Electron and Muon g-2 in a LFUV 2HDM

Flavor at the Crossroads 2022

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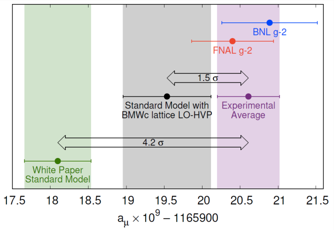
GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN | IFIC INSTITUT DE FÍSICA CORPUSCULAR | CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS | VNIVERSITAT DE VALÈNCIA | cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

INTRODUCTION → ARXIV: 2006.01934 AND 2204.XXXX

We consider the two leptonic (g-2) anomalies



- Muon g-2 collaboration, Phys. Rev. Lett. 126 (2021) 14 2104.03281

$$\delta a_\mu \equiv a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (2.5 \pm 0.6) \times 10^{-9} (4.2\sigma)$$

- Parker et al. Science (2018) 360:191, α from Cs recoil 1812.04130

$$\delta a_e = -(8.7 \pm 3.6) \times 10^{-13} (2.4\sigma)$$

Comment on: Morel et al. Nature (2020) 588:61, α from Ru recoil

$$\delta a_e = (4.8 \pm 3.0) \times 10^{-13} (1.6\sigma)$$

Comment on: $\phi(400 GeV) \to \tau\tau$ bump (ATLAS, 2.2σ) 2002.12223

See also: N2HDM and NMSSM. Biekötter et al. (2021) 2109.01128

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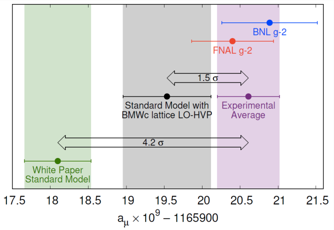

WE USE WP20 SM $(g-2)_\mu$ PREDICTION

No anomaly with new lattice BMW 2002.12347

(tension with EW fits.) 2003.04886

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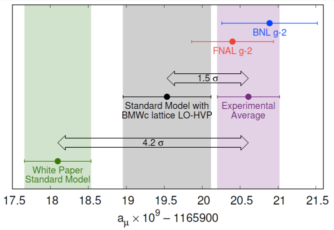

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Two Higgs Doublet Model

Yukawa Lagrangian: Higgs Basis

$$\mathscr{L}_{\mathrm{Y}} = -\frac{\sqrt{2}}{v}\bar{Q}_L^0\left(H_1 \mathrm{M}_d^0 + H_2 \mathrm{N}_d^0\right) d_R^0 - \frac{\sqrt{2}}{v}\bar{Q}_L^0\left(\tilde{H}_1 \mathrm{M}_u^0 + \tilde{H}_2 \mathrm{N}_u^0\right) u_R^0$$
$$-\frac{\sqrt{2}}{v}\bar{L}_L^0\left(H_1 \mathrm{M}_\ell^0 + H_2 \mathrm{N}_\ell^0\right) \ell_R^0 + \text{h.c.}\ .$$

where

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+H^0+iG^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \mathrm{H}^+ \\ \frac{R^0+iI^0}{\sqrt{2}} \end{pmatrix},$$

Fermion mass basis: $\mathrm{M}_f = \mathrm{diag}(m_{f_1}, m_{f_2}, m_{f_3})$ but $\mathrm{N}_f \rightarrow$ not diagonal

$\mathrm{N}_f \rightarrow$ New flavor structure very constrained (FCNC)

⬇

Can it explain the anomalies?

General Flavor Conserving Models

Both Yukawa matrices are diagonalizable simultaneously, leading to:

$$N_f = \begin{pmatrix} n_{f_1} & 0 & 0 \\ 0 & n_{f_2} & 0 \\ 0 & 0 & n_{f_3} \end{pmatrix}$$

Not protected by a symmetry $\rightarrow$ Big corrections?

Proved in 1803.08521 (Botella, FCG, Nebot)

Lepton Sector General Flavor Conserving 2HDM

$\Downarrow$

RGE: One-loop stable

Quark Sector $\rightarrow$ Natural Flavor Conserving: Type I & II ($\mathbb{Z}_2$ symmetry)

Required $e-\mu$ decoupling in:

- I-gℓFC: Type I + gFC in the lepton sector

$$N_d = \cot\beta\, M_d \quad N_u = \cot\beta\, M_u \quad N_\ell = \begin{pmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{pmatrix}$$

No CP-violation neither in the scalar nor in the new Yukawa sector

$$\mathrm{Im}(n_f) = 0 \quad \text{and} \quad \begin{pmatrix} \mathrm{h} \\ \mathrm{H} \\ \mathrm{A} \end{pmatrix} = \begin{pmatrix} s_{\alpha\beta} & c_{\alpha\beta} & 0 \\ -c_{\alpha\beta} & s_{\alpha\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H^0 \\ R^0 \\ I^0 \end{pmatrix}$$

Electron and Muon (g-2)

We consider the two leptonic anomalies

$$\delta a_\ell \equiv a_\ell^{\mathrm{Exp}} - a_\ell^{\mathrm{SM}}$$

$$\delta a_e = -(8.7 \pm 3.6) \times 10^{-13}\,, \quad \delta a_\mu = (2.5 \pm 0.6) \times 10^{-9}\,.$$

A naive 1-loop inspired parametrization

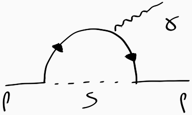
$$\delta a_\ell = K_\ell \Delta_\ell\,, \qquad K_\ell = \frac{1}{8\pi^2}\left(\frac{m_\ell}{v}\right)^2$$

where K_ℓ collect the typical factors arising in one loop contributions; $K_e \simeq 5.5 \times 10^{-14}$ and $K_\mu \simeq 2.3 \times 10^{-9}$, to reproduce the anomalies:

$$\Delta_e \simeq -16\,, \qquad \Delta_\mu \simeq 1\,.$$

The 1-loop contribution $\left(\mathcal{O}\left(\frac{m_\ell^2}{m_S^2}\right) \text{ and } s_{\alpha\beta} \to 1\right)$

$$\Delta_\ell^{(1)} \simeq n_\ell^2 \left(\frac{I_{\ell\mathrm{H}}}{m_\mathrm{H}^2} - \frac{I_{\ell\mathrm{A}} - 2/3}{m_\mathrm{A}^2} - \frac{1}{6 m_{\mathrm{H}^\pm}{}^2} \right)$$



where

$$I_{\ell\mathrm{S}} = -\frac{7}{6} - 2 \ln \left(\frac{m_\ell}{m_\mathrm{S}} \right) .$$

For a typical range $m_\mathrm{S} \in [0.2;\ 2.0]$ TeV, the loop functions $I_{\ell\mathrm{S}}$ obey

$$I_{e\mathrm{S}} \in [24.6; 29.2] , \qquad I_{\mu\mathrm{S}} \in [13.9; 18.5] ,$$

and thus the dominant contributions to $\Delta_\ell^{(1)}$ are the logarithmically enhanced contributions from H and A.

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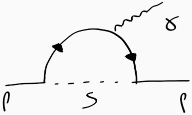

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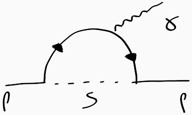

where

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We need $\Delta_e \simeq -16$ that is only possible through the A contribution:

$$\Delta_e \simeq -[n_e]^2 I_{eA}/m_A^2 \quad \text{with} \quad I_{eA} \in [24.6; 29.2]$$

$$\Downarrow$$

$$[n_e]^2 \sim m_A^2$$

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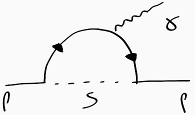


where

$$I_{\ell \mathrm{S}} = -\frac{7}{6} - 2 \ln \left(\frac{m_\ell}{m_{\mathrm{S}}} \right) .$$

We need $\Delta_\mu \simeq 1$ that is only possible through the H contribution:

$$\Delta_\mu \simeq [n_\mu]^2 I_{\mu \mathrm{H}} / m_{\mathrm{H}}^2 \quad \text{with} \quad I_{\mu \mathrm{H}} \in [13.9; 18.5]$$

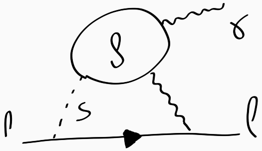
$$\Downarrow$$

$$[n_\mu]^2 \sim \left[\frac{m_{\mathrm{H}}}{4} \right]^2$$

2-LOOP

The 2-loop Barr-Zee contribution

$$\Delta_\ell^{(2)} = -\left(\frac{2\alpha}{\pi}\right)\left(\frac{n_\ell}{m_\ell}\right)F$$



$$F = \frac{\cot\beta}{3}\left[4(f_{t\mathrm{H}} + g_{t\mathrm{A}}) + (f_{b\mathrm{H}} - g_{b\mathrm{A}})\right] + \frac{n_\tau}{m_\tau}(f_{\tau\mathrm{H}} - g_{\tau\mathrm{A}})$$

If δ_{a_e} and δ_{a_μ} explained by dominant two loop contribution

$$\frac{\delta a_e}{\delta a_\mu} = \frac{m_e\, n_e}{m_\mu\, n_\mu},$$

In order to solve the discrepancies through the two loop contributions:

$$n_\mu \approx -15 n_e$$

DECOUPLED YUKAWA INTERACTION

The possibility of explaining both anomalies relies in the freedom of

$\mathrm{sgn}(n_e) \neq \mathrm{sgn}(n_\mu)$

CONSTRAINTS

- Scalar sector: boundness, perturbative unitarity and oblique parameters.
  - Softly broken $\mathbb{Z}_2 \rightarrow \mu_{12}^2 \neq 0$ (otherwise $m_S < 1\text{TeV}$)
- Perturbativity of the Yukawa couplings:

$$\frac{|n_f|}{v} \leq \mathcal{O}(1) \longrightarrow |n_f| \lessapprox 250\text{GeV}$$

- Signal strengths (production$\times$ decay) 125GeV Higgs.
- LFU constraints ($\ell \rightarrow \ell' \nu \bar{\nu}$, $P \rightarrow \ell \nu$)
- Flavour constraints: Meson-mixing and $b \rightarrow s\gamma$
- $e^+e^- \rightarrow \ell^+\ell^-$ from LEP
- LHC direct searches

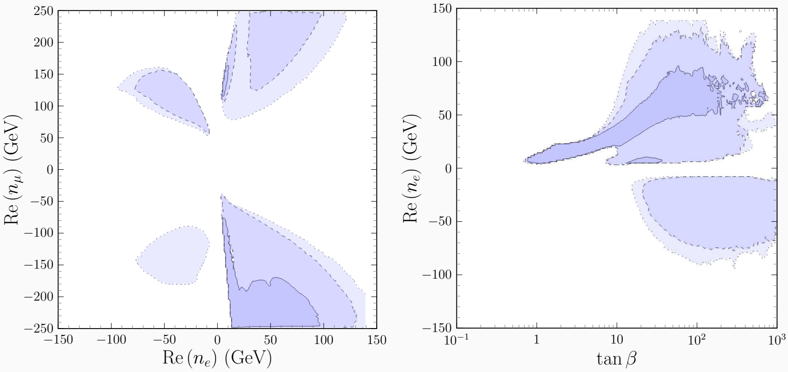
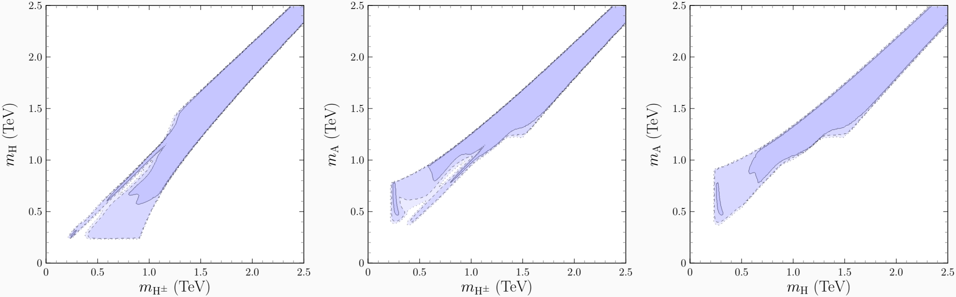


Figure 1: From darker to lighter, 1, 2 and 3σ regions.

HOW CAN $n_e < 0$?

Low mass $\rightarrow$ big t_β $\rightarrow$ top loop suppressed $\rightarrow$ tau loop dominant

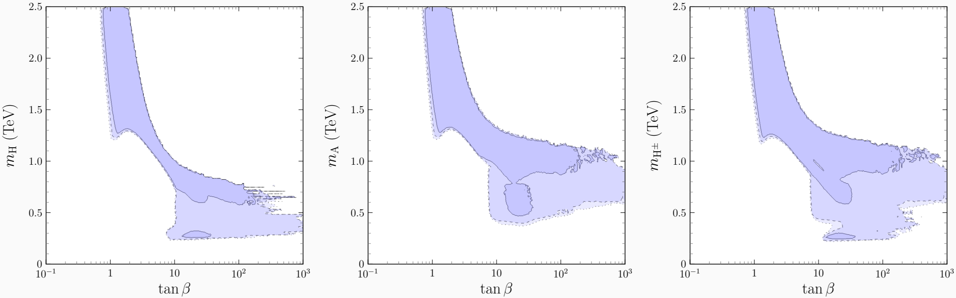
Note: $\Delta_\ell^{(2)} \propto -\frac{n_\ell}{m_\ell}\left\{\frac{\cot\beta}{3}\left[4(f_{tH}+g_{tA})+(f_{bH}-g_{bA})\right]+\frac{n_\tau}{m_\tau}(f_{\tau H}-g_{\tau A})\right\}$



Scalar masses

- $m_{\rm H^\pm}$ must be degenerated with $m_{\rm H}$ or $m_{\rm A}$ (EW contraints)
- In the low mass region, we expect that $m_{\rm H} < m_{\rm A}$ (LHC $S \to \mu^+\mu^-$ since $[pp]_{ggF} \to {\rm A} \approx 6 \times [pp]_{ggF} \to {\rm H}$, need ${\rm A} \to {\rm HZ}$ channel)

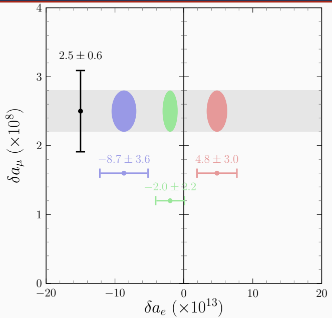
Results I-gℓFC

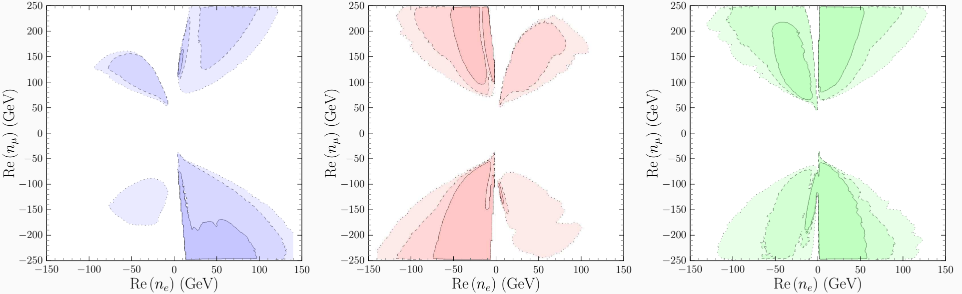


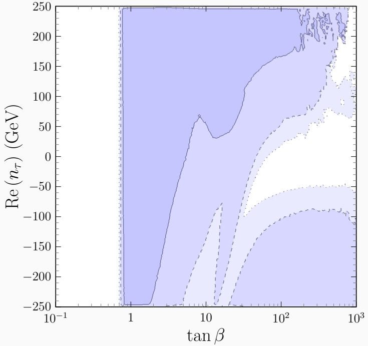
Scalar masses vs. t_β

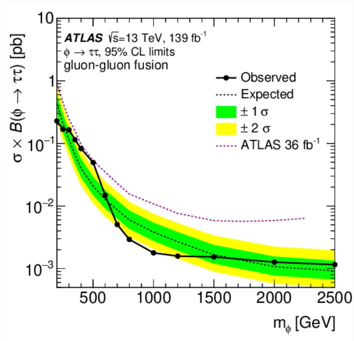
- Shaped on the left by $B_q - \bar{B}_q$ meson mixing
- Low mass $\rightarrow$ muon anomaly 1-loop dominated.
- $m_{\rm A} \gtrsim 500$GeV. Electron anomaly 1-loop would require non perturbative coupling ($n_e \approx 500$ GeV)

RESULTS I-GℓFC: DIFFERENT δa_e









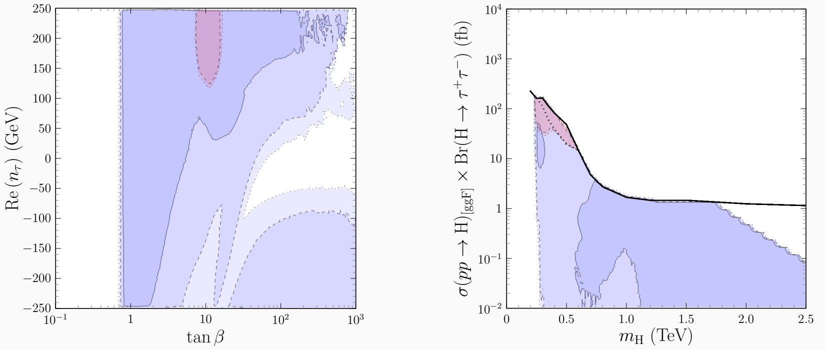
2002.12223

In this framework n_τ is almost unconstrained

↓

Can we explain ATLAS bump?

RESULTS: $\phi \to \tau\tau$



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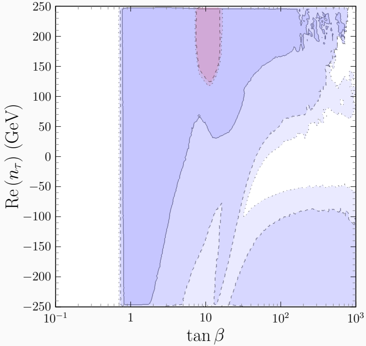

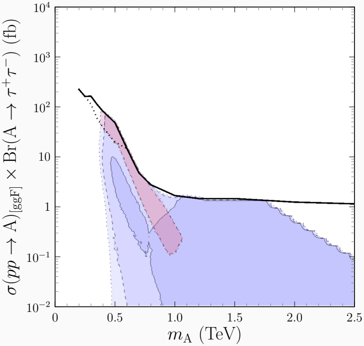

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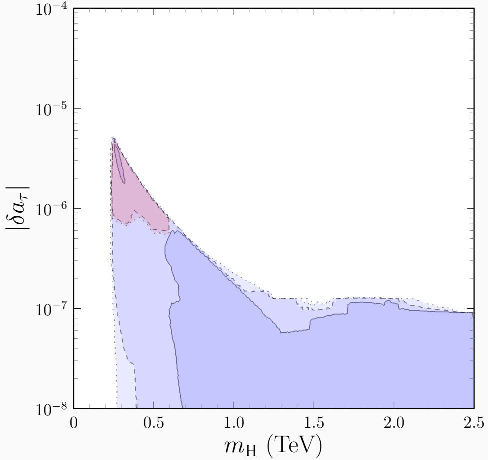
Can we explain ATLAS bump?

Results: $\phi \to \tau\tau$. Prediction to δa_τ



Similar level of experimental precision to other BSM scenarios is required, see Crivellin et al. 2021

2111.10378

Conclusions

- General Flavor Conserving 2HDM in the lepton sector are a robust framework (RGE stable)
- Lepton Flavor Universality Violation
  - Key if g-2 anomalies present different signs.
- Two types of solutions in agreement with constraints
  - both δa_ℓ from two loop Barr-Zee contributions
    - new scalars have masses in the 1–2.5 TeV range
    - $t_\beta \approx 1$
  - δa_e from two loop Barr-Zee contributions, δa_μ from one loop
    - new scalars have masses below 1 TeV
    - $t_\beta > 1$
- The different available δa_e can be explained
- Deviations wrt SM in $(pp)_{ggF} \to S \to \tau^+\tau^-$?

Thank you

HVP: Lattice vs data-driven

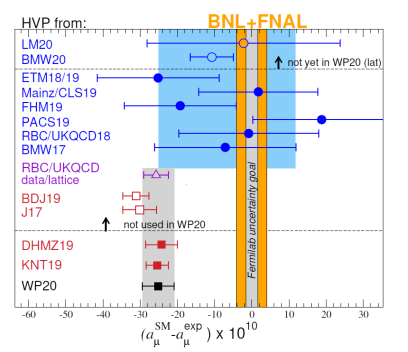


Figure 2: G. Colangelo, EPJ Web Conf. 258 (2022), 01004

Hadronic Vacuum Polarization enters in the running of fine structure constant α

Crivellin, Hoferichter, Manzari, Montull, 2003.04886

"removing the tension between SM prediction and experiment for $(g-2)_\mu$ by a change in HVP increases the existing tensions within the EW fit."

BackUp: Constraints

- The natural δa_ℓ constraint

$$\chi_0^2(\delta a_e, \delta a_\mu) = \left(\frac{\delta a_e - c_e}{\sigma_e}\right)^2 + \left(\frac{\delta a_\mu - c_\mu}{\sigma_\mu}\right)^2$$

We impose a stronger requirement:

$$\chi^2(\delta a_e, \delta a_\mu) = \begin{cases} 0, & \text{if } \chi_0^2(\delta a_e, \delta a_\mu) \leq \frac{1}{4} \\ 10^6 \times (\chi_0^2(\delta a_e, \delta a_\mu) - \frac{1}{4}), & \text{if } \chi_0^2(\delta a_e, \delta a_\mu) > \frac{1}{4} \end{cases}$$

- Fermion sector: perturbative Yukawa couplings

$$\chi^2_{\text{Pert}}(n_\ell) = \begin{cases} 0, & \text{if } |n_\ell| \leq n_0 \\ \left(\frac{|n_\ell| - n_0}{\sigma_{n_0}}\right)^2, & \text{if } |n_\ell| > n_0 \end{cases}$$

with $n_0 = 95$ or 245 GeV and $\sigma_{n_0} = 1$ GeV.

BackUp: Constraints

- Higgs signal strengths:
  - production × decay signal strengths of the usual channels
  - large lepton couplings: also include $h \to \mu^+\mu^-$, e^+e^- information
- $\mathrm{H}^\pm$ mediated contributions:
  - Lepton flavour universality: purely leptonic decays $\ell_j \to \ell_k \nu \bar{\nu}$, decays with light pseudoscalar mesons K, $\pi \to e\nu$, $\mu\nu$ and $\tau \to K\nu, \pi\nu$
  - $b \to s\gamma$, $B_q^0 - \bar{B}_q^0$
- $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ at LEP
- LHC searches:
  - searches of dilepton resonance: $\sigma(pp \to S)[ggF] \times$ Br$S \to \ell^+\ell^-)$ S=H, A and $\ell = \mu, \tau$
  - searches of charged scalars: $\sigma(pp \to \mathrm{H}^\pm tb) \times$ Br$(\mathrm{H}^\pm \to f)$, $f = \tau\nu$, tb

BackUp: Constraints

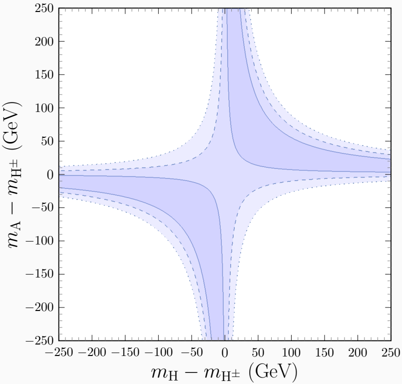


Figure 3: Oblique parameters: allowed regions in $m_A - m_{H^\pm}$ vs. $m_H - m_{H^\pm}$. The plot corresponds to $m_{H^\pm} = 1$ TeV, but the regions do not change significantly for different values of $m_{H^\pm}$.

BackUp: Constraints

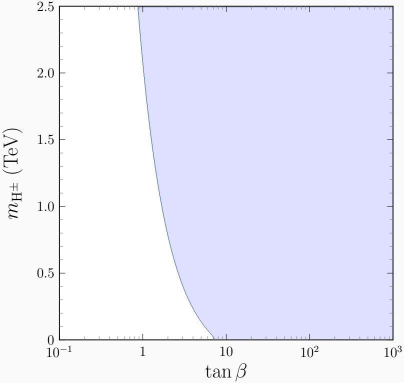
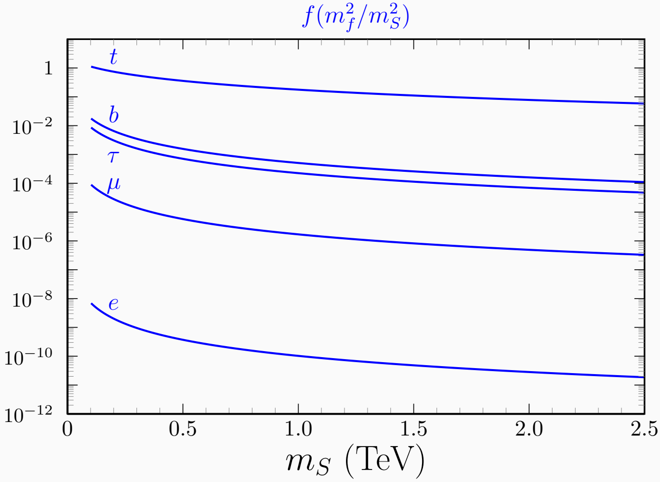


Figure 4: $\mathrm{H}^{\pm}$ FCNC: $m_{\mathrm{H}^{\pm}}$ vs. t_{β} allowed region when contributions of $\mathrm{H}^{\pm}$ to B_q–$\bar{B}_q$ are below experimental uncertainty in ΔM_{B_q}.

BackUp:Two loop functions



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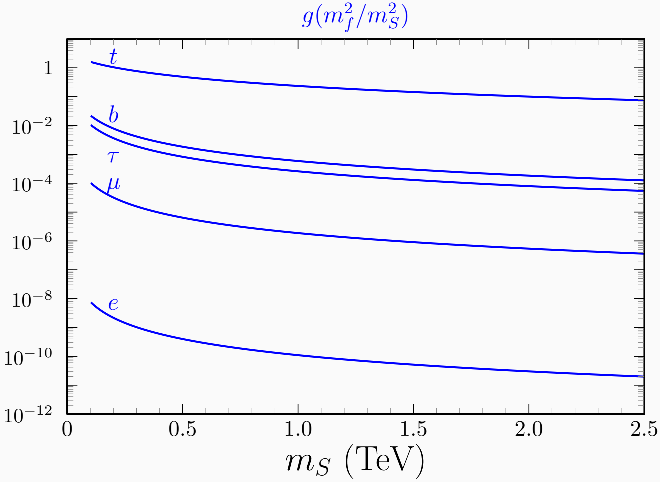
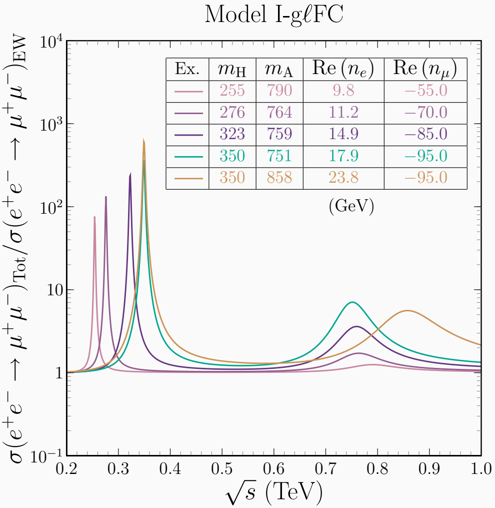


BackUp: Future colliders



$e^+e^- \to \mu^+\mu^-$ for $\sqrt{s} \in [0.2; 1.0]$ TeV.

LFU Constraints

$$R^P_{\mu e} = \frac{\Gamma(P^+ \to \mu^+ \nu)}{\Gamma(P^+ \to \mu^+ \nu)_{\text{SM}}} \frac{\Gamma(P^+ \to e^+ \nu)_{\text{SM}}}{\Gamma(P^+ \to e^+ \nu)},$$

the current constraints are

$$R^\pi_{\mu e} = 1 + (4.1 \pm 3.3) \times 10^{-3}, \qquad R^K_{\mu e} = 1 - (4.8 \pm 4.7) \times 10^{-3}.$$

In the present scenario,

$$R^P_{\mu e} = \frac{|1 - \Delta^P_\mu|^2}{|1 - \Delta^P_e|^2}, \qquad |1 - \Delta^P_\ell|^2 = \left|1 - \frac{M_P^2}{t_\beta m^2_{\text{H}^\pm}} \frac{n_\ell}{m_\ell}\right|^2,$$

and thus, for $\Delta^P_\ell \ll 1$,

$$R^P_{\mu e} \simeq 1 + 2\frac{M_P^2}{t_\beta m^2_{\text{H}^\pm}} \left(\frac{\text{Re}\,(n_e)}{m_e} - \frac{\text{Re}\,(n_\mu)}{m_\mu}\right).$$

BackUp: $R_{D^{(*)}}$

$$R_D^{NP}/R_D^{SM} \approx 1 + 1.55\,\mathrm{Re}\left(\frac{n_\tau m_b}{t_\beta m_{\mathrm{H}^\pm}^2}\right) + 1.10\left|\frac{n_\tau m_b}{t_\beta m_{\mathrm{H}^\pm}^2}\right|^2 ,$$

and the prediction for the SM, $R_D^{SM} = 0.300$.

We need $R_D^{NP}/R_D^{SM} \approx 1.35$ leading to

$$\frac{n_\tau m_b}{t_\beta m_{\mathrm{H}^\pm}^2} \approx 0.2$$

$$R_{D^*}^{NP}/R_{D*}^{SM} = 1 + 0.12\,\mathrm{Re}\left(\frac{n_\tau m_b}{t_\beta m_{\mathrm{H}^\pm}^2}\right) + 0.05\left|\frac{n_\tau m_b}{t_\beta m_{\mathrm{H}^\pm}^2}\right|^2 ,$$

and the prediction for the SM, $R_{D^*}^{SM} = 0.259$. We need $R_{D^*}^{NP}/R_{D^*}^{SM} \approx 1.22$.