Reconsidering the one leptoquark solution

Flavor anomalies and neutrino mass

Michael A. Schmidt

24 July 2017

TeV Physics Workshop 2017

based on

Y. Cai, J. Gargalionis, MS, R. Volkas [1704.05849]

P. Angel, Y. Cai, MS, R. Volkas [JHEP 1310 (2013) 118]

Y. Cai, J. Clarke, MS, R. Volkas [JHEP 1502 (2015) 161]

THE UNIVERSITY OF SYDNEY

CoEPP

ARC Centre of Excellence for Particle Physics at the Terascale

A circumstantial case for new physics coupling to leptons

1. The measurement of mass-driven neutrino oscillations
2. Discrepancy between prediction and measurement of $(g-2)_\mu$
3. Hints for violations of LFU in $R_{K^{(*)}}$ and $R_{D^{(*)}}$

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)} \qquad R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

LHCb

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad R_K^{SM} = 1.0003 \pm 0.0001 \qquad 1\mathrm{GeV}^2 < q^2 < 6\mathrm{GeV}^2$$

$$R_{K*}^{low} = 0.660^{+0.110}_{-0.070} \pm 0.024 \qquad R_{K*}^{low,SM} = 0.906 \pm 0.028 \qquad 0.045\mathrm{GeV}^2 < q^2 < 1.1\mathrm{GeV}^2$$

$$R_{K*}^{mid} = 0.685^{+0.113}_{-0.069} \pm 0.047 \qquad R_{K*}^{mid,SM} = 1.00 \pm 0.01 \qquad 1.1\mathrm{GeV}^2 < q^2 < 6\mathrm{GeV}^2$$

BaBar/Belle/LHCb [HFAG fit]

$$R_D = 0.397 \pm 0.040 \pm 0.028 \qquad R_D^{SM} = 0.299 \pm 0.011$$

$$R_{D*} = 0.316 \pm 0.016 \pm 0.010 \qquad R_{D*}^{SM} = 0.252 \pm 0.003$$

4. Anomalous angular observables and branching ratios in $b \to s\mu\mu$

Aims

(i) Fully explore the explanation of (2)-(4) by *one leptoquark* scenario

(ii) Study the overlap with radiative neutrino mass

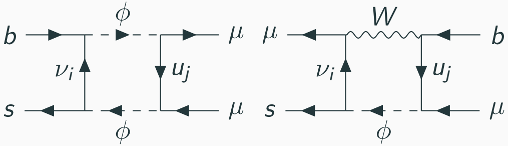
The protagonist

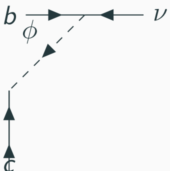
One leptoquark model has been postulated as explanation of $b \to c$ anomalies at tree level but $b \to s$ through one-loop box diagrams

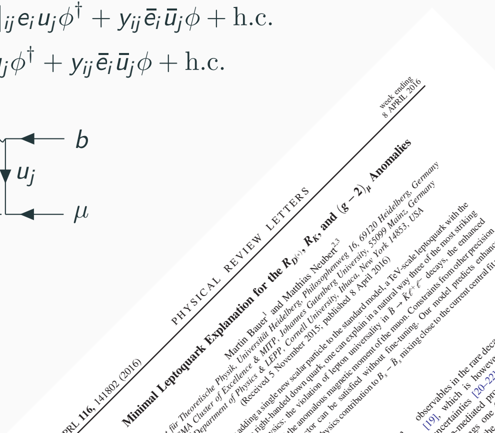
Bauer, Neubert 1511.01900

The scalar leptoquarks transforms like d_R: $\phi \sim (\mathbf{3}, \mathbf{1}, -1/3)$

$$
\begin{aligned}
\mathcal{L}_\phi &\supset \hat{x}_{ij}\hat{L}^i\hat{Q}^j\phi^\dagger + \hat{y}_{ij}\hat{\bar{e}}^i\hat{\bar{u}}^j\phi + \mathrm{h.c.} \\
&= x_{ij}\breve{\nu}_i d_j\phi^\dagger - [\mathbf{x}\mathbf{V}^\dagger]_{ij} e_i u_j\phi^\dagger + y_{ij}\bar{e}_i\bar{u}_j\phi + \mathrm{h.c.} \\
&\equiv x_{ij}\breve{\nu}_i d_j\phi^\dagger - z_{ij} e_i u_j\phi^\dagger + y_{ij}\bar{e}_i\bar{u}_j\phi + \mathrm{h.c.}
\end{aligned}
$$






PRL 116, 141802 (2016)

PHYSICAL REVIEW LETTERS

week ending
8 APRIL 2016

Minimal Leptoquark Explanation for the $R_{D^{(*)}}$, R_K, and $(g-2)_\mu$ Anomalies

Martin Bauer[1] and Matthias Neubert[2,3]

(Received 5 November 2015; published 8 April 2016)

Phenomenological analysis

Signals and constraints

LQ Yukawa couplings: $\mathcal{L}_\phi \supset x_{ij}\breve{\nu}_i d_j \phi^\dagger - z_{ij} e_i u_j \phi^\dagger + y_{ij}\bar{e}_i \bar{u}_j \phi + \mathrm{h.c.}$

Data-driven ansatz for the couplings x_{ij} and y_{ij} with values dictated by constraints and anomalies

$K^+ \to \pi^+ \nu\nu$
$\mu N \to eN$
$\tau \to \ell\pi, \ell\rho$
$B \to K\nu\nu$
$B_s - \bar{B}_s$ mixing
Precision EW measurements
$D^0 \to \mu\mu$
$D^+ \to \pi^+\mu\mu$
$P \to P'\ell\nu$, $\tau \to P\nu$ + LFU ratios
$\tau \to \mu\mu\mu$
$\tau \to \mu\gamma$

$R_{D^{(*)}}$ $R_{K^{(*)}}$ $(g-2)_\mu$

$$\mathbf{x} = \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ & \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{array}\right) \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \end{array}$$

$$\mathbf{y} = \begin{array}{cc} & \begin{array}{ccc} u & c & t \end{array} \\ & \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{array}\right) \begin{array}{c} e \\ \mu \\ \tau \end{array} \end{array}$$

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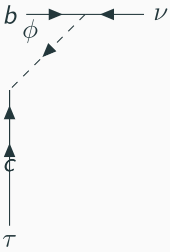
Charged current processes: R_D and R_{D^*} (1)

Contributions $b \to c\tau\nu_i$ parameterized by

$$\mathcal{L}_{CC} = -\frac{4G_F}{\sqrt{2}V_{cb}}\Big[C_V^i\,(\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L\nu_i) + C_S^i\,(\bar{c}P_L b)\,(\bar{\tau}P_L\nu_i) + C_T^i\,(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_i)\Big] + \mathrm{h.c.}$$



Wilson coefficients

$$C_V^i = \frac{1}{2\sqrt{2}G_F V_{cb}}\frac{z_{32}^* x_{i3}}{2m_\phi^2} + \delta_{i3}$$

$$C_S^i = \frac{1}{2\sqrt{2}G_F V_{cb}}\frac{y_{32} x_{i3}}{2m_\phi^2}$$

$$C_T^i = -\frac{1}{4}C_S^i$$

$$\mathbf{x} = \begin{array}{cc} \begin{array}{ccc} d & s & b \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \end{array}$$

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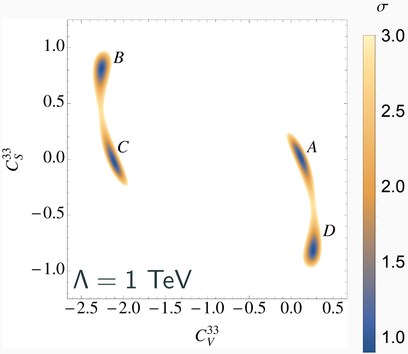
Charged current processes: R_D and R_{D^*} (2)

Implemented the calculation of Bardhan, Byakti, Ghosh and validated against Tanaka, Watanabe Bardhan, Byatki, Ghosh 1610.03038 Tanaka, Watanabe 1212.1878

Lattice QCD form factors for R_D MILC 1503.07237

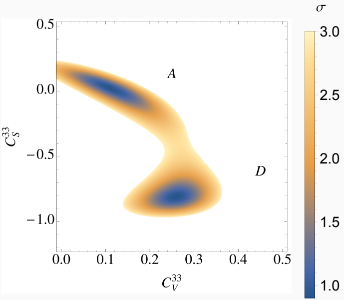
Form factors extracted from $\bar{B} \to D^*(\mu, e)\nu$ measurement for R_{D^*}
$\Rightarrow$ calculation becomes unreliable for large x_{2i}, y_{2i}

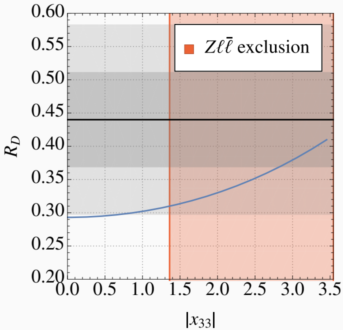


Perform χ^2 fit to operators $C_{V,S,T}$ with C_S/C_T relation dictated by running

Four interesting regions, we only study region A

Charged current processes: R_D and R_{D^*} (3)





Constraints involving LH couplings
sufficient to impede this scenario:

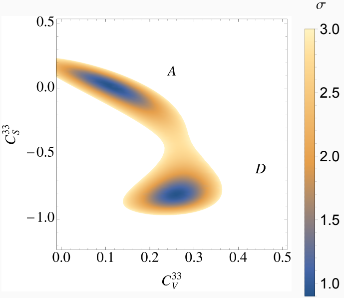
- $B \to K\nu\nu$
- $B_s - \bar{B}_s$ mixing
- Precision EW measurements: $Z \to \tau\tau$

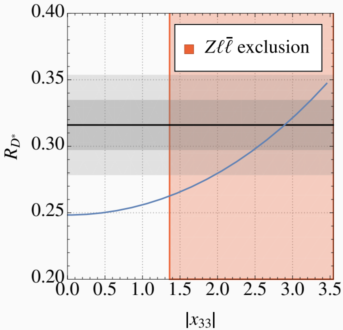
$$\begin{array}{cc} & \begin{array}{ccc} d/u & s/c & b/t \end{array} \\ \mathbf{x} = & \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix} \begin{array}{l} \nu_e/e \\ \nu_\mu/\mu \\ \nu_\tau/\tau \end{array} \end{array}$$

$$C_V^{NP} = \frac{1}{4\sqrt{2}G_F V_{cb}} \frac{x_{33}(x_{32}^* V_{cs} + x_{33}^* V_{ts})}{m_\phi^2}$$

x_{33} implies large z_{32}
and thus large correction to $Z \to \tau\tau$

Charged current processes: R_D and R_{D^*} (3)





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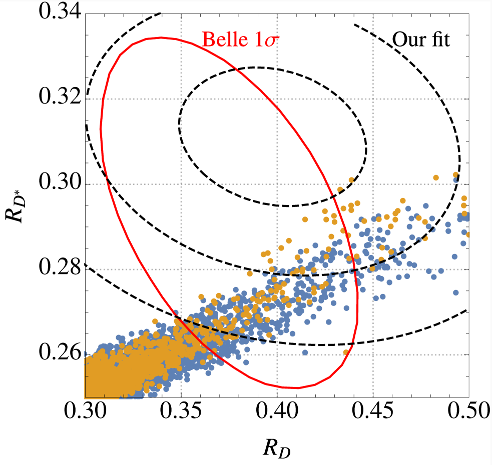
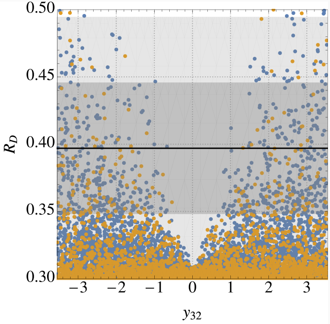
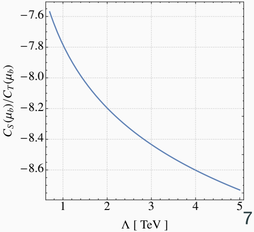
Charged current processes: R_D and R_{D^*} (4)

Orange points keep $b \longrightarrow s$ observables SM-like; Scan II results





sizable RH coupling y_{32}



$$C_V^{NP}(\mu_b) = \frac{1}{4\sqrt{2}G_F V_{cb}} \frac{x_{33}(x_{32}^* V_{cs} + x_{33}^* V_{ts})}{m_\phi^2}$$

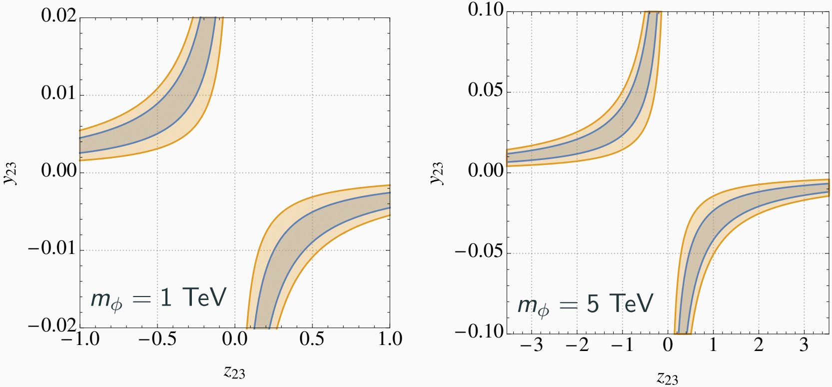
$$C_{S,T}^{NP}(\mu_b) = \left\{ \begin{array}{c} 1 \\ -1/7.8 \end{array} \right\} \frac{1.65}{4\sqrt{2}G_F V_{cb}} \frac{x_{33}\, y_{32}}{m_\phi^2} \qquad \text{for } m_\phi = 1 \text{ TeV}$$

Anomalous magnetic moment of the muon: $(g-2)_\mu$

With $y_{22} = 0$ tension in $(g-2)_\mu$ requires

$$-20.7\left(1 + 1.06 \ln \frac{m_\phi}{\mathrm{TeV}}\right) \mathrm{Re}(y_{23} z_{23}) \approx \frac{0.08 m_\phi}{\mathrm{TeV}}$$

Can be accommodated with $R_{D^{(*)}}$ for $y_{23} \sim 10^{-2}$



1σ and 2σ contours

Neutral current processes: R_K and R_{K^*} (1)

Leptoquark generates the operators

$$O^{\mu}_{LL,LR} \equiv \frac{O^{\mu}_{9} \mp O^{\mu}_{10}}{2} \sim (\bar{s}\gamma^{\mu} P_L b)\,(\bar{\mu}\gamma_{\mu} P_{L,R}\mu)$$

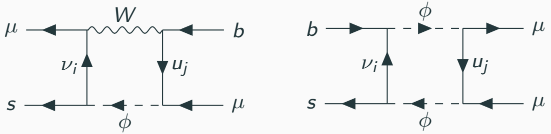
$$\mathbf{x} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{ccc|c} d & s & b & \\ \end{array}$$

$$\mathbf{x} = \begin{array}{cccc} d & s & b & \\ \left(\begin{matrix} 0 \\ 0 \\ 0 \end{matrix}\right. & \begin{matrix} 0 \\ x_{22} \\ x_{32} \end{matrix} & \left.\begin{matrix} 0 \\ x_{23} \\ x_{33} \end{matrix}\right) & \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \end{array}$$

Effective Lagrangian

$$\mathcal{L}_{NC} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V^{*}_{ts} \frac{\alpha}{4\pi} \sum_{f=e,\mu} \sum_{X=L,R} C^{f}_{LX} O^{f}_{LX}$$

$$\mathbf{y} = \begin{array}{cccc} u & c & t & \\ \left(\begin{matrix} 0 \\ 0 \\ 0 \end{matrix}\right. & \begin{matrix} 0 \\ y_{22} \\ y_{32} \end{matrix} & \left.\begin{matrix} 0 \\ y_{23} \\ 0 \end{matrix}\right) & \begin{matrix} e \\ \mu \\ \tau \end{matrix} \end{array}$$

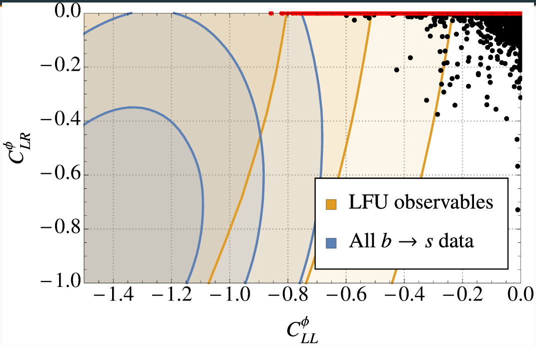


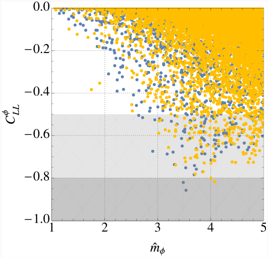
$$C^{\phi,\mu}_{LL} = \overbrace{\frac{m_t^2}{8\pi\alpha m_\phi^2}|z_{23}|^2} \overbrace{- \frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb} V^{*}_{ts}} \sum_i x_{i3} x^{*}_{i2} \sum_j |z_{2j}|^2} \approx -1.2$$

$$C^{\phi,\mu}_{LR} = \frac{m_t^2}{8\pi\alpha m_\phi^2}|y_{23}|^2 \left[\ln\frac{m_\phi^2}{m_t^2} - 0.47\right] - \frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb} V^{*}_{ts}} \sum_i x_{i3} x^{*}_{i2} \sum_j |y_{2j}|^2 \approx 0$$

⇒ large LQ-muon couplings: $|z_{22}| \gtrsim 2.4$ for $m_\phi \sim 1$ TeV Bauer,Neubert 1511.01900

Neutral current processes: R_K and R_{K^*} (2)





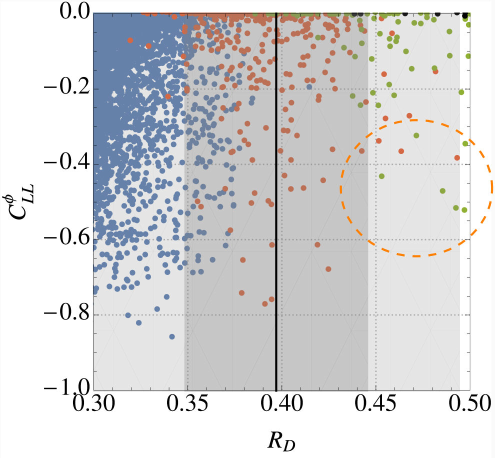
$D^0 \to \mu\mu \Rightarrow |z_{22}| < 0.48 m_\phi/\mathrm{TeV}$ for $y_{ij} = 0$, model prefers large $|z_{23}|$

LFU respected in ratios $R^{\mu/e}_{D^{(*)}}$, constraint alleviated for LQ masses > 1 TeV Belle 1510.03657, 1702.01521

Becirevic, Kosnik, Sumensari, Funchal 1608.07583

Hierarchy in x_{i3} necessary to avoid $\tau \to \mu$ constraints: $|x_{23}| \gg |x_{33}|$

A combined explanation: $R_{K^{(*)}}$ and $R_{D^{(*)}}$



R_{D^*} fit: 1σ, 2σ, 3σ, $> 3\sigma$

Points in the region of interest look like

$$m_\phi \approx 3\text{TeV}$$

$$\mathbf{x} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.15 & -3 \\ 0 & 0.12 & 0.3 \end{pmatrix}$$

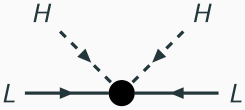
$$\mathbf{y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0.005 \\ 0 & 3 & 0 \end{pmatrix}$$

Connection to neutrino mass

Neutrino mass

- Neutrinos oscillations imply massive neutrinos
- They are neutral and can be their own antiparticle

$\Rightarrow$ Majorana fermions with mass generated from Weinberg operator



$$\mathcal{L}_\nu = \frac{1}{2}\frac{\kappa}{\Lambda} LHLH + \mathrm{h.c.}$$

- Effective operator *LHLH* suppressed by $\Lambda \gg \langle H \rangle \simeq 100\mathrm{GeV} \gg m_\nu$
- All $\Delta L = 2$ operators lead to neutrino mass Schechter, Valle Phys. Rev. D25 (1982) 2951

dimension	5	7	9	11
field strings[1] Babu,Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344	1	6	21	101
Lorentz structures[2] Henning,Lu,Melia,Murayama 1512.03433	2	22	368	6632

[1] no gauge fields, no Lorentz structure, no products of SM singlets (e.g. $LHLHH^\dagger H$)

[2] includes hermitean conjugates

- Many UV completions for each operator at tree and loop level

Different classifications

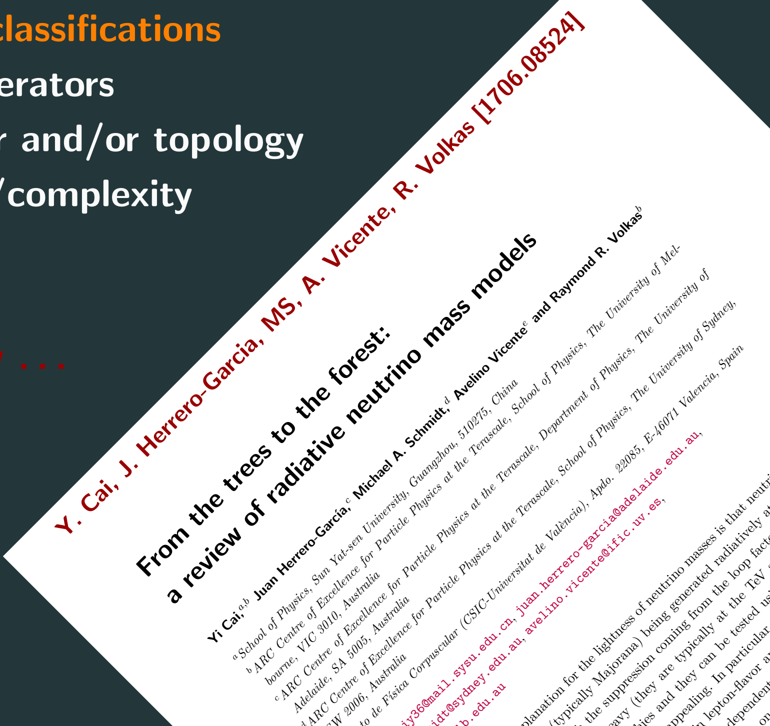
$\Delta L = 2$ operators

Loop-order and/or topology

Simplicity/complexity

. . .

See review . . .



Y. Cai, J. Herrero-Garcia, MS, A. Vicente, R. Volkas [1706.08524]

From the trees to the forest:
a review of radiative neutrino mass models

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planation for the lightness of neutrino masses is that neutri
(typically Majorana) being generated radiatively at
the suppression coming from the loop fact
eavy (they are typically at the TeV
ies and they can be tested usi
ppealing. In particular
in lepton-flavor a
dependent

Minimal UV completions of the dimension-7 operators

Y. Cai, J. Clarke, MS, R. Volkas 1410.0689

Any $\Delta L = 2$ operator induces Majorana mass term for neutrinos

Effective $\Delta L = 2$ operators of dimension 7

$$\mathcal{O}'_1 = LL\tilde{H}HHH \qquad \mathcal{O}_2 = LLL\bar{e}H$$

$$\mathcal{O}_3 = LLQ\bar{d}H \qquad \mathcal{O}_4 = LLQ^\dagger \bar{u}^\dagger H \qquad \mathcal{O}_8 = L\bar{d}\bar{e}^\dagger \bar{u}^\dagger H$$

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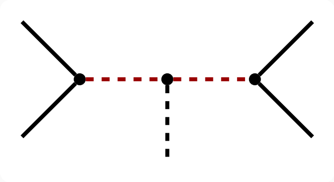

Scalars: leptoquarks, singly charged scalars, EW doublets and quartets

Fermions: vector-like quarks/charged leptons mixing with third generation

Scalar	Scalar	Operator
$(1, 2, \frac{1}{2})$	$(1, 1, 1)$	$\mathcal{O}_{2,3,4}$
$(3, 2, \frac{1}{6})$	$(3, 1, -\frac{1}{3})$	$\mathcal{O}_{3,8}$
$(3, 2, \frac{1}{6})$	$(3, 3, -\frac{1}{3})$	$\mathcal{O}_3$

Leptoquarks $(3, 2, \frac{1}{6})$ and $(3, 1, -\frac{1}{3})$ used to explain R_K (and R_D)

Päs, Schumacher 1510.08757 Deppisch, Kulkarni, Päs, Schumacher 1603.07672

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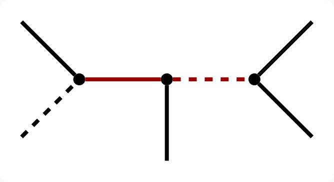

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Dirac fermion	Scalar	Operator
$(1,2,-\frac{3}{2})$	$(1,1,1)$	$\mathcal{O}_2$
$(3,2,-\frac{5}{6})$	$(1,1,1)$	$\mathcal{O}_3$
$(3,1,\frac{2}{3})$	$(1,1,1)$	$\mathcal{O}_3$
$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$\mathcal{O}_3$
$(3,2,-\frac{5}{6})$	$(3,1,-\frac{1}{3})$	$\mathcal{O}_{3,8}$
$(3,2,-\frac{5}{6})$	$(3,3,-\frac{1}{3})$	$\mathcal{O}_3$
$(3,3,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$\mathcal{O}_3$
$(3,2,\frac{7}{6})$	$(1,1,1)$	$\mathcal{O}_4$
$(3,1,-\frac{1}{3})$	$(1,1,1)$	$\mathcal{O}_4$
$(3,2,\frac{7}{6})$	$(3,2,\frac{1}{6})$	$\mathcal{O}_8$
$(1,2,-\frac{1}{2})$	$(3,2,\frac{1}{6})$	$\mathcal{O}_8$

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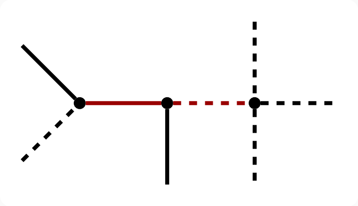

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Fermions: vector-like quarks/charged leptons mixing with third generation

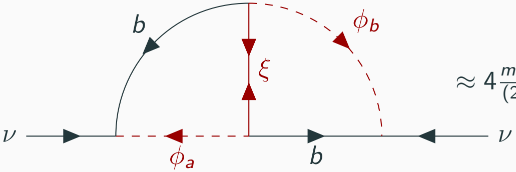
Dirac fermion	Scalar	Operator
$(1, 3, -1)$	$(1, 4, \frac{3}{2})$	$\mathcal{O}_1'$

B-physics anomalies and neutrino mass: Angelic model

based on dimension-9 operator $\mathcal{O}_{11} = LLQd^cQd^c$ P. Angel, Y. Cai, N. Rodd, MS, R. Volkas 1308.0463

Two LQs $\phi \sim (\mathbf{3}, \mathbf{1}, -1/3)$ and Majorana fermion $\xi \sim (\mathbf{8}, \mathbf{1}, 0)$

$\Rightarrow$ new Yukawa coupling $w_{ia}\bar{d}_i \xi \phi_a$



$$\approx 4 \frac{m_\xi m_b^2}{(2\pi)^8} \sum_{a,b}^{2} (x_{i3a} w_{3a}) I_{ab} (x_{j3b} w_{3b})$$

$$x_{i3a} = \frac{(2\pi)^4}{2 w_{3a} m_b \sqrt{m_\xi}} U_{ij}^* [\tilde{\mathbf{M}}^{1/2}]_{jk} R_{kb} \left[\tilde{\mathbf{I}}^{-1/2} \mathbf{S}\right]_{ba}$$

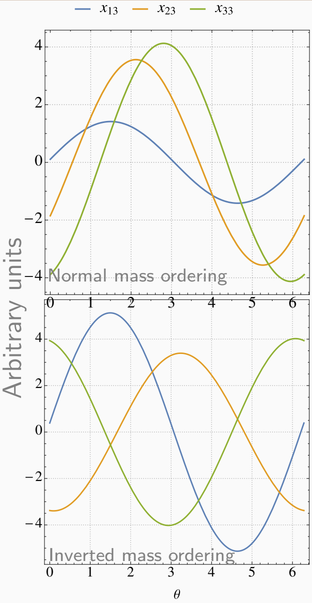
$$\mathbf{R} = \begin{pmatrix} 0 & 0 \\ \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad \mathbf{x} = \begin{pmatrix} 0 & 0 & x_{13} \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix}$$

- Casas-Ibarra parameter $\theta \in \mathbb{C}$ fixes ratio of x_{i3} Casas, Ibarra hep-ph/0103065
- Minimal scenario: only necessary to consider non-negligible w_{3a} (scale factor)

Neutrino mass and $R_{D^{(*)}}$

Important points:

- Divorce ϕ_2 and ξ from anomalies by taking $m_{\phi_2}, m_\xi \gg m_{\phi_1}$
- Extra loop and additional vertex factors keep neutrino mass small
- x_{13} cannot be turned off *ad libitum* $\Rightarrow \mu N \to eN$ serious constraint
- No major difference to explanation of $R_{D^{(*)}}$, inconsistent with hierarchy $|x_{23}| \gg |x_{33}|$ needed for $R_{K^{(*)}}$



Conclusions

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- *One leptoquark* solution can seperately explain $R_{K^{(*)}}$ or $R_{D^{(*)}}$ to 1σ along with $(g-2)_\mu$
- Good fit to $R_{D^{(*)}}$ inconsistent with vanishing RH coupling y_{32}
- $R_{K^{(*)}}$ requires large bottom-muon coupling x_{23} and LQ mass ~ 3 TeV
- Model can accommodate $R_{K^{(*)}}$ and $R_{D^{(*)}}$ together to 2σ
- Leptoquarks can easily be incorporated into neutrino mass models – two-loop scenario considered can explain $R_{D^{(*)}}$ and $(g-2)_\mu$ well

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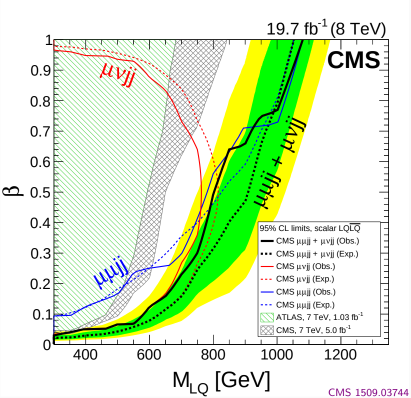
Thank you!

Backup slides

Searches and mass limits

Final states of interest: $\ell\ell jj$, $\ell jj + \not{E}_T$ and $jj + \not{E}_T$ where $\ell \in \{\mu, \tau\}$



CMS 1509.03744

CMS 13 TeV @ 2.6 fb^{-1} $[\beta = 1]$

$eejj$: $M_{LQ} \geq 1130$ GeV CMS-PAS-EXO-16-043

$\mu\mu jj$ $M_{LQ} \geq 1165$ GeV CMS-PAS-EXO-16-007

$\tau\tau jj$: $M_{LQ} \geq 900$ GeV CMS-PAS-EXO-16-023

Explanation of $R_{D^{(*)}} \Rightarrow m_\phi > [400, 640]$ GeV.

Current search strategies can be too restrictive: *e.g.* preclude the search for LQs in radiative neutrino mass models

Cai, Clarke, MS, Volkas 1410.0689; Sierra, Hirsch, Kovalenko 0710.5699; Dumont, Nishiwaki, Watanbe 1603.05248

The full Lagrangian

Introduces the scalar leptoquark $\phi \sim (\mathbf{3}, \mathbf{1}, -1/3)$

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) + m_\phi^2 \phi^\dagger \phi - \kappa H^\dagger H \phi^\dagger \phi + \hat{x}_{ij} \hat{L}_i \hat{Q}_j \phi^\dagger + \hat{y}_{ij} \hat{\bar{e}}_i \hat{\bar{u}}_j \phi + \mathrm{h.c.}$$

Rotate into the mass basis (except for neutrinos)

$$\begin{aligned} \hat{u}_i &= (L_u)_{ij} u_j & \hat{d}_i &= (L_d)_{ij} d_j & \hat{\bar{u}}_i &= (R_u)_{ij} \bar{u}_j \\ \hat{e}_i &= (L_e)_{ij} e_j & \hat{\nu}_i &= (L_\nu)_{ij} \breve{\nu}_j & \hat{\bar{e}}_i &= (R_e)_{ij} \bar{e}_j \end{aligned}$$

$$\begin{aligned} \mathcal{L}_\phi &\supset x_{ij} \breve{\nu}_i d_j \phi^\dagger - [\mathbf{x}\mathbf{V}^\dagger]_{ij} e_i u_j \phi^\dagger + y_{ij} \bar{e}_i \bar{u}_j \phi + \mathrm{h.c.} \\ &\equiv x_{ij} \breve{\nu}_i d_j \phi^\dagger - z_{ij} e_i u_j \phi^\dagger + y_{ij} \bar{e}_i \bar{u}_j \phi + \mathrm{h.c.} \end{aligned}$$

Anomalous magnetic moment of the muon

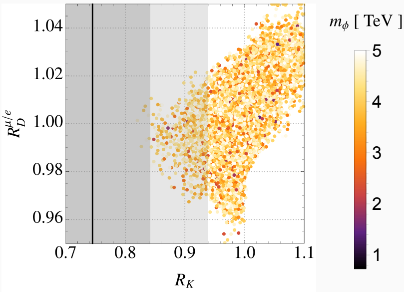
Measured values of $a_\mu = (g-2)_\mu/2$ in $\gtrsim 3\sigma$ tension with hte SM

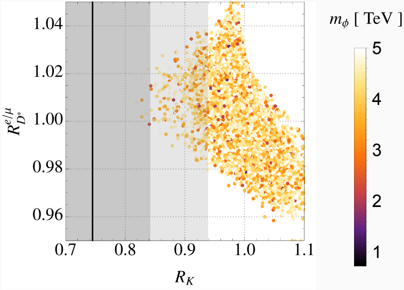
$$\Delta a_\mu = \begin{cases} (28.7 \pm 8.0) \times 10^{-10} & \text{Davier et al 1010.4180} \\ (26.1 \pm 8.0) \times 10^{-10} & \text{Hagiwara et al 1105.3149} \end{cases}$$

Same-chirality contribution from leptoquark ϕ suppressed by m_μ^2 – dominant contribution from top loop

$$a_\mu^\phi = \sum_{i=1}^{3} \frac{m_\mu m_{u_i}}{4\pi^2 m_\phi^2} \left(\frac{7}{4} - \ln \frac{m_\phi^2}{m_{u_i}^2} \right) \mathrm{Re}(y_{2i} z_{2i}) - \frac{m_\mu^2}{32\pi^2 m_\phi^2} \sum_i \left[|z_{2i}|^2 + |y_{2i}|^2 \right]$$

Comments on $R_{D^{(*)}}^{\mu/e}$





$$R_D^{\mu/e} = 0.995 \pm 0.022 \pm 0.039$$

$$R_{D^*}^{\mu/e} = 1.04 \pm 0.05 \pm 0.01$$

Belle 1510.03657 1702.01521

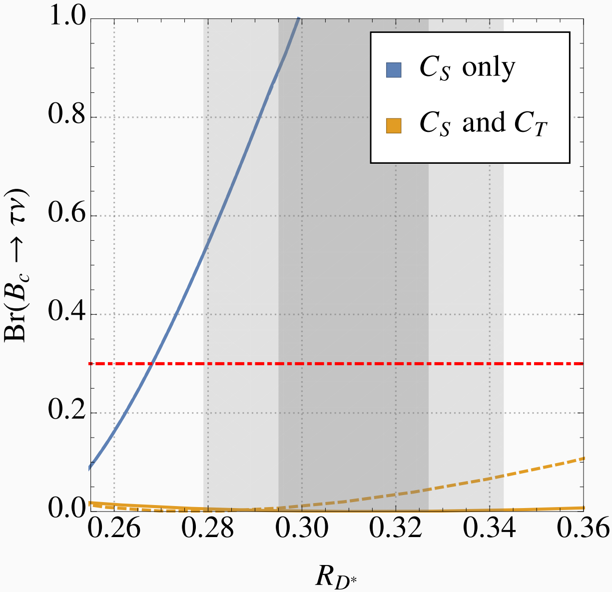
$$C_{LL}^{\phi} \sim \frac{x^4}{m_\phi^2}$$

$$R_{D^{(*)}}^{\ell/\ell'} \sim \frac{x^2}{m_\phi^2}$$

$\Rightarrow C_{LL}^{\phi}$ constant for $m_\phi \rightarrow \beta m_\phi$ as long as $x \rightarrow \sqrt{\beta} x$

$\Rightarrow C_{S,V,T}$ suppressed by $1/\beta$

Comments on $B_c \to \tau\nu$



Numerical scans

Scan I. $6 \cdot 10^6$ points sampled from the region

- $B \to K\nu\nu$: $-0.05 \lesssim \frac{[\mathbf{x}^\dagger \mathbf{x}]_{23}}{\hat{m}_\phi^2} \lesssim 0.1$
- $\hat{m}_\phi \in [0.6, 5]$,
- $|x_{ij}| \leq \sqrt{4\pi}$ for $i, j \neq 1$,
- $|y_{22}|, |y_{23}| \leq \sqrt{4\pi}$,
- All other couplings are set to zero.

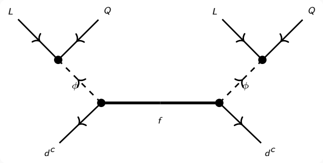
$\to\ \sim 5 \cdot 10^3$ pass all of the constraints.

Scan II. $6 \cdot 10^6$ points sampled from the region

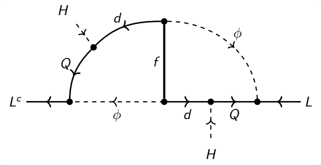
- $B \to K\nu\nu$: $-0.05 \lesssim \frac{[\mathbf{x}^\dagger \mathbf{x}]_{23}}{\hat{m}_\phi^2} \lesssim 0.1$
- $\hat{m}_\phi \in [0.6, 5]$,
- $|x_{ij}| \leq \sqrt{4\pi}$ for $i, j \neq 1$,
- $|y_{23}| \leq 0.05$, $|y_{32}| \leq \sqrt{4\pi}$,
- All other couplings, including y_{22}, are set to zero.

$\to\ \sim 4 \cdot 10^4$ pass all of the constraints.

Angelic model: $\mathcal{O}_{11b} \equiv L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$



Scalar: $\phi_i = (\bar{3}, 1, \frac{1}{3})$
Fermion: $f = (8, 1, 0)$



P. Angel, Y. Cai, N. Rodd, MS, R. Volkas 1308.0463

- Interaction

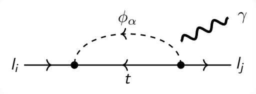
$$-\Delta\mathcal{L} = m^2_{\phi_\alpha}\,\phi^\dagger_\alpha\,\phi_\alpha + \frac{1}{2}\,m_f\,\overline{f}^c f + \lambda^{LQ}_{ij\alpha}\,\overline{L}^c_i\,Q_j\,\phi_\alpha + \lambda^{df}_{i\alpha}\,\overline{d}_i\,f\,\phi^*_\alpha$$
$$-\lambda^{eu}_{ij\alpha}\,\overline{e}^c_i\,u_j\,\phi_\alpha + \lambda^{QQ}_{ij\alpha}\,\overline{Q}_i\,Q^c_j\,\phi_\alpha + \lambda^{ud}_{ij\alpha}\,\overline{u}_i\,d^c_j\,\phi_\alpha + h.c.$$

- Large hierarchy in the down quark sector

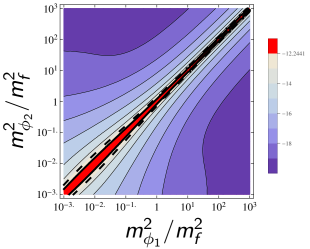
$$(M_\nu)_{ij} \simeq 4\frac{m_f\,V^2_{tb} m^2_b}{(2\pi)^8}\sum_{\alpha,\beta=1}^{N_\phi}\left(\lambda^{LQ}_{i3\alpha}\lambda^{df}_{3\alpha}\right)(I_{\alpha\beta})\left(\lambda^{LQ}_{j3\beta}\lambda^{df}_{3\beta}\right)$$

- $N_\phi \geq 2$ to obtain rank-2 M_ν

Angelic model: flavour physics



$$\mathrm{Br}(\mu \to e\gamma) \simeq \frac{3s_W^2}{8\pi^3\alpha} F(t_{3m})^2$$
$$\times \left(\sum_{m=1}^{2} \lambda_{\mu 3m}^{LQ} \lambda_{e3m}^{LQ*} \frac{m_W^2}{m_{\phi_m}^2}\right)^2$$



$m_f = 1\mathrm{TeV}$

Large hierarchy in eigenvalues of I.

$$\lambda_{i3\alpha}^{LQ} \lambda_{3\alpha}^{df} = \sum_{j,k,\beta} \frac{(2\pi)^4}{2m_b\sqrt{m_f}}$$
$$\times \left(V_\nu^*\right)_{ij} \left(\hat{M}_\nu^{\frac{1}{2}}\right)_{jk} O_{k\beta} \left(\hat{I}^{-\frac{1}{2}} S\right)_{\beta\alpha}$$

with $\hat{M}_\nu = V_\nu^T M_\nu V_\nu$, $\hat{I} = S^T I S$ and $t_i = \frac{m_{\phi_i}^2}{m_f^2}$

Parameter Choice

- Neutrino mass parameters at best-fit values
- Parameter in Casas-Ibarra "orthogonal matrix" $\theta_{CI} = 0$
- $\delta = \varphi_2 = 0$ and $\lambda_{3\alpha}^{df} = 1$

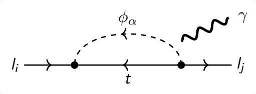
$\mathrm{Br}(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$ MEG $6 \cdot 10^{-14}$

Other Flavour Constraints

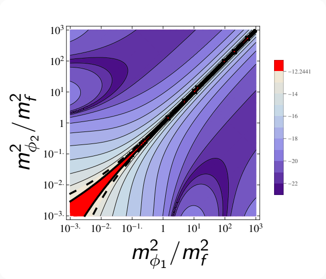
Top decay, meson mixing, $b \to s$ transition and more

Mathematica package ANT `http://ant.hepforge.org`

Angelic model: flavour physics



$$\mathrm{Br}(\mu \to e\gamma) \simeq \frac{3s_W^2}{8\pi^3\alpha} F(t_{3m})^2 \times \left(\sum_{m=1}^{2} \lambda^{LQ}_{\mu 3m} \lambda^{LQ*}_{e3m} \frac{m_W^2}{m^2_{\phi_m}} \right)^2$$



$m_f = 10\mathrm{TeV}$

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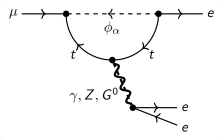

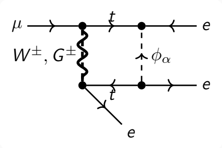

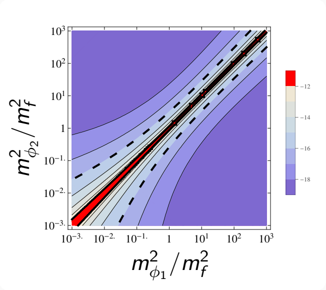

$m_f = 1\mathrm{TeV}$

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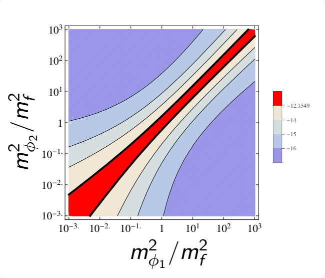
$\mathrm{Br}(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$	MEG	$6 \cdot 10^{-14}$
$\mathrm{Br}(\mu \to eee) < 10^{-12}$	SINDRUM	10^{-16}

Other Flavour Constraints

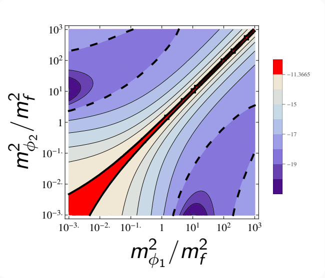
Top decay, meson mixing, $b \to s$ transition and more

Mathematica package ANT `http://ant.hepforge.org`

Angelic model: flavour physics



$m_f = 1\mathrm{TeV}$ in Au



$m_f = 10\mathrm{TeV}$ in Ti

Large hierarchy in eigenvalues of I.

$$\lambda^{LQ}_{i3\alpha}\lambda^{df}_{3\alpha} = \sum_{j,k,\beta}\frac{(2\pi)^4}{2m_b\sqrt{m_f}} \times \left(V_\nu^*\right)_{ij}\left(\hat{M}_\nu^{\frac{1}{2}}\right)_{jk} O_{k\beta}\left(\hat{I}^{-\frac{1}{2}}S\right)_{\beta\alpha}$$

with $\hat{M}_\nu = V_\nu^T M_\nu V_\nu$, $\hat{I} = S^T IS$ and $t_i = \frac{m^2_{\phi_i}}{m^2_f}$

Parameter Choice

- Neutrino mass parameters at best-fit values
- Parameter in Casas-Ibarra "orthogonal matrix" $\theta_{CI} = 0$
- $\delta = \varphi_2 = 0$ and $\lambda^{df}_{3\alpha} = 1$

$\mathrm{Br}(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$	MEG	$6 \cdot 10^{-14}$
$\mathrm{Br}(\mu \to eee) < 10^{-12}$	SINDRUM	10^{-16}
$\mathrm{Br}(\mu N \to eN) < 7 \cdot 10^{-13}$(Au)	SINDRUM II	10^{-18} (Ti)

Other Flavour Constraints

Top decay, meson mixing, $b \to s$ transition and more

Mathematica package ANT `http://ant.hepforge.org`