“Vectorlike chiral” fourth family
to explain muon anomalies

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Outline

- Review of experimental anomalies related to muons
- Interpretation of anomalies, EFT and models
- “Vector like chiral” fourth family model
- Show how it fits the observables and avoids the constraints
- Testable predictions
- Conclusion

Recent anomalies

Existing experimental anomalies

1) Muon anomalous magnetic moment $(g-2)_\mu$:

Discrepancy between SM prediction and measurement:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11}\,.$$

[Bennett et al., 2006, Patrignani et al., 2016]

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1) Muon anomalous magnetic moment $(g-2)_\mu$:

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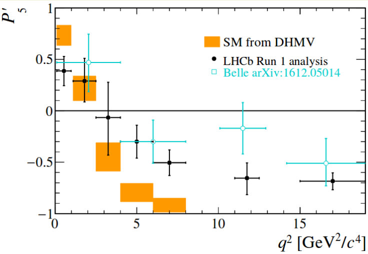
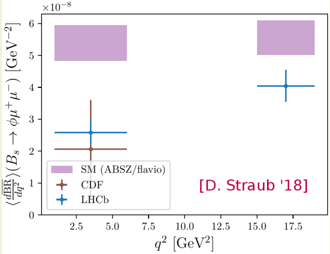
2) Semi-leptonic $B_{d,s}$ decays, $b \to s\mu\overline{\mu}$:

- Angular observables in $B \to K^*\mu^+\mu^-$ [LHCb, BaBar]
- Branching ratios of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ [LHCb, BaBar, CMS, Belle, ATLAS]





Existing experimental anomalies

3) Lepton flavor universality in semi-leptonic B decays:

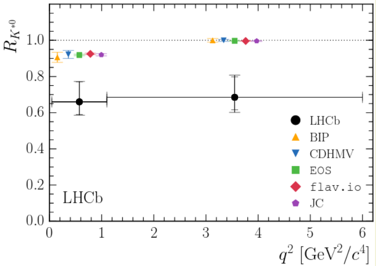
$$R_{K^{(*)}} := \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \, \frac{\mathrm{d}\,\Gamma}{\mathrm{d}q^2}(B \to K^{(*)}\mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \, \frac{\mathrm{d}\,\Gamma}{\mathrm{d}q^2}(B \to K^{(*)}e^+e^-)}$$

Experiment: [Aaij et al., 2014, Aaij et al., 2017]

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$



Theory (SM): $R_{K^{(*)}} \approx 1$ see e.g. [Bordone, Isidori, Pattori]

Significance of muon anomalies? ... growing!

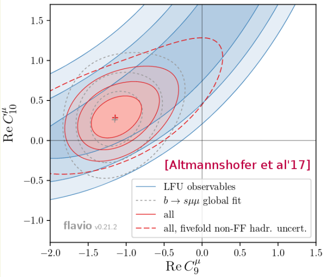
Interpretation of $b \to s\mu\mu$ anomalies

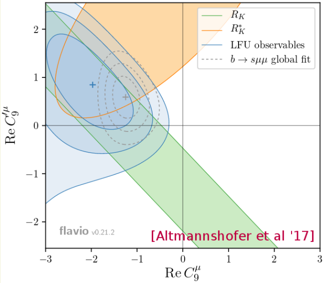
Curiously, **all** of the $b \to s\mu\mu$ anomalies can **simultaneously** be fit by deviations from the SM in one (or more) of the Wilson coefficients:

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4\,G_{\text{F}}}{\sqrt{2}}\,V_{tb}V_{ts}^{*}\,\frac{e^2}{16\pi^2}\sum_{j=9,10}\left(C_j\mathcal{O}_j + C_j'\mathcal{O}_j'\right) + \text{h.c.}\,,$$

$$\mathcal{O}_9 := (\bar{s}\gamma_\mu P_L b)\,(\bar{\mu}\gamma^\mu\mu) \qquad \mathcal{O}_9' := (\bar{s}\gamma_\mu P_R b)\,(\bar{\mu}\gamma^\mu\mu)$$

$$\mathcal{O}_{10} := (\bar{s}\gamma_\mu P_L b)\,(\bar{\mu}\gamma^\mu\gamma_5\mu) \qquad \mathcal{O}_{10}' := (\bar{s}\gamma_\mu P_R b)\,(\bar{\mu}\gamma^\mu\gamma_5\mu)$$





Broad qualitative agreement: [Altmannshofer et al., 2017a, Alok et al., 2017, Capdevila et al., 2017, Ciuchini et al., 2017, D'Amico et al., 2017, Geng et al., 2017, Ghosh, 2017, Hiller and Nisandzic, 2017], [Arbey, Hurth, Mahmoudi, Neshatpour '18]

Models to explain the anomalies

- Leptoquarks for $b \to s\mu\mu$ $\gg$ see talks by Jim Talbert, Gino Isidori

  [Hiller and Schmaltz, 2014], [Bauer and Neubert, 2016], [Päs and Schumacher, 2015], [Alonso et al., 2015], [Fajfer and Košnik, 2016], [de Medeiros Varzielas and Hiller, 2015], [Greljo, Isidori, Marzocca '15], [Barbieri, Isidori, Pattori, Senia '15], [Becirevic, Kosnik, Sumensari, Funchal '16], [Buttazzo et al., 2017], [Bečirević and Sumensari, 2017], ... many more ...

  also with g-2 see e.g. [Das et al., 2016, Coluccio Leskow et al., 2017]

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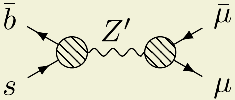
- Z' models for $b \to s\mu\mu$ see e.g. [Gauld et al., 2014, Buras et al., 2014], [King, 2017]
  - Z' from gauged $\mathrm{U}(1)_{\mu-\tau}$ + VL quarks. [Altmannshofer et al '14] [Crivellin et al '15]



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  [Czarnecki and Marciano, 2001, Kannike et al., 2012, Dermíšek and Raval, 2013]

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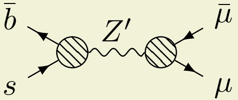

- VL leptons can explain $(g-2)_\mu$.
  [Czarnecki and Marciano, 2001, Kannike et al., 2012, Dermíšek and Raval, 2013]

$\Rightarrow$ Simultaneous explanation of $(g-2)_\mu$ **and** $b \to s\mu\mu$ via Z'+ VL leptons + VL quarks [Allanach et al '15, Altmannshofer et al '16] [Megias et al '17]

Typically:

- ⋆ upper bound on Z' mass from $B_s - \overline{B}_s$ oscillations. [Altmannshofer et al., 2014b]
- ⋆ Significant deviations from SM in $h \to \mu\mu$, $h \to \mu\tau$. [Kannike et al '11, Dermisek et al '13, Crivellin et al '15, Altmannshofer et al '16]

But: Hints for $h \to \mu\tau$ *are gone*: $\mathrm{BR}_{h\to\mu\tau} < 0.25\%$ [CMS 1712.07173]

Our model: “Vector-like” chiral fourth family

A “holistic” solution to $(g-2)_\mu$ **and** $b \to s\mu^+\mu^-$ anomalies.

Philosophy of this model:

- Take a new twist to the simple and nice ideas of $\mathrm{U}(1)_{\mu-\tau}$ + VL quarks + VL leptons:
- Add a whole new generation of fermions which are:
  - Vector-like with respect to the SM, but
  - Chiral with respect to a **new** $\mathbf{U(1)_{3-4}}$ gauge symmetry.
  - Only “one” new scale $\langle v_\Phi \rangle \sim M_{\mathrm{VL}} \sim M_{Z'} \sim \mathrm{TeV}$.

  $\Rightarrow$ Can explain $(g-2)_\mu$ and $b \to s\mu^+\mu^-$, while there is:
  - ⋆ no upper bound on $M_{Z'}$,
  - ⋆ no sizable deviations in SM-h couplings.
- GUT compatible Fermion content.
  - “Interlocked” assignment of 3_L&4_L into $\mathbf{16}$ of $\mathrm{SO}(10)$.
- Motivated by heterotic string orbifold models ($\to$ MSSM):
  - Typical feature: Fermions which are VL w.r.t SM, but chiral w.r.t. extra $\mathrm{U}(1)$'s + NA discrete fam. symmetry [Kobayashi et al., 2004, Kobayashi et al., 2005, Buchmuller et al., 2006, Lebedev et al., 2007, Lebedev et al., 2008a, Lebedev et al., 2008b, Blaszczyk et al., 2010, Kappl et al., 2011]

“Vector-like” chiral fourth family

The model: Gauge group $G_{\rm SM} \times \mathrm{U}(1)_{3-4}$

- Fermion sector

$G_{\rm SM}$ family	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{1})_{0}$	$\mathrm{U}(1)_{3-4}$
$a=1,2$	$q_{\rm L}^a$	$u_{\rm R}^a$	$d_{\rm R}^a$	$\ell_{\rm L}^a$	$e_{\rm R}^a$	$\nu_{\rm R}^a$	0
3	$q_{\rm L}^3$	$u_{\rm R}^3$	$d_{\rm R}^3$	$\ell_{\rm L}^3$	$e_{\rm R}^3$	$\nu_{\rm R}^3$	1
$4_{\rm L}$	$Q_{\rm L}$	$U_{\rm R}$	$D_{\rm R}$	$L_{\rm L}$	$E_{\rm R}$	$N_{\rm R}$	-1
$4_{\rm R}$	$Q_{\rm R}$	$U_{\rm L}$	$D_{\rm L}$	$L_{\rm R}$	$E_{\rm L}$	$N_{\rm L}$	0

- Scalar sector

	H	Φ	(φ_1,φ_2)
$G_{\rm SM}$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{1})_{0}$	$(\mathbf{1},\mathbf{1})_{0}$
$\mathrm{U}(1)_{3-4}$	0	1	0
D_4	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$

- Notation: $q_{\rm L}^i = (u_{\rm L}^i, d_{\rm L}^i)$, $\ell_{\rm L}^i = (\nu_{\rm L}^i, e_{\rm L}^i)$, but

$$Q_{\rm L} = (U'_{\rm L}, D'_{\rm L}),\, Q_{\rm R} = (U'_{\rm R}, D'_{\rm R}),\, L_{\rm L} = (N'_{\rm L}, E'_{\rm L}),\, L_{\rm R} = (N'_{\rm R}, E'_{\rm R})$$

Model Lagrangian

$$\mathcal{L} \supset \mathcal{L}_{3,H} + \mathcal{L}_{\mathrm{VL},H} + \mathcal{L}_{3,\Phi} + \mathcal{L}_{\mathrm{VL},\Phi} + \mathcal{L}_{12,\varphi} + \mathcal{L}_{\mathrm{Maj}} ~,$$

$$\begin{aligned}
\mathcal{L}_{3,H} &:= -\, y_b\, \overline{q}_L^3 H d_R^3 - y_\tau\, \overline{\ell}_L{}^3 H e_R^3 - y_\nu\, \overline{\ell}_L{}^3 \widetilde{H} \nu_R^3 + \text{h.c.}~, \\
\mathcal{L}_{3,\Phi} &:= -\, \lambda_3\, \Phi \left(\overline{q}_L^3 Q_R + \overline{d}_R^3 D_L + \overline{\ell}_L^3 L_R + \overline{e}_R^3 E_L \right) + \text{h.c.}~, \\
\mathcal{L}_{\mathrm{VL},H} &:= -\, \lambda_{LR} \left(\overline{Q}_L H D_R + \overline{L}_L H E_R + \overline{L}_L \widetilde{H} N_R \right) + \text{h.c.} \\
&\quad -\, \lambda_{RL} \left(\overline{Q}_R H D_L + \overline{L}_R H E_L + \overline{L}_R \widetilde{H} N_L \right) + \text{h.c.}~, \\
\mathcal{L}_{\mathrm{VL},\Phi} &:= -\, \Phi^* \left(\lambda_Q \overline{Q}_L Q_R + \lambda_D \overline{D}_R D_L + \lambda_L \overline{L}_L L_R + \lambda_E \overline{E}_R E_L + \lambda_N \overline{N}_R N_L \right) + \text{h.c.}~, \\
\mathcal{L}_{12,\varphi} &:= -\, \lambda_2\, \varphi^a \left(\overline{q}_L^a Q_R + \overline{d}_R^a D_L + \overline{\ell}_L^a L_R + \overline{e}_R^a E_L \right) + \text{h.c.}~. \\
\mathcal{L}_{\mathrm{Maj}} &:= -\, \frac{1}{2} M_L \overline{N_L^{\mathcal{C}}} N_L - \frac{1}{2} M_R^{ab} \overline{\left(\nu_R^a\right)^{\mathcal{C}}} \nu_R^b - \left(M_R \overline{N_R^{\mathcal{C}}} \nu_R^3 + \text{h.c.} \right)~.
\end{aligned}$$

(In our notation $P_L N_L = N_L$ is a two component Dirac spinor which can be written in terms of the two component Weyl spinor, η, as $N_L = (\eta, 0)^{\mathrm{T}}$. Then $N_L^{\mathcal{C}} = (0, \mathrm{i}\sigma_2 \eta^*)^{\mathrm{T}}$.)

Mass matrices - gauge basis

Charged lepton mass matrix: (assuming $\mathbf{2} \oplus \mathbf{1}$ structure from high scale D_4)

$$\overline{\boldsymbol{e}}_L\,\mathcal{M}^\ell\,\boldsymbol{e}_R \equiv \begin{pmatrix} \overline{E}_L \\ \overline{E}'_L \\ \overline{e}^3_L \\ \overline{e}^2_L \\ \overline{e}^1_L \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \lambda_{RL}\,v & \lambda_E\,v_\Phi & \lambda_3\,v_\Phi & \lambda_2\,v_\varphi & 0 \\ \lambda_L\,v_\Phi & \lambda_{LR}\,v & 0 & 0 & 0 \\ \lambda_3\,v_\Phi & 0 & y_\tau\,v & 0 & 0 \\ \lambda_2\,v_\varphi & 0 & 0 & y_{22}\,v & y_{21}\,v \\ 0 & 0 & 0 & y_{12}\,v & y_{11}\,v \end{pmatrix} \begin{pmatrix} E'_R \\ E_R \\ e^3_R \\ e^2_R \\ e^1_R \end{pmatrix}\;.$$

(Assumption: all VEVs and couplings $\in \mathbb{R}$)

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(Assumption: all VEVs and couplings $\in \mathbb{R}$)

Completely analogous: Down-type quark mass matrix:

$$\mathcal{M}^d \equiv \mathcal{M}^\ell \Big|_{\lambda_E \to \lambda_D, \lambda_L \to \lambda_Q, y_\tau \to y_b, y_\mu \to y_s} .$$

Both mass matrices have the same structure.

$$\overline{\boldsymbol{d}}_L \, \mathcal{M}^d \, \boldsymbol{d}_R .$$

where

$$\boldsymbol{d}_L := \left(D_L,\, D'_L,\, d^3_L,\, d^2_L\right)^T$$
$$\boldsymbol{d}_R := \left(D'_R,\, D_R,\, d^3_R,\, d^2_R\right)^T .$$

Mass matrices - gauge basis

Neutrino masses:

$$\begin{pmatrix}\overline{\boldsymbol{\nu}}_L \\ \overline{\boldsymbol{\nu}}_R^{\mathcal{C}}\end{pmatrix}^{\mathrm{T}} \begin{pmatrix}\mathcal{M}_L & \mathcal{M}_D \\ \mathcal{M}_D^{\mathrm{T}} & \mathcal{M}_R\end{pmatrix} \begin{pmatrix}\boldsymbol{\nu}_L^{\mathcal{C}} \\ \boldsymbol{\nu}_R\end{pmatrix} ,$$

where

$$\boldsymbol{\nu}_L := \left(N_L,\, N_L',\, \nu_L^3,\, \nu_L^2\right)^T$$
$$\boldsymbol{\nu}_R := \left(N_R',\, N_R,\, \nu_R^3,\, \nu_R^2\right)^T .$$

Dirac mass matrix $\mathcal{M}^D$, again has the same structure as $\mathcal{M}^\ell$:

$$\mathcal{M}^D \equiv \mathcal{M}^\ell\big|_{\lambda_E\to\lambda_N,\, y_\tau\to y_{\nu_1},\, y_\mu\to y_{\nu_2}} .$$

Majorana mass matrices $\mathcal{M}_{L,R}$: all entries are zero, besides

$$[\mathcal{M}_L]_{11} = \frac{1}{2}M_L ,$$
$$[\mathcal{M}_R]_{44} = \frac{1}{2}M_R^{11} , \qquad [\mathcal{M}_R]_{23} = [\mathcal{M}_R]_{32} = M_R .$$

Mass matrices - mass basis

Physical fields in the mass basis: $(A, B = 1, .., 4; \alpha, \beta = 1, .., 8)$

$$\left[\hat{\boldsymbol{e}}_{L,R}\right]^A = \left[(U^\ell_{L,R})^\dagger\right]^{AB} \left[\boldsymbol{e}_{L,R}\right]^B , \qquad [\hat{\mathbf{N}}_R]^\alpha = \left[(U^\nu)^\dagger\right]^{\alpha\beta} [\mathbf{N}_R]^\beta ,$$

$$[\hat{\boldsymbol{d}}_{L,R}]^A = \left[(U^d_{L,R})^\dagger\right]^{AB} \left[\boldsymbol{d}_{L,R}\right]^B , \qquad [\hat{\mathbf{N}}_L]^\alpha = \left[(U^\nu)^{\mathrm{T}}\right]^{\alpha\beta} [\mathbf{N}_L]^\beta .$$

With unitary matrices $U^{\ell,d}_{L,R}$, U^ν that diagonalize the mass matrices,

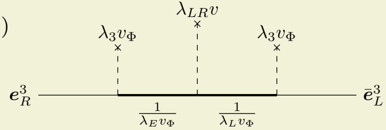
$$(U^\ell_L)^\dagger \, \mathcal{M}^\ell \, U^\ell_R = \left(\mathcal{M}^\ell\right)^{\text{diag}} \equiv \mathrm{diag}\left(m_E, m_L, m_\tau, m_\mu\right) ,$$

$$(U^d_L)^\dagger \, \mathcal{M}^d \, U^d_R = \left(\mathcal{M}^d\right)^{\text{diag}} \equiv \mathrm{diag}\left(m_D, m_Q, m_b, m_s\right) ,$$

$$(U^\nu)^{\mathrm{T}} \, \mathcal{M}^\nu \, U^\nu = (\mathcal{M}^\nu)^{\text{diag}} \approx \mathrm{diag}\left(M, M, \frac{M}{2}, \frac{M}{2}, M_D, M_D, \mathcal{O}\left(\frac{v^2}{M}\right), \mathcal{O}\left(\frac{v^2}{M}\right)\right) .$$

Analytically $(M \sim M_{L,R} \gg v_{\Phi,\varphi} \gg v)$

$$m_\tau \approx \frac{v}{N_3} \left| \lambda_\tau + \frac{\lambda_3^2 \, \lambda_{LR}}{\lambda_E \, \lambda_L} \right|$$



TeV scale Dirac neutrino $M_D = \sqrt{(\lambda_L \, v_\Phi)^2 + (\lambda_3 \, v_\Phi)^2 + (\lambda_2 \, v_\varphi)^2}$.

Z-boson couplings in mass basis

1) Z-lepton couplings in mass basis:

$$\mathcal{L} \supset Z_\mu \left(\hat{\bar{\boldsymbol{e}}}_L \, \gamma^\mu \, \hat{g}_L^Z \, \hat{\boldsymbol{e}}_L + \hat{\bar{\boldsymbol{e}}}_R \, \gamma^\mu \, \hat{g}_R^Z \, \hat{\boldsymbol{e}}_R \right) \,,$$

with coupling matrices

$$\hat{g}_{L,R}^Z = (U_{L,R}^\ell)^\dagger g_{L,R}^Z U_{L,R}^\ell \,,$$

where

$$g_{L,R}^Z = \frac{g}{c_W} \left[\mathbb{1} \, g_{L,R}^{Z,\mathrm{SM}} \pm \mathrm{diag}\left(\frac{1}{2}, 0, 0, 0 \right) \right] \,.$$

$[g_L^{Z,\mathrm{SM}} = (-1/2 + s_W^2), \, g_R^{Z,\mathrm{SM}} = s_W^2 \; (s_W = \sin\theta_W, \, c_W = \cos\theta_W)]$

Note: The Z-lepton couplings are **not diagonal** in the mass basis.

$\Rightarrow$ LFV Z boson decays!
But: They are only effective amongst the heavy VL quarks and leptons.

W-boson couplings in mass basis

2) W-lepton couplings in mass basis: $(\mathbf{N}_L^{\mathcal{C}} = \mathbf{N}_R)$

$$\mathcal{L} \supset W_\mu^+ \left(\overline{\hat{\mathbf{N}}}{}^{\alpha}_L \gamma^\mu \left[\hat{g}_L^W\right]_{\alpha B} \hat{\boldsymbol{e}}_L^B + \overline{\hat{\mathbf{N}}}{}^{\alpha}_R \gamma^\mu \left[\hat{g}_R^W\right]_{\alpha B} \hat{\boldsymbol{e}}_R^B \right) + \text{h.c.}\,,$$

with

$$\hat{g}_L^W = \frac{g}{\sqrt{2}}[(U^\nu)^{\mathrm{T}} g_L^W U_L^\ell] \quad \text{and} \quad \hat{g}_R^W = \frac{g}{\sqrt{2}}[(U^\nu)^\dagger g_R^W U_R^\ell]\,,$$

with the 8×4 coupling matrices of the gauge basis

$$g_L^W = \begin{pmatrix} \mathrm{diag}\,(0,1,1,1) \\ \mathbf{0}_{4\times 4} \end{pmatrix} \quad \text{and} \quad g_R^W = \begin{pmatrix} \mathbf{0}_{4\times 4} \\ \mathrm{diag}\,(1,0,0,0) \end{pmatrix}\,.$$

Higgs couplings in mass basis

3) Physical Higgs h and charged lepton couplings in mass basis

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}}\, h\, \hat{\bar{\boldsymbol{e}}}_L\, \hat{Y}^\ell\, \hat{\boldsymbol{e}}_R + \text{h.c.}\,,$$

where

$$\hat{Y}^\ell = \left(U_L^\ell\right)^\dagger\, Y^\ell\, U_R^\ell\,,$$

with gauge basis couplings

$$Y^\ell = \begin{pmatrix} \lambda_{RL} & 0 & 0 & 0 \\ 0 & \lambda_{LR} & 0 & 0 \\ 0 & 0 & y_\tau & 0 \\ 0 & 0 & 0 & y_\mu \end{pmatrix}\,.$$

- Higgs couplings are (approx.) diagonal in the 2×2 SM block.
- Masses of SM families are (approx.) linear in the Higgs VEV
- Higgs couplings to SM generations are SM-like: **no** significant Higgs FV couplings to SM states!
- But: FV couplings SM-VL, VL-VL can be sizable.

Z' couplings in mass basis

4) Z' couplings to charged leptons / down-type quarks in mass basis

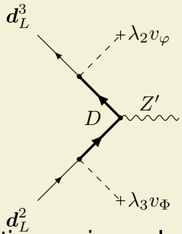
$$\mathcal{L} \supset g' Z'_\mu \left(\bar{\hat{\boldsymbol{e}}}_L \gamma^\mu \hat{g}^\ell_L \hat{\boldsymbol{e}}_L + \bar{\hat{\boldsymbol{e}}}_R \gamma^\mu \hat{g}^\ell_R \hat{\boldsymbol{e}}_R \right) ,$$
$$\mathcal{L} \supset g' Z'_\mu \left(\bar{\hat{\boldsymbol{d}}}_L \gamma^\mu \hat{g}^d_L \hat{\boldsymbol{d}}_L + \bar{\hat{\boldsymbol{d}}}_R \gamma^\mu \hat{g}^d_R \hat{\boldsymbol{d}}_R \right) ,$$

with

$$\hat{g}^{\ell,d}_{L,R} = (U^{\ell,d}_{L,R})^\dagger g_{L,R} U^{\ell,d}_{L,R} ,$$

and the $\mathrm{U}(1)_{3-4}$ charge matrices

$$g_L = g_R = \mathrm{diag}(0, -1, 1, 0) .$$



- Z' couplings here are *not* left-right symmetric.
- Z' mediated FCNCs between $2 \leftrightarrow 3$ SM generations arise only from mixing with the heavy VL states.

$\Rightarrow$ Z' mediated FCNCs between $2 \leftrightarrow 3$ are naturally suppressed!

Gauge and Higgs couplings in mass basis

- The W, Z and h couplings are to a very high degree SM-like amongst the SM families:
  - Z or h mediated FCNCs amongst the SM generations are quasi-absent.
  - h couplings to SM generations are very SM-like.
  - Z and h mediated FCNCs between SM generations and the new heavy (VL) states or amongst the VL states can be sizable.

- Z' FCNCs among SM generations are naturally suppressed by SM-VL mixing.
- Z' FCNCs between SM and VL, and VL-VL are unsuppressed.

Observables overview

Anomalies:

- Lepton flavor non–universality R_K, R_{K^*} & $b \to s\mu\mu$:
  - Contributions to $\mathcal{O}_{i=9,10}^{(\prime)}$ by tree-level Z' exchange.
- Muon anomalous magnetic moment $g-2$.

Observational constraints:

- $B_s - \overline{B}_s$ mixing (by tree-level Z' exchange)
- Flavor violating decays of Z, h, Neutrino trident, $h \to \gamma\gamma$, $h \to gg$, ...
- $h \to bb$, $h \to \tau\tau$, $h \to \mu\mu$, $h \to \mu\tau$, ...

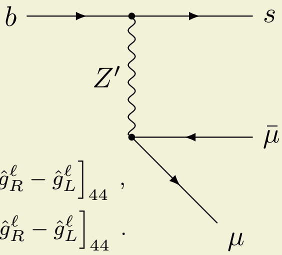
Predictions:

- Lepton flavor violating τ decays: $\tau \to 3\mu$, $\tau \to \mu\gamma$
- $\mathrm{BR}(B \to K^{(*)}\tau\overline{\tau})$, $\mathrm{BR}(B \to K^{(*)}\nu\overline{\nu})$, $\mathrm{BR}(B_s \to \phi\tau\overline{\tau})$

Observables - Lepton non–universality $R_{K^{(*)}}$

Contributions to $\mathcal{O}^{(\prime)}_{i=9,10}$ by tree-level Z' exchange. Wilson coefficients for $bs\mu\mu$:

$$C^{(\prime),\mathrm{NP}}_{i=9,10} = -\left(\frac{\sqrt{2}}{4\,G_\mathrm{F}}\,\frac{1}{V_{tb}V_{ts}^*}\,\frac{16\pi^2}{e^2}\right)\frac{1}{2\,v_\Phi^2}\,g^{(\prime)}_{\mathrm{eff},i}\;,$$



with

$$g_{\mathrm{eff},9} = \left[\hat{g}^d_L\right]_{43}\left[\hat{g}^\ell_R + \hat{g}^\ell_L\right]_{44}\;, \qquad g_{\mathrm{eff},10} = \left[\hat{g}^d_L\right]_{43}\left[\hat{g}^\ell_R - \hat{g}^\ell_L\right]_{44}\;,$$

$$g'_{\mathrm{eff},9} = \left[\hat{g}^d_R\right]_{43}\left[\hat{g}^\ell_R + \hat{g}^\ell_L\right]_{44}\;, \qquad g'_{\mathrm{eff},10} = \left[\hat{g}^d_R\right]_{43}\left[\hat{g}^\ell_R - \hat{g}^\ell_L\right]_{44}\;.$$

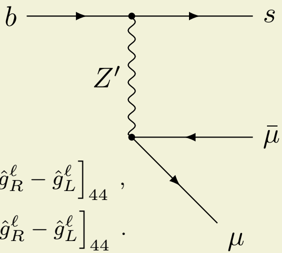
The FC couplings arise from mixing with the heavy VL fermions.
All couplings can be expressed as combinations of mixing matrix elements, e.g. :

$$g_{\mathrm{eff},9} = \left([U_L^{d\,\dagger}]_{43}[U_L^d]_{33} - [U_L^{d\,\dagger}]_{42}[U_L^d]_{23}\right)\times$$
$$\left([U_L^{\ell\,\dagger}]_{43}[U_L^\ell]_{34} - [U_L^{\ell\,\dagger}]_{42}[U_L^\ell]_{24} + [U_R^{\ell\,\dagger}]_{43}[U_R^\ell]_{34} - [U_R^{\ell\,\dagger}]_{42}[U_R^\ell]_{24}\right)\;.$$

Observables - Lepton non–universality $R_{K^{(*)}}$

Contributions to $\mathcal{O}^{(\prime)}_{i=9,10}$ by tree-level Z' exchange. Wilson coefficients for $bs\mu\mu$:

$$C^{(\prime),\mathrm{NP}}_{i=9,10} = -\left(\frac{\sqrt{2}}{4\,G_\mathrm{F}}\,\frac{1}{V_{tb}V^*_{ts}}\,\frac{16\pi^2}{e^2}\right)\frac{1}{2\,v^2_\Phi}\,g^{(\prime)}_{\mathrm{eff},i}\;,$$



with

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$$g'_{\mathrm{eff},9} = \left[\hat{g}^d_R\right]_{43}\left[\hat{g}^\ell_R + \hat{g}^\ell_L\right]_{44}\;,\qquad g'_{\mathrm{eff},10} = \left[\hat{g}^d_R\right]_{43}\left[\hat{g}^\ell_R - \hat{g}^\ell_L\right]_{44}\;.$$

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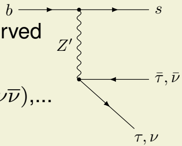
$$\left([U^{\ell\,\dagger}_L]_{43}[U^\ell_L]_{34} - [U^{\ell\,\dagger}_L]_{42}[U^\ell_L]_{24} + [U^{\ell\,\dagger}_R]_{43}[U^\ell_R]_{34} - [U^{\ell\,\dagger}_R]_{42}[U^\ell_R]_{24}\right)\;.$$

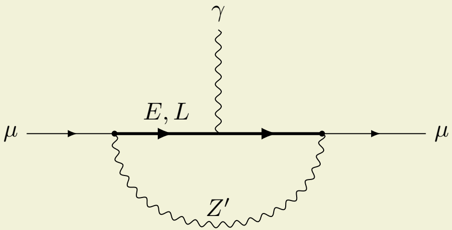
Note: We focus on the Z' coupling to muons in order to explain the observed anomalies. But our model also generates NP in $C^{(\prime),\tau\tau}_{9,10}$ and $C^{(\prime),\nu\nu}_{9,10}$.
$\Rightarrow$ Modifications of $\mathrm{BR}(B\to K^{(*)}\tau\overline{\tau})$, $\mathrm{BR}(B_s\to\phi\tau\overline{\tau})$, $\mathrm{BR}(B\to K^{(*)}\nu\overline{\nu})$,...



Observables - Muon anomalous magnetic moment

- Z, W, h contributions are completely SM like.
- The observed anomaly is completely matched by a new special Z' contribution, parametrically:

$$\delta a_\mu^{Z'} \simeq \frac{m_\mu}{16\pi^2\, v_\Phi} \sum_{a\in\mathrm{VL}} [\hat{g}_L^\ell]_{4a}[\hat{g}_R^\ell]_{4a} \,.$$



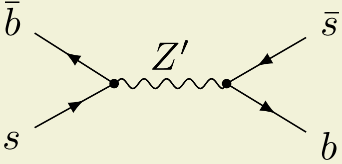
In more detail:

$$\delta a_\mu^{Z'} = -g'^{\,2}\,\frac{m_\mu^2}{8\pi^2\, M_{Z'}^2} \sum_a \left[\left(|[\hat{g}_L^\ell]_{4a}|^2 + |[\hat{g}_R^\ell]_{4a}|^2 \right) F(x_a) + \mathrm{Re}([\hat{g}_L^\ell]_{4a}[\hat{g}_R^{\ell,*}]_{4a})\,\frac{m_a}{m_\mu}\,G(x_a) \right] \,,$$

[Jegerlehner and Nyffeler, 2009, Dermíšek and Raval, 2013]

Observables - $B_s - \overline{B}_s$ mixing

- There is a new tree-level contribution to $B_s - \overline{B}_s$ from Z' exchange.



- Change in the mixing matrix element:

[Buras et al., 2013, Altmannshofer et al., 2014b]

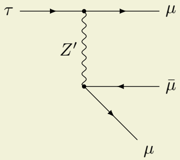
$$\delta M_{12} \simeq \left(\frac{g^2}{16\pi^2 M_W^2} \left(V_{ts}V_{tb}\right)^2 2.3 \right)^{-1} \frac{1}{2\,v_\Phi^2} \times \left(\left|[\hat{g}_L^d]_{34}\right|^2 + \left|[\hat{g}_R^d]_{34}\right|^2 + 9.7\,\mathrm{Re}([\hat{g}_L^d]_{34}[\hat{g}_R^{d,*}]_{34}) \right) \,.$$

- Large hadronic uncertainties allow for deviations from SM of $\delta M_{12} \lesssim 6\%$. [Di Luzio et al., 2018]
- This gives the most important constraint on the flavor changing $Z' - bs$ coupling.

Observables - LFV τ decays

- New Z' tree level contribution to $\tau \to 3\mu$: [Okada et al., 2000, Kuno and Okada, 2001]

$$\mathrm{BR}(\tau \to 3\mu) \approx \frac{1}{\Gamma_\tau} \frac{m_\tau^5}{1536\,\pi^3} \frac{1}{4\,v_\Phi^4} \times \Big(2\left|[\hat{g}_L^\ell]_{43}[\hat{g}_L^\ell]_{44}\right|^2 + 2\left|[\hat{g}_R^\ell]_{43}[\hat{g}_R^\ell]_{44}\right|^2 + \left|[\hat{g}_L^\ell]_{43}[\hat{g}_R^\ell]_{44}\right|^2 + \left|[\hat{g}_R^\ell]_{43}[\hat{g}_L^\ell]_{44}\right|^2 \Big) \,.$$



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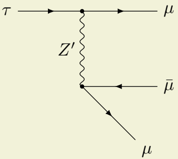
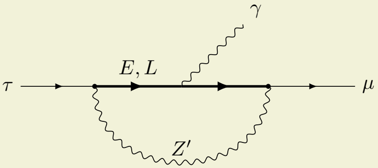




- New Z' loop contribution to $\tau \to \mu\gamma$:

$$\mathrm{BR}(\tau \to \mu\gamma) \simeq \frac{1}{\Gamma_\tau} \frac{\alpha\, m_\tau^3}{1024\,\pi^4} \frac{1}{4\,v_\Phi^2} \left\{ \left| \sum_{a\in \mathrm{VL}} [\hat{g}_L^\ell]_{4a}[\hat{g}_R^\ell]_{a3} \right|^2 + \left| \sum_{a\in \mathrm{VL}} [\hat{g}_R^\ell]_{4a}[\hat{g}_L^\ell]_{a3} \right|^2 \right\} ,$$

[Lavoura, 2003]
(cf. also [Hisano et al., 1996, Ishiwata and Wise, 2013, Abada et al., 2014])

Other Observables

- FV couplings of Z or h to the SM families are generally suppressed far below experimental thresholds.
- FC couplings to heavy VL states can be large, but is unobservable.
- Neutrino trident production does not give constraints for heavy Z'. [Altmannshofer et al., 2014b, Altmannshofer et al., 2014a]
- Lepton unitarity bounds are fulfilled. (cf. e.g. [Antusch and Fischer, 2014, Fernandez-Martinez et al., 2016])
- $h \to \gamma\gamma$ or $h \to gg$ via triangle loops are suppressed by factors of $(v/M_{\mathrm{VL}})^2$ (see e.g. [del Aguila et al., 2008, Joglekar et al., 2012, Kearney et al., 2012, Ishiwata and Wise, 2013]).

Analysis - Strategy

Perform χ^2-fit to show that the model can explain the anomalis w/o violating other constraints. We fit to:

- Consistent explanation of $b \to s\mu^+\mu^-$ anomalies:

$$\begin{aligned} &\textbf{I.} : \quad C_9^{\rm NP} \approx -1.21 \pm 0.2 \,, \quad C_9' \approx C_{10}^{\rm NP} \approx C_{10}' \approx 0 \,, \\ \text{or} \quad &\textbf{II.} : \quad C_9^{\rm NP} \approx -1.25 \pm 0.2 \,, \quad C_9' \approx 0.59 \pm 0.2 \,, C_{10}^{\rm NP} \approx C_{10}' \approx 0 \,. \end{aligned}$$

taken from [Altmannshofer, Niehoff, Stangl, Straub 1703.09189]

- Explanation of $(g-2)_\mu$ anomaly:

$$\delta a_\mu^{Z'} = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11} \,.$$

- The masses m_d, m_s, m_μ, and m_τ at the weak scale.

[Antusch and Maurer, 2013]

- Require $\delta M_{12} \lesssim 15\%$.

All other observables are not constrained in the fit, i.e. they arise as predictions.

[Note: This is a *proof of principle*, there could be more points that work since there are currently more parameters than observables.]

Analysis - Results

- Good fits for the cases **I.** (only $C_9^{\rm NP}$) and **II.** ($C_9^{\rm NP}$&C_9').
- No good fit for $C_9^{\rm NP} \simeq -C_{10}^{\rm NP}$!

For example: Best fit for case **I.**:

Best fit point I.					
λ_μ	=	-0.00008520346	λ_τ	=	0.010031941
λ_s	=	-0.002313419	λ_b	=	-0.01639676
λ_L	=	0.8595483	λ_E	=	0.8596570
λ_D	=	-1.7819031	λ_Q	=	-0.3253384
λ_3	=	-0.018705093	λ_2	=	-0.7701059
λ_{RL}	=	-0.9926161	λ_{LR}	=	0.0014518601
v_φ	=	1603.0788	v_ϕ	=	1622.5729
g'	=	-0.7518533			

Analysis - Results

- Good fits for the cases **I.** (only C_9^{NP}) and **II.** (C_9^{NP}&C_9').
- No good fit for $C_9^{\mathrm{NP}} \simeq -C_{10}^{\mathrm{NP}}$!

Best fit results for observables:

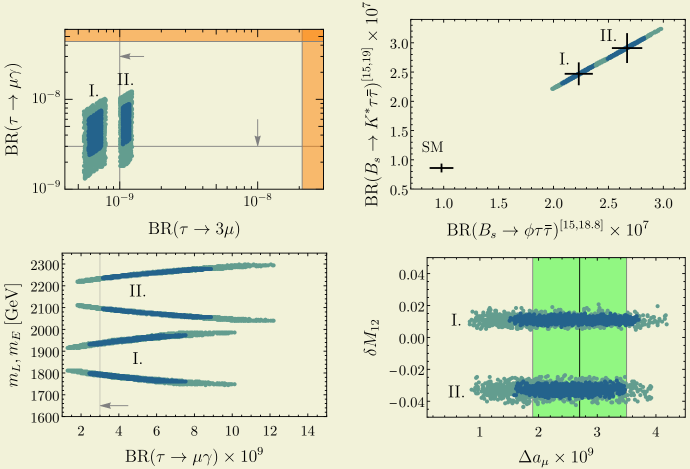
Observable	Best Fit I.	Best Fit II.	Bound
m_L, m_E	$1.78\,\mathrm{TeV}, 1.95\,\mathrm{TeV}$	$2.08\,\mathrm{TeV}, 2.25\,\mathrm{TeV}$	> 450 GeV
m_Q, m_D	$1.34\,\mathrm{TeV}, 3.15\,\mathrm{TeV}$	$1.61\,\mathrm{TeV}, 3.49\,\mathrm{TeV}$	> 900 GeV
M_D	$1.86\,\mathrm{TeV}$	$2.16\,\mathrm{TeV}$	
$M_{Z'}$	$1.73\,\mathrm{TeV}$	$2.25\,\mathrm{TeV}$	
$\tau \to \mu\gamma$	4.6×10^{-9}	5.3×10^{-9}	$< 4.4 \times 10^{-8}$
$\tau \to 3\mu$	6.7×10^{-10}	1.1×10^{-9}	$< 2.1 \times 10^{-8}$
$\delta M_{12}(B_s - \overline{B}_s)$	1%	-3%	$\lesssim \pm 6\%$
$\mathrm{BR}(B \to K\tau\overline{\tau})^{[15,22]}$	1.8×10^{-7}	1.4×10^{-7}	$< 2.25 \times 10^{-3}$
$\mathrm{BR}(B \to K^*\tau\overline{\tau})^{[15,19]}$	2.5×10^{-7}	2.9×10^{-7}	
$\mathrm{BR}(B_s \to \phi\tau\overline{\tau})^{[15,18.8]}$	2.2×10^{-7}	2.6×10^{-7}	
$R_K^{\nu\overline{\nu}}$	0.91	0.93	< 4.3
$R_{K^*}^{\nu\overline{\nu}}$	0.91	0.93	< 4.4

Bounds from [Falkowski et al., 2014, Khachatryan et al., 2016b, Aubert et al., 2010, Hayasaka et al., 2010, Di Luzio et al., 2018, Lees et al., 2017, Lees et al., 2013, Lutz et al., 2013]

Analysis - Results

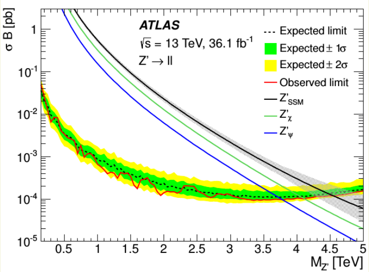
- Good fits for the cases **I.** (only C_9^{NP}) and **II.** (C_9^{NP}&C_9').
- No good fit for $C_9^{\mathrm{NP}} \simeq -C_{10}^{\mathrm{NP}}$!

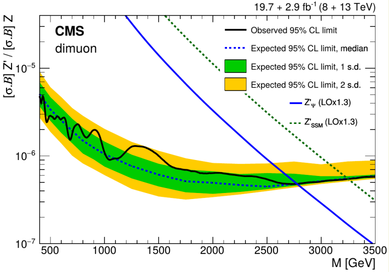
Best fit results for observables:



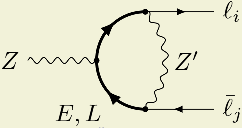
Coming up next...

- Include up sector and first family (including detailed flavor structure).
- RGE running from high to low scale. see e.g. [Feruglio et al., 2017b]
- Prediction for direct Z' production at the (HL)LHC as well as Z' branching fractions.
  e.g. [Alonso, Cox, Han, Yanagida '17], [Bonilla, Modak, Srivastava, Valle '17], [Bian, Choi, Kang, Lee '17]





- Refine predictions for $Z \to \ell_i \bar{\ell}_j$ and other observables.



Summary

- B and $(g-2)_\mu$ anomalies are more interesting than ever, experimental results to come.  : 

- A new VL complete generation with chiral, family dependent $\mathrm{U}(1)_{3-4}$ gauge symmetry can simultaneously explain $b \to s\mu\mu$, $R_{K^{(*)}}$ and $(g-2)_\mu$ anomalies.

- Anatomy: Model can fit data with
  - ✔ $C_9^{\mathrm{NP}} \neq 0$,
  - ✔ $C_9^{\mathrm{NP}} \neq 0 \;\; \& \;\; C_9' \neq 0$,
  - ✘ **not** for $C_9^{\mathrm{NP}} \simeq -C_{10}^{\mathrm{NP}}$.

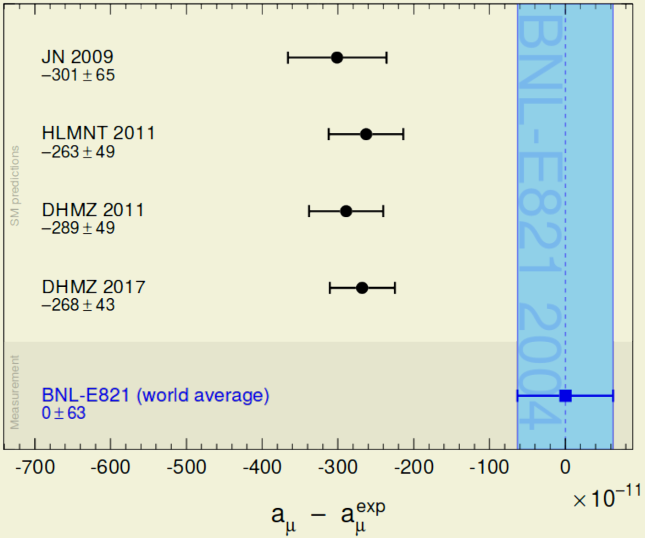
- Key predictions:
  - $Z' \to \mu\mu$ (LHC run 2 and HL-LHC)
  - $\tau \to \mu\gamma$, $\tau \to 3\mu$ (LHCb, Belle II)

- Upcoming: full three family fit $\Rightarrow$ improved predictions.

Thank You!

Backup slides

Hardonic uncertainties in $(g-2)_\mu$



Normalization of masses with

$$N_{2(3)} := \sqrt{\left[1 + \left(\lambda_{2(3)}/\lambda_E\right)^2\right]\left[1 + \left(\lambda_{2(3)}/\lambda_L\right)^2\right]} \,.$$

The analytical results agree with the numerical values to $\mathcal{O}(1\%)$.

Z' neutrino couplings

The Z' couplings to neutrinos in the mass basis can be written as

$$\mathcal{L} \supset g' Z'_\mu \left(\overline{\hat{\mathbf{N}}}{}^{\alpha}_{L} \gamma^\mu \left[\hat{g}^n\right]_{\alpha\beta} \hat{\mathbf{N}}^{\beta}_{L} \right) ,$$

with the coupling

$$\hat{g}^n = \left(U^\nu\right)^{\mathrm{T}} \, g^n \, \left(U^\nu\right)^* ,$$

and the gauge basis charge matrix

$$g^n = \mathrm{diag}\left(0, -1, 1, 0, 0, 1, -1, 0\right) .$$

Details of $\delta a_\mu^{Z'}$

The leading order contribution to the muon $g-2$ arising from the Z' coupling to leptons is given by (see e.g. [Jegerlehner and Nyffeler, 2009, Dermíšek and Raval, 2013])

$$\delta a_\mu^{Z'} = -g'^{\,2}\,\frac{m_\mu^2}{8\pi^2\,M_{Z'}^2}\sum_a\left[\left(|[\hat{g}_L^\ell]_{4a}|^2+|[\hat{g}_R^\ell]_{4a}|^2\right)F(x_a)+\mathrm{Re}([\hat{g}_L^\ell]_{4a}[\hat{g}_R^{\ell,*}]_{4a})\,\frac{m_a}{m_\mu}\,G(x_a)\right]$$

where a runs over all leptons with mass m_a in the loop, $x_a := (m_a/M_{Z'})^2$, and the loop functions

$$F(x) := \left(5\,x^4-14\,x^3+39\,x^2-38\,x-18\,x^2\ln x+8\right)/\left[12\,(1-x)^4\right]\;,$$

$$G(x) := \left(x^3+3\,x-6\,x\ln x-4\right)/\left[2\,(1-x)^3\right]\;.$$

Details of $\tau \to \mu\gamma$

The leading order contribution to $\tau \to \mu\gamma$ arises from the flavor off-diagonal Z' couplings between $\tau - \mathrm{VL}$ and $\mu - \mathrm{VL}$. We have used the general results given in [Lavoura, 2003] to find the leading order contributions to the partial width

$$\Gamma(\tau \to \mu\gamma) = \frac{\alpha\, g'^{\,4}}{1024\,\pi^4} \frac{m_\tau^5}{M_{Z'}^4} \left(\left|\tilde{\sigma}_L\right|^2 + \left|\tilde{\sigma}_R\right|^2 \right) \,,$$

with

$$\tilde{\sigma}_L = \sum_a \left([\hat{g}_L^\ell]_{4a} [\hat{g}_L^\ell]_{a3}\, F(x_a) + \frac{m_a}{m_\tau} [\hat{g}_L^\ell]_{4a} [\hat{g}_R^\ell]_{a3}\, G(x_a) \right) \,,$$

$$\tilde{\sigma}_R = \sum_a \left([\hat{g}_R^\ell]_{4a} [\hat{g}_R^\ell]_{a3}\, F(x_a) + \frac{m_a}{m_\tau} [\hat{g}_R^\ell]_{4a} [\hat{g}_L^\ell]_{a3}\, G(x_a) \right) \,,$$

where a runs over all leptons with mass m_a in the loop, $x_a := (m_a/M_{Z'})^2$, and the loop functions are the same as for the $g-2$.

Best fit point $\mathbf{II}$.

Best fit point II.					
λ_μ	=	-0.00023171652	λ_τ	=	0.010033469
λ_s	=	-0.0009612744	λ_b	=	-0.016371133
λ_L	=	0.8806972	λ_E	=	0.8835616
λ_D	=	-1.8024639	λ_Q	=	-0.2965286
λ_3	=	-0.02561451	λ_2	=	-0.8882496
λ_{RL}	=	-1.021554	λ_{LR}	=	0.0014201883
v_φ	=	1717.639	v_ϕ	=	1738.4050
g'	=	-0.9171299			

Table: Best fit point to the data for case (II.). We do not list M_R, $\lambda_{\nu 1,2}$ and λ_N because their precise values do not affect the results.

Z' couplings at best fit point $\mathbf{I}$.

$$\hat{g}_L^\ell = \begin{pmatrix} -0.2669 & 0.2798 & 0.01800 & 0.3425 \\ 0.2798 & -0.2934 & -0.01890 & -0.3591 \\ 0.01800 & -0.01890 & 0.9996 & -0.0100 \\ 0.3425 & -0.3591 & -0.0100 & -0.4393 \end{pmatrix}$$

$$\hat{g}_R^\ell = \begin{pmatrix} -0.2674 & -0.2799 & -0.01800 & -0.3427 \\ -0.2799 & -0.2930 & -0.01890 & -0.3588 \\ -0.01800 & -0.01890 & 0.9996 & -0.0100 \\ -0.3427 & -0.3588 & -0.0100 & -0.4392 \end{pmatrix}$$

$$\hat{g}_L^d = \begin{pmatrix} -0.000100 & -0.004400 & 0.0007000 & 0.01030 \\ -0.004400 & -0.1539 & 0.02570 & 0.3613 \\ 0.0007000 & 0.02570 & 0.9994 & -0.006300 \\ 0.01030 & 0.3613 & -0.006300 & -0.8454 \end{pmatrix}$$

$$\hat{g}_R^d = \begin{pmatrix} -0.8418 & 0.05670 & 0.01670 & 0.3604 \\ 0.05670 & -0.003800 & -0.001100 & -0.02430 \\ 0.01670 & -0.001100 & 0.9998 & 5.546 \times 10^{-6} \\ 0.3604 & -0.02430 & 5.546 \times 10^{-6} & -0.1542 \end{pmatrix}$$

Z couplings at best fit point I.

$$\hat{g}_L^{Z,\ell} = \frac{g}{c_W}\begin{pmatrix} -0.01592 & 0.2497 & 5.064\times10^{-6} & -2.580\times10^{-5} \\ 0.2497 & -0.03948 & 4.831\times10^{-6} & -2.461\times10^{-5} \\ 5.064\times10^{-6} & 4.831\times10^{-6} & -0.2777 & -4.990\times10^{-10} \\ -2.580\times10^{-5} & -2.461\times10^{-5} & -4.990\times10^{-10} & -0.2777 \end{pmatrix}$$

$$\hat{g}_R^{Z,\ell} = \frac{g}{c_W}\begin{pmatrix} -0.03910 & 0.2497 & 5.061\times10^{-6} & -2.578\times10^{-5} \\ 0.2497 & -0.01640 & -4.835\times10^{-6} & 2.463\times10^{-5} \\ 5.061\times10^{-6} & -4.835\times10^{-6} & 0.2223 & 4.991\times10^{-10} \\ -2.578\times10^{-5} & 2.463\times10^{-5} & 4.991\times10^{-10} & 0.2223 \end{pmatrix}$$

$$\hat{g}_L^{Z,d} = \frac{g}{c_W}\begin{pmatrix} 0.07369 & -0.01430 & -4.141\times10^{-6} & -4.387\times10^{-5} \\ -0.01430 & -0.4255 & 1.185\times10^{-7} & 1.255\times10^{-6} \\ -4.141\times10^{-6} & 1.185\times10^{-7} & -0.4259 & 3.636\times10^{-10} \\ -4.387\times10^{-5} & 1.255\times10^{-6} & 3.636\times10^{-10} & -0.4259 \end{pmatrix}$$

$$\hat{g}_R^{Z,d} = \frac{g}{c_W}\begin{pmatrix} 0.07185 & -0.03344 & 1.568\times10^{-6} & 9.477\times10^{-6} \\ -0.03344 & -0.4237 & 2.334\times10^{-5} & 1.410\times10^{-4} \\ 1.568\times10^{-6} & 2.334\times10^{-5} & 0.0741 & -6.614\times10^{-9} \\ 9.477\times10^{-6} & 1.410\times10^{-4} & -6.614\times10^{-9} & 0.0741 \end{pmatrix}$$

Higgs couplings to light generations

Effective Higgs couplings in the mass basis for best-fit point $\mathbf{I}$.

$$\hat{Y}^{\ell}_{\text{light}} = \frac{\text{GeV}}{v}\begin{pmatrix} 1.74618 & 3.46843\times 10^{-7} \\ 3.47055\times 10^{-7} & 0.102717 \end{pmatrix} ,$$

$$\hat{Y}^{d}_{\text{light}} = \frac{\text{GeV}}{v}\begin{pmatrix} 2.85391 & 7.71892\times 10^{-7} \\ 1.41639\times 10^{-6} & 0.0543716 \end{pmatrix} .$$

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