal{M}^2_{\tilde{q}})^\dagger$.

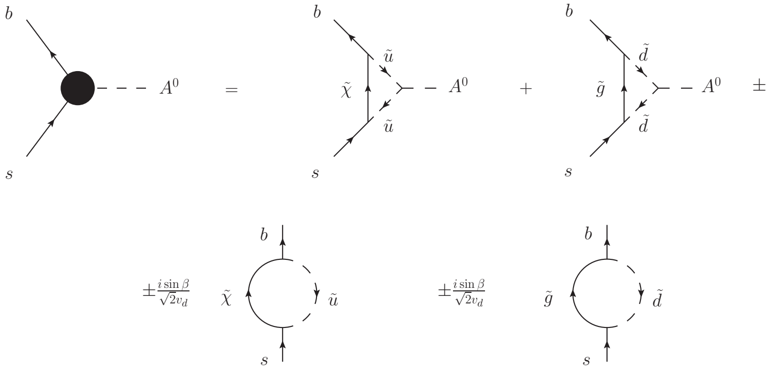
$\Rightarrow$ For the B^0_s decay only $\delta^{23}_{\tilde{u},LL}, \delta^{23}_{\tilde{u},RR}, \delta^{23}_{\tilde{u},LR}, \delta^{32}_{\tilde{u},LR}, \delta^{23}_{\tilde{d},RR}, \delta^{23}_{\tilde{d},LR}, \delta^{32}_{\tilde{d},LR}$ are relevant.

Structure of penguin diagrams for $B_s^0 \to \mu^+\mu^-$



In the large $\tan\beta$ region, dominant contribution to the $B_s^0 \to \mu^+\mu^-$ comes from Higgs penguin diagrams - 1PI vertex corrections and $Z^{1/2}$-factors (LSZ reduction).

Dominant contributions to $b - s - A^0$ vertex



- 'Chargino' diagrams due to extra $\tan\beta$.
- 'Gluino' diagrams due to strong coupling - only in the NMFV case (P.H.Chankowski, L.Slawianowska (2000)).

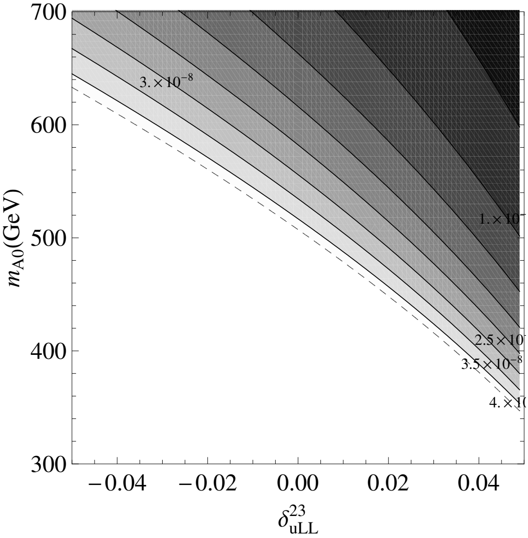
In our numerical analyses we used following values of SUSY parameters

$\tan\beta$	M_2	M_3	μ
50	600 GeV	2 TeV	110 GeV
m_{Q_1}	m_{Q_3}	m_{u_1}	m_{u_3}
500 GeV	300 GeV	500 GeV	200 GeV
m_{d_1}	m_{d_3}	A	f_B
500 GeV	180 GeV	-300 GeV	210 MeV

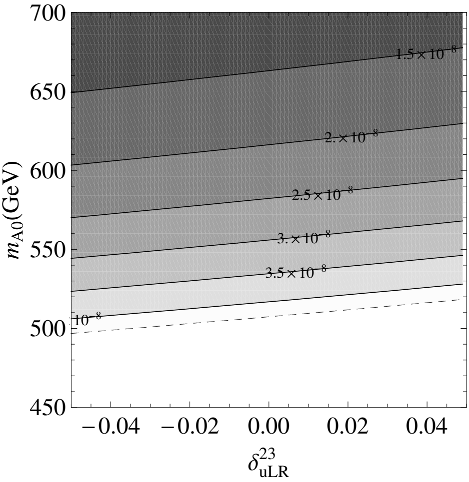
Light pseudoscalar Higgs scenario

- Thanks to the Higgs propagator all the considered diagrams depend on the Higgs mass as $\propto m^{-2}$.
- In the MFV the Minimal Supersymmetric Standard Model predicts too large decay rate of the $B_s^0 \to \mu^+\mu^-$ decay. We can solve this by putting $m_{A^0} \gtrsim 800\mathrm{GeV}$.
- In our work we study the allowed MSSM parameter space where non-minimal flavour violation ($\delta^{23}_{\tilde{u},LR}, \ldots$) significantly affect the CKM contribution and reduces it, so that lower values of the pseudoscalar higgs mass can be OK in the $B_s^0 \to \mu^+\mu^-$ amplitude.

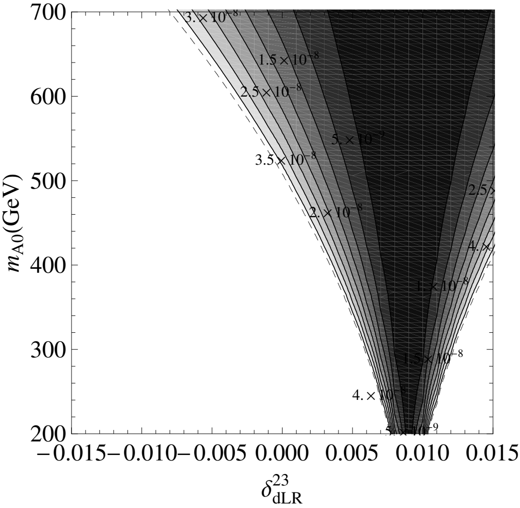
$m_{A^0} - \delta^{23}_{u,LL}$



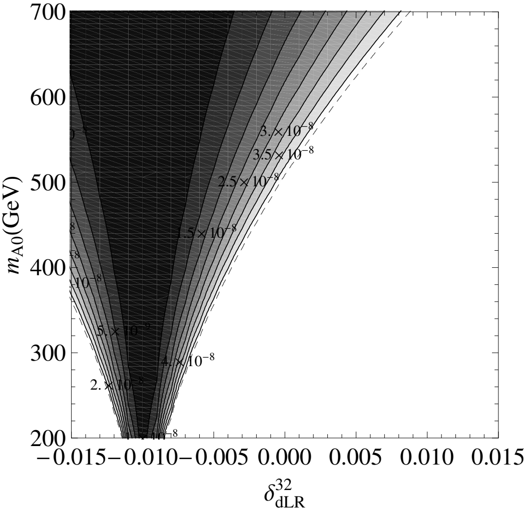
$m_{A^0} - \delta^{23}_{u,LR}$



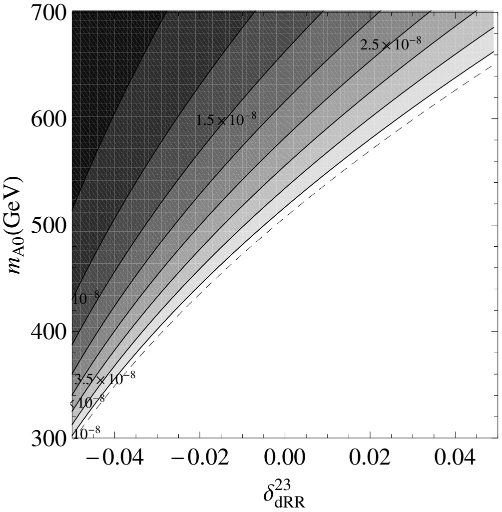
$m_{A^0} - \delta^{23}_{d,LR}$



$m_{A^0} - \delta^{32}_{d,LR}$



$m_{A^0} - \delta^{23}_{d,RR}$



Conclusion

Conclusions

- In the MSSM with large value of $\tan\beta$ the light pseudoscalar higgs A^0 is still allowed.
- For suppression of the large CKM matrix contribution off-diagonal mass insertions in the squark mass matrices can be used.