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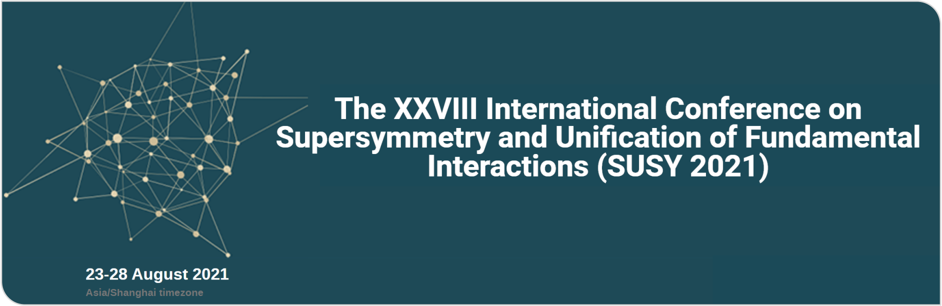
A supersymmetric solution to the $R_{K^{(*)}}$ anomalies

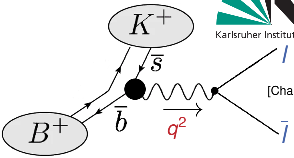
[arXiv:21XX.XXXX]

SUSY 2021

Ulrich Nierste, **Mustafa Tabet** | 26th August 2021



Overview $R_{K^{(*)}}$ anomalies



[Chala et al., '19]

R_M is a theoretically clean observable, defined as:

$$R_M^{[q^2_{\text{min}}, q^2_{\text{max}}]} = \frac{\text{BR}(B \to M\mu^+\mu^-)^{[q^2_{\text{min}}, q^2_{\text{max}}]}}{\text{BR}(B \to Me^+e^-)^{[q^2_{\text{min}}, q^2_{\text{max}}]}}, \qquad M = K^+, K^{0*}$$

Standard Model

$$R_{K^{(*)}} = 1 \pm 0.01 \text{ für } q^2_{\text{min}} \geq 1.1\,\text{GeV}^2$$

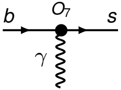
Experiment [LHCb, 2017; LHCb, 2021]

$$R_K^{[1.1,6]} = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}, \qquad R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

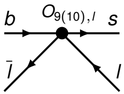
$\Rightarrow$ 2.1–3.1 σ downward deviation of the measurement.

Overview b anomalies

Effective Hamiltonian for $b \to s l^+ l^-$



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i \,,$$



$$O_7 = \frac{e^2}{16\pi^2} m_b \left(\bar{s}\sigma_{\mu\nu} P_R b\right) F^{\mu\nu} \,, \qquad O_{9,l} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_L b\right) \left(\bar{l}\gamma_\mu l\right) \,,$$

$$O_{10,l} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_L b\right) \left(\bar{l}\gamma_\mu \gamma_5 l\right)$$

- global analyses of all observablen in $b \to s l^+ l^-$ transitions [Algueró et al., 2021]
  $\Rightarrow C_{9,\mu}^{\text{NP}} = -C_{10,\mu}^{\text{NP}} = -0.44$ und $6.2\,\sigma$ preferred with regard to the SM

$\Rightarrow$ violation of lepton flavour universality

Explanations of the $R_{K^{(*)}}$ anomalies

- Many explanations: Z' models, leptoquarks, R parity violating MSSM ...
  [e.g. Capdevila et al., 2017; Buttazzo et al., 2017; Bauer et al., 2015,...]
- How about R parity conserving MSSM?

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- How about R parity conserving MSSM?
  General believe: not possible. Why?
  - Z penguins suppressed by small factor $1 - 4s_{\mathrm{W}}^2 \approx 0.08$
  - box diagrams
    - • need maximal mixing and small masses ↯ direct searches
      or
    - • suppressed by tiny Yukawa couplings

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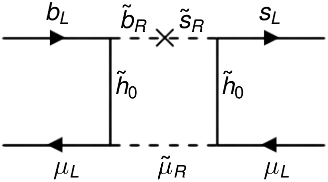
How about $\mathcal{O}(1)$ Yukawa couplings?



$$\propto y_\mu^2 y_s y_b \Delta^D_{RR,32}$$

$$\Rightarrow -C_9^{\mathrm{NP}} \approx C_{10}^{\mathrm{NP}} \sim \mathcal{O}(1)$$

$$m_{R,\tilde{\mu}} \sim m_{D,\tilde{s}(\tilde{b})} \sim \mu \sim \mathcal{O}(1\ \mathrm{TeV})$$

$$y_{d,s,\mu} \sim \mathcal{O}(1),\ m_{R,\tilde{f}} \ll m_{L,\tilde{f}}$$

MSSM Yukawa couplings

- Two Higgs doublets:

$$\mathcal{L}_Y^{\text{SM}} \supset Q_L\, H\, Y_d d_R + Q_L\, H\, Y_u u_R \qquad \Rightarrow m_d = v y_d$$

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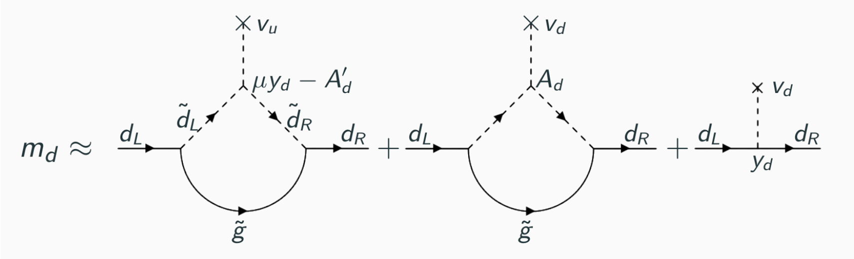
$$\mathcal{L}_Y^{\text{MSSM}} \supset Q_L\, H_d\, Y_d d_R + Q_L\, H_u\, Y_u u_R \qquad \Rightarrow m_d = v_d y_d + \Sigma_d$$

$\rightarrow$ relations between mass and Yukawa coupling modified

$\rightarrow$ in the limit $v_d \rightarrow 0$ one has $y_d \sim \mathcal{O}(1)$ if down-type masses can be generated radiatively, i.e. $m_{d,l} \approx \Sigma_{d,l}$.

Radiative generation of down-type quark masses



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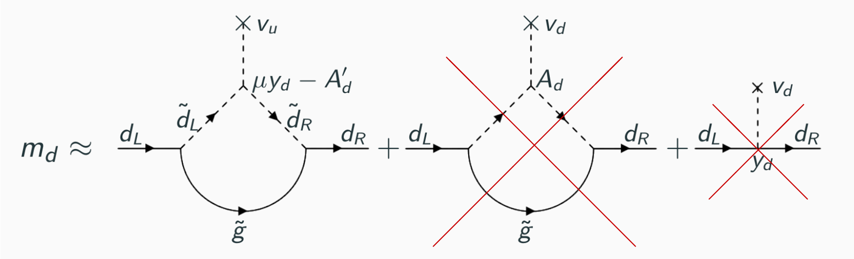

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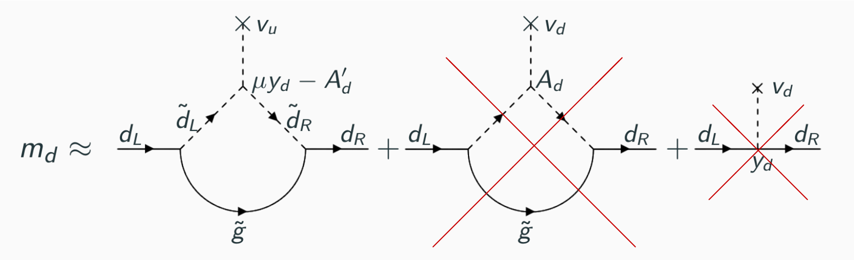


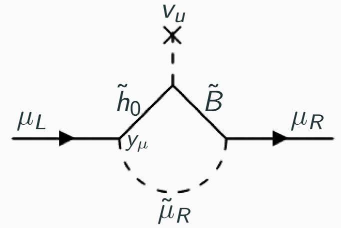
- Squark masses can be controlled by non-holomorphic A'_d terms
- However, A'_d is trilinear coupling in the scalar potential
  $\rightarrow$ vacuum stability?
  $\rightarrow$ check global minimum numerically,
  for metastability follow approach of [Hollik et al. 1812.04644]

$\Rightarrow \; y_d \approx \mathcal{O}(1) \checkmark$

Radiative generation of charged lepton masses

- Non-holomorphic contributions only subleading to the charged lepton masses

  $\rightarrow$ dominant contributions are proportional to the Yukawa couplings



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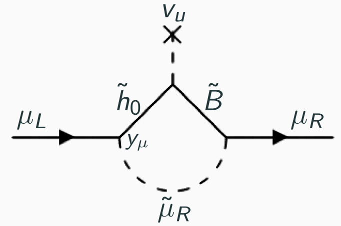


- suppose muon mass can be generated for $y_\mu \sim 1$
  - $\rightarrow$ tau $\approx$ 15 times heavier than the muon
  - $\rightarrow$ perturbativity of y_τ hinders us to generate the tau mass for a stau spectrum similar to the smuon spectrum

Radiative generation of charged lepton masses

$\Rightarrow$ (i) large right-handed mass $m_{\tilde{\tau}_R}$

(ii) light left-handed mass $m_{\tilde{\tau}_L} \lesssim 500\,\text{GeV}$

(iii) up to $y_\tau \approx 3 < \sqrt{4\pi}$ and $\text{sign}(y_\mu y_\tau) = -1$

$\Rightarrow$ Mass spectrum to generate tau mass radiatively yields

$$C_{9,\tau} \approx C_{10,\tau}\,, \qquad \left|\frac{C_{9,\tau}}{C_{9,\mu}}\right| \approx \left(\frac{y_\tau}{y_\mu}\right)^2 \times \text{ratio of LF} \sim \mathcal{O}(1)$$

$\Rightarrow$ No large enhancement of $b \to s\tau\tau$ (in contrast to leptoquark models)

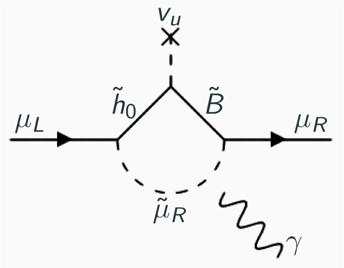
$\Rightarrow$ For $B_s \to ll$ one has

$$\frac{C_{S(P),\tau}}{C_{S(P),\mu}} \sim \mathcal{O}\left(\frac{1}{2}\right)$$

Flavour constraints

- Heavy Higgs contributions are ignored
  $\rightarrow$ see later
- Check constraints on $b \rightarrow s$ transition and muon
  - $(\mathbf{g}-\mathbf{2})_\mu$
  - $B_s - \overline{B}_s$ mixing
  - $B_s \rightarrow \mu\mu$ and $B \rightarrow X_s\gamma$

- $(\mathbf{g-2})_\mu$:
  - Most contributions suppressed by large left-handed smuon mass
  - Dominant contribution:



$$a_\mu^{\chi^0} = -\frac{e^2 m_\mu v y_\mu}{48\pi^2 c_W^2} \frac{\mu M_1}{m_{R,\tilde{\mu}}^2} \frac{F_2^N\left(M_1^2/m_{R,\tilde{\mu}}^2\right) - F_2^N\left(\mu^2/m_{R,\tilde{\mu}}^2\right)}{M_1^2 - \mu^2}$$

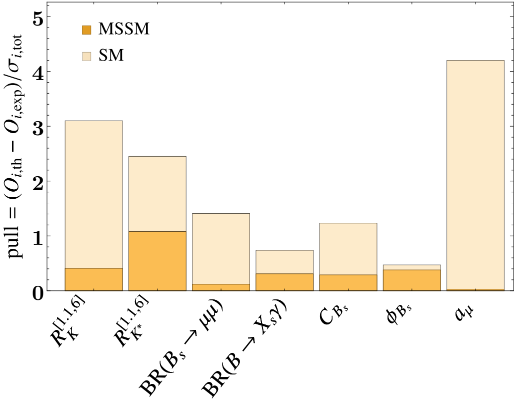
  - The 4.2 σ tension between experiment and SM prediction can be easily resolved within the considered parameter space given $\mathrm{sign}(\mu M_1) = -1$

Results

Experimental constraints

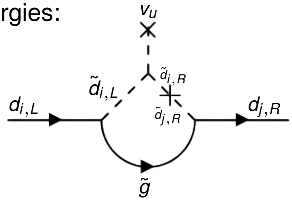
Scenario: radiative fermion masses and vacuum (meta)stability

$\chi^2_{\rm min} \approx 1.67, C_9^{\rm NP} = -0.41, C_{10}^{\rm NP} = 0.44$



Comment

- There are flavour changing self-energies:

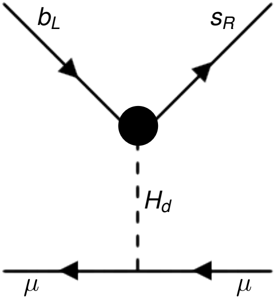


- The generated effective Higgs coupling is large compared to typical values of Yukawa couplings in the SM and MSSM

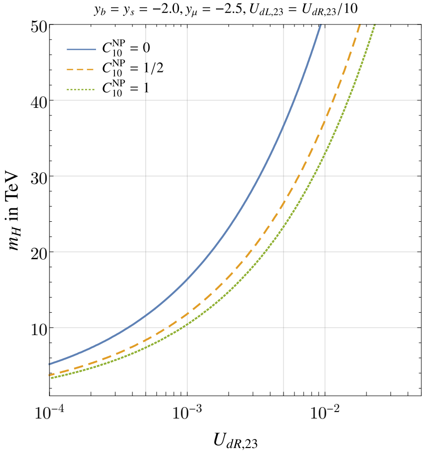
$\rightarrow$ Lower bound on the heavy Higgs masses

Lower bound on heavy Higgs masses

Most stringent constraint comes from $B_s \to \mu\mu$:



$$\boxed{\Rightarrow m_H \gtrsim \mathcal{O}(10\,\text{TeV})}$$



Conclusion

- For $\tan\beta \to \infty$ it is possible to explain the $b \to sll$ anomalies
- Explanation of $(g-2)_\mu$ at the same time possible

$\Rightarrow$ Higgsino and right-handed squark fields around $\sim \mathcal{O}(1\,\text{TeV})$

$\Rightarrow$ Sub-TeV sleptons:

$$m_{L,\tilde{\mu}} \gg m_{R,\tilde{\mu}} \sim \mathcal{O}(500\,\text{GeV}) \sim m_{L,\tilde{\tau}} \ll m_{R,\tilde{\tau}}$$

$\Rightarrow C_{9,\tau}^{\text{NP}} \approx C_{10,\tau}^{\text{NP}}$ in contrast to $C_{9,\mu}^{\text{NP}} \approx -C_{10,\mu}^{\text{NP}}$

$\Rightarrow C_{S(P),\tau}/C_{S(P),\mu} \sim \mathcal{O}\left(1/2\right)$

$\Rightarrow$ $m_H \gtrsim \mathcal{O}(10\,\text{TeV})$