A connection between neutrino mass and the recent B physics anomalies

Michael A. Schmidt

29 September 2017

NuFact 2017

based on
Y. Cai, J. Gargalionis, MS, R. Volkas [JHEP accepted 1704.05849]
Y. Cai, J. Herrero-Garcia, MS, A. Vicente, R. Volkas [1706.08524]
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 $R_{D^{(*)}}$
4. Anomalous angular observables and branching ratios in $b \to s\mu\mu$

Neutrino masses

Neutrino masses

- Dirac vs. Majorana neutrinos

$\Rightarrow$ Majorana mass generated by Weinberg operator $LHLH$ suppressed by a scale $\Lambda \gg \langle H \rangle \simeq 100\mathrm{GeV} \gg m_\nu$

- Can be generated via seesaw mechanisms

  T1:Minkowski; Yanagida; Glashow;Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic T3: Foot, Lew, He, Joshi

  T2: Mohapatra, Senjanovic; Magg, Wetterich; Lazarides, Shafi, Wetterich; Schechter, Valle

Neutrino masses

- Dirac vs. Majorana neutrinos

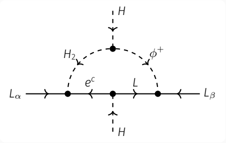
$\Rightarrow$ Majorana mass generated by Weinberg operator $LHLH$ suppressed by a scale $\Lambda \gg \langle H \rangle \simeq 100\mathrm{GeV} \gg m_\nu$

- Can be generated via seesaw mechanisms

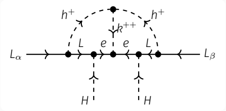
T1:Minkowski; Yanagida; Glashow;Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic T3: Foot, Lew, He, Joshi

T2: Mohapatra, Senjanovic; Magg, Wetterich; Lazarides, Shafi, Wetterich; Schechter, Valle

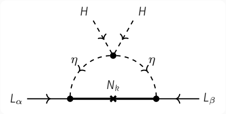
- However not the only possibility to generate neutrino mass



Zee (1980)



Zee (1986); Babu (1988) [Cheng, Li (1980)]



Ma hep-ph/0601225

...

Neutrino masses

- Dirac vs. Majorana neutrinos

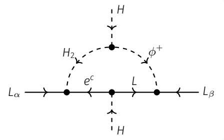
⇒ Majorana mass generated by Weinberg operator $LHLH$
suppressed by a scale $\Lambda \gg \langle H \rangle \simeq 100\mathrm{GeV} \gg m_\nu$

- Can be generated via seesaw mechanisms

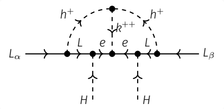
T1:Minkowski; Yanagida; Glashow;Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic T3: Foot, Lew, He, Joshi

T2: Mohapatra, Senjanovic; Magg, Wetterich; Lazarides, Shafi, Wetterich; Schechter, Valle

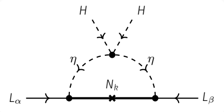
- However not the only possibility to generate neutrino mass



Zee (1980)



Zee (1986); Babu (1988) [Cheng, Li (1980)]



Ma hep-ph/0601225

...

Why should I be interested in anything beyond the seesaw mechanisms?

Connections to other physics

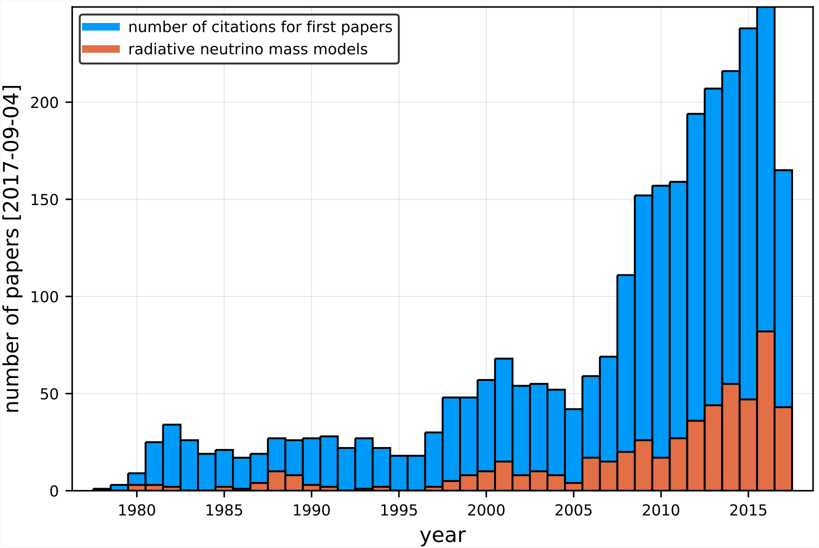
- Dark matter (e.g. scotogenic model Ma hep-ph/0601225)
- Anomalous magnetic moment $(g-2)_\mu$
- Recent B-physics anomalies
- New bosons help with stability of electroweak vacuum
- New scalars can induce strong electroweak phase transition
- baryogenesis, leptogenesis
- ...

Connections to other physics

- Dark matter (e.g. scotogenic model Ma hep-ph/0601225)
- Anomalous magnetic moment $(g-2)_\mu$
- Recent B-physics anomalies
- New bosons help with stability of electroweak vacuum
- New scalars can induce strong electroweak phase transition
- baryogenesis, leptogenesis
- ...

Interesting phenomenology testable in current/future experiments

Papers on radiative neutrino mass generation



A systematic approach: generalized Weinberg operator

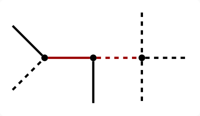
Consider operators of type

$$LLHH(H^\dagger H)^n$$

possibly with multiple Higgs fields

Bonnet, Hernandez, Ota, Winter 0907.3143

dimension-7 operator at tree-level

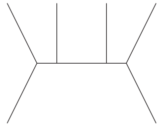


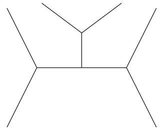
electroweak
triplet fermion
quadruplet scalar

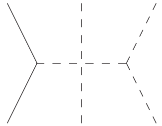
Babu, Nandi, Tavartkiladze 0905.2710

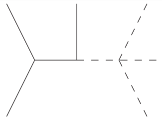
Construct all possible topologies:

- tree-level topologies Bonnet, Hernandez, Ota, Winter 0907.3143
- 1-loop topologies of Weinberg operator Bonnet, Hirsch, Ota, Winter 1204.5862
- 2-loop topologies of Weinberg operator Arisitizabal Sierra, Degee, Dorame, Hirsch 1411.7038
- 1-loop topologies of dimension-7 operator Cepedello, Hirsch, Helo 1705.01489









The dashed lines always denote scalars and solid lines are either fermions or scalars.

A systematic approach: generalized Weinberg operator

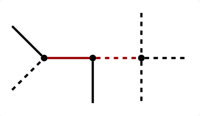
Consider operators of type

$$LLHH(H^\dagger H)^n$$

possibly with multiple Higgs fields

Bonnet, Hernandez, Ota, Winter 0907.3143

dimension-7 operator at tree-level

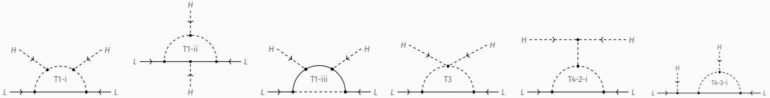


electroweak
triplet fermion
quadruplet scalar

Babu, Nandi, Tavartkiladze 0905.2710

Construct all possible topologies:

- tree-level topologies Bonnet, Hernandez, Ota, Winter 0907.3143
- 1-loop topologies of Weinberg operator Bonnet, Hirsch, Ota, Winter 1204.5862
- 2-loop topologies of Weinberg operator Arisitizabal Sierra, Degee, Dorame, Hirsch 1411.7038
- 1-loop topologies of dimension-7 operator Cepedello, Hirsch, Helo 1705.01489



A systematic approach: generalized Weinberg operator

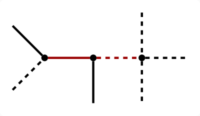
Consider operators of type

$$LLHH(H^\dagger H)^n$$

possibly with multiple Higgs fields

Bonnet, Hernandez, Ota, Winter 0907.3143

dimension-7 operator at tree-level

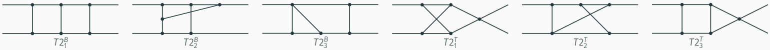


electroweak triplet fermion quadruplet scalar

Babu, Nandi, Tavartkiladze 0905.2710

Construct all possible topologies:

- tree-level topologies Bonnet, Hernandez, Ota, Winter 0907.3143
- 1-loop topologies of Weinberg operator Bonnet, Hirsch, Ota, Winter 1204.5862
- 2-loop topologies of Weinberg operator Arisitizabal Sierra, Degee, Dorame, Hirsch 1411.7038
- 1-loop topologies of dimension-7 operator Cepedello, Hirsch, Helo 1705.01489



A systematic approach: generalized Weinberg operator

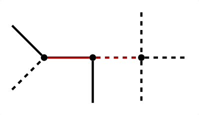
Consider operators of type

$$LLHH(H^\dagger H)^n$$

possibly with multiple Higgs fields

Bonnet, Hernandez, Ota, Winter 0907.3143

dimension-7 operator at tree-level

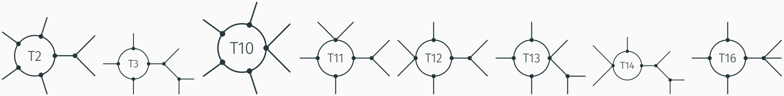


electroweak triplet fermion quadruplet scalar

Babu, Nandi, Tavartkiladze 0905.2710

Construct all possible topologies:

- tree-level topologies Bonnet, Hernandez, Ota, Winter 0907.3143
- 1-loop topologies of Weinberg operator Bonnet, Hirsch, Ota, Winter 1204.5862
- 2-loop topologies of Weinberg operator Arisitizabal Sierra, Degee, Dorame, Hirsch 1411.7038
- 1-loop topologies of dimension-7 operator Cepedello, Hirsch, Helo 1705.01489



A systematic approach: $\Delta L = 2$ operators

- Neutrinoless double beta decay implies Majorana neutrinos

  Schechter, Valle Phys. Rev. D25 (1982) 2951

- Every $\Delta L = 2$ operator leads to neutrino mass
- Consider all possible $\Delta L = 2$ operators Babu, Leung hep-ph/0106054; de Gouvea, Jenkins 0708.1344

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

$\Rightarrow$ neutrinoless double beta decay, LNV processes at a collider

- Indication of quantum numbers of new particles
- UV completions Angel, Rodd, Volkas 1212.6111

A systematic approach: $\Delta L = 2$ operators

- Neutrinoless double beta decay implies Majorana neutrinos

  Schechter, Valle Phys. Rev. D25 (1982) 2951

- Every $\Delta L = 2$ operator leads to neutrino mass
- Consider all possible $\Delta L = 2$ operators Babu, Leung hep-ph/0106054; de Gouvea, Jenkins 0708.1344

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

$\Rightarrow$ neutrinoless double beta decay, LNV processes at a collider

- Indication of quantum numbers of new particles
- UV completions Angel, Rodd, Volkas 1212.6111

Other criteria: topology, complexity, flavour, common features, …

Farzan, Pascoli, Schmidt 1208.2732; Law, McDonald 1303.6384; Kanemura, Sugiyama 15010.08726; Ho, Toma, Tsumura1604.07894; …

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

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

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

Minimal UV completions of the dimension-7 operators

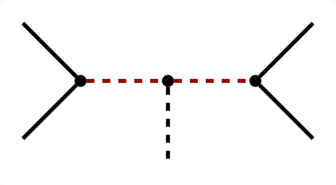
Y. Cai, J. Clarke, MS, R. Volkas 1410.0689

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

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

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

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



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

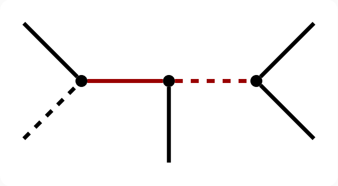
Y. Cai, J. Clarke, MS, R. Volkas 1410.0689

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

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

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

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



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

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

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

Minimal UV completions of the dimension-7 operators

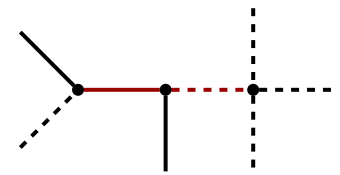
Y. Cai, J. Clarke, MS, R. Volkas 1410.0689

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

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

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

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



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

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

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

Different classifications

Introduction

Discussion

Survey of models

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

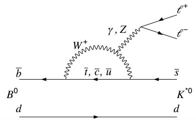
Yi Cai,[a,b] Juan Herrero-García,[c] Michael A. Schmidt,[d] Avelino Vicente[e] and Raymond R. Volkas[b]

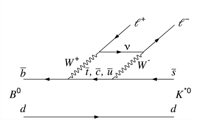
[a] School of Physics, Sun Yat-sen University, Guangzhou, 510275, China
[b] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Melbourne, VIC 3010, Australia
[c] ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, The University of Adelaide, SA 5005, Australia
[d] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia
[e] Instituto de Física Corpuscular (CSIC-Universitat de València), Apdo. 22085, E-46071 Valencia, Spain

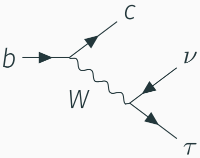
Anomalies in LFU ratios in B physics

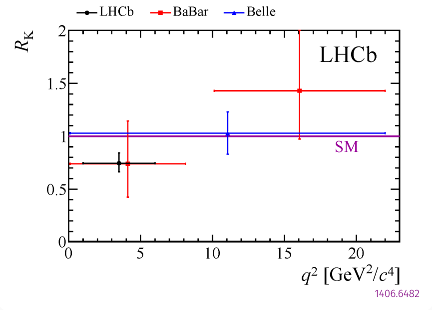
Hints for violations of LFU in $R_{K(*)}$ and $R_{D(*)}$

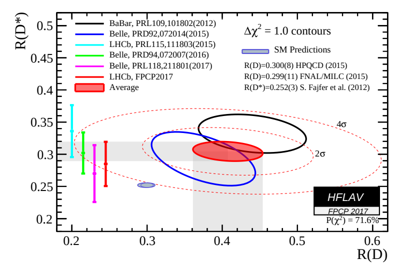
$$R_{K(*)} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)} \qquad R_{D(*)} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$





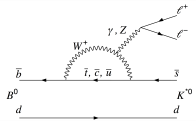


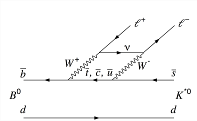


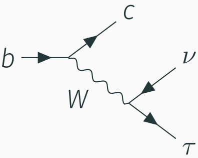


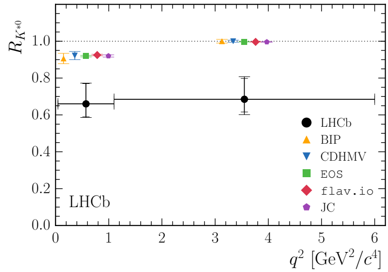
Hints for violations of LFU in $R_{K^{(*)}}$ and $R_{D^{(*)}}$

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

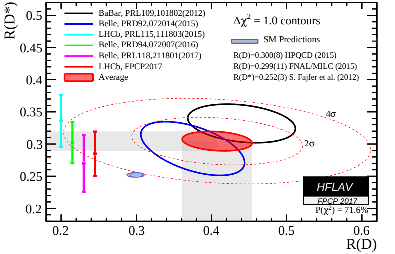








1705.05902

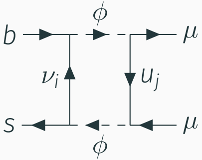


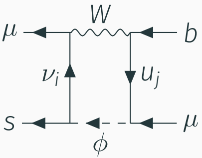
The protagonist

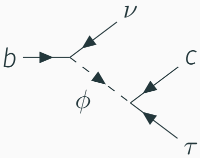
One leptoquark model postulated as explanation of $b \to c$ anomalies at tree level and $b \to s$ through one-loop box diagrams Bauer, Neubert 1511.01900

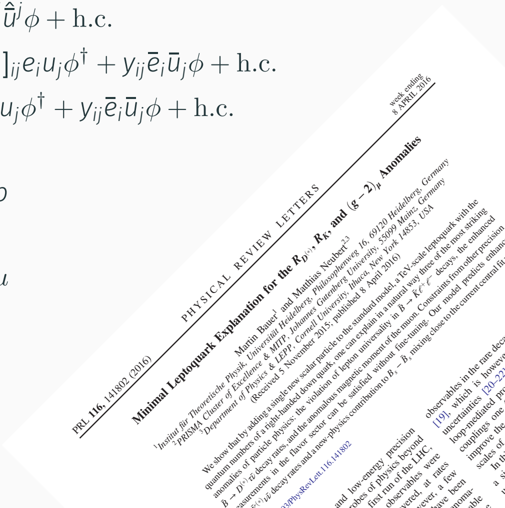
The scalar leptoquarks transforms like d_R: $\phi \sim (3, 1, -\frac{1}{3})$

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








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]

[1]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
[2]PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany
[3]Department of Physics & LEPP, Cornell University, Ithaca, New York 14853, USA
(Received 5 November 2015; published 8 April 2016)

We show that by adding a single new scalar particle to the standard model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit

Phenomenological analysis

Signals and constraints

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

Data-driven ansatz for the couplings x_{ij} and y_{ij} [$z = xV^\dagger$] in weak interaction basis with values dictated by constraints and anomalies

$K^+ \to \pi^+ \nu\nu$
$\mu N \to eN$
$\tau \to \ell\pi, \ell\rho$
$\Rightarrow$ first generation couplings = 0
$B \to K\nu\nu$
$B_s - \bar{B}_s$ 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
$\tau \to \mu\mu\mu$
$\tau \to \mu\gamma$

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

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

$$\begin{array}{cc} & \begin{array}{ccc} u & c & t \end{array} \\ \mathrm{y} = & \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} \end{array} \begin{array}{c} e \\ \mu \\ \tau \end{array}$$

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} $[z = xV^\dagger]$ in weak interaction basis with values dictated by constraints and anomalies

$K^+ \to \pi^+ \nu\nu$
$\mu N \to eN$
$\tau \to \ell\pi, \ell\rho$
$\Rightarrow$ first generation couplings = 0
$B \to K\nu\nu$
$B_s - \bar{B}_s$ 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
$\tau \to \mu\mu\mu$
$\tau \to \mu\gamma$

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

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

$$\begin{array}{cc} & \begin{array}{ccc} u & c & t \end{array} \\ y = & \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} \end{array} \begin{array}{c} \\ e \\ \mu \\ \tau \end{array}$$

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} [$z = xV^\dagger$] in weak interaction basis with values dictated by constraints and anomalies

$K^+ \to \pi^+\nu\nu$
$\mu N \to eN$
$\tau \to \ell\pi, \ell\rho$
$\Rightarrow$ first generation couplings = 0
$B \to K\nu\nu$
$B_s - \bar{B}_s$ 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
$\tau \to \mu\mu\mu$
$\tau \to \mu\gamma$

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

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

$$\mathrm{y} = \begin{array}{cc} \begin{array}{ccc} u & c & t \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} & \begin{array}{c} e \\ \mu \\ \tau \end{array} \end{array}$$

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} [$z = xV^\dagger$] in weak interaction basis with values dictated by constraints and anomalies

$K^+ \to \pi^+ \nu\nu$
$\mu N \to eN$
$\tau \to \ell\pi, \ell\rho$
$\Rightarrow$ first generation couplings = 0
$B \to K\nu\nu$
$B_s - \bar{B}_s$ 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
$\tau \to \mu\mu\mu$
$\tau \to \mu\gamma$

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

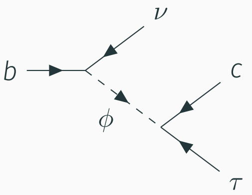
$$\mathrm{x} = \begin{array}{cc} \begin{array}{ccc} d & s & b \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \end{array}$$

$$\mathrm{y} = \begin{array}{cc} \begin{array}{ccc} u & c & t \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} & \begin{array}{c} e \\ \mu \\ \tau \end{array} \end{array}$$

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

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

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

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

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

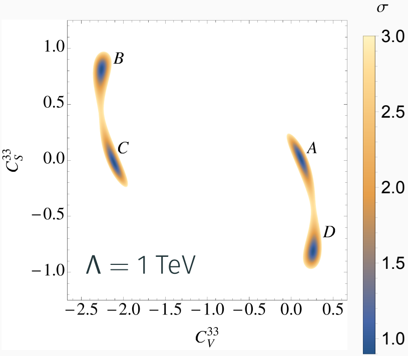
$$\begin{array}{c}
y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix}
\begin{array}{c} e \\ \mu \\ \tau \end{array} \\
\begin{array}{ccc} u & c & t \end{array}
\end{array}$$

$[z = xV^\dagger]$

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

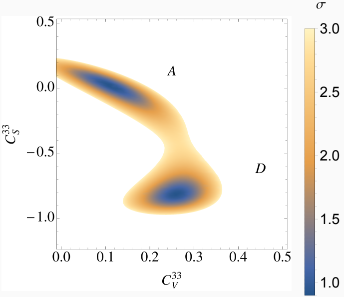
Lattice QCD form factors for R_D MILC 1503.07237

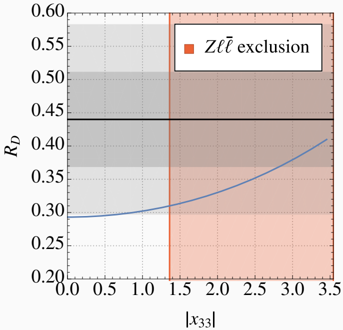
Form factors extracted from $\bar{B} \to D^*(\mu, e)\nu$ measurement for R_{D^*}
$\Rightarrow$ calculation becomes unreliable for large x_{2i}, y_{2i}



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





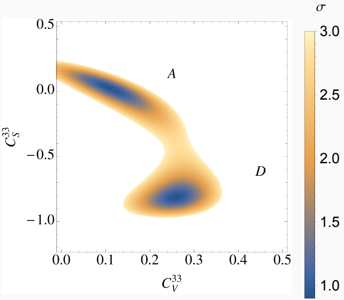
Constraints involving LH couplings sufficient to impede this scenario:

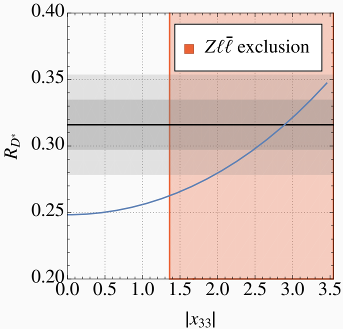
- $B \to K\nu\nu$
- $B_s - \bar{B}_s$ mixing
- Precision EW measurements: $Z \to \tau\tau$

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

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

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





Constraints involving LH couplings sufficient to impede this scenario:

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

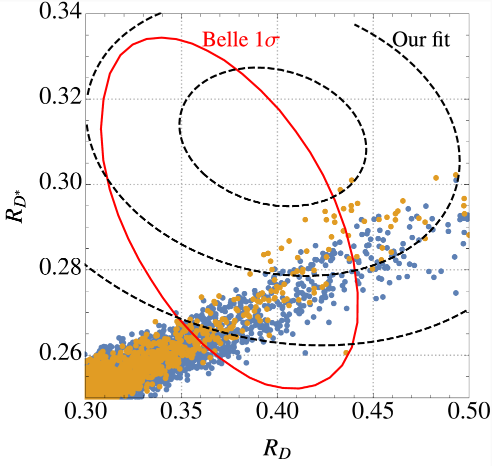
$$\begin{array}{cc} & \begin{array}{ccc} d/u & s/c & b/t \end{array} \\ \mathrm{x} = & \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix} \begin{array}{c} \nu_e/e \\ \nu_\mu/\mu \\ \nu_\tau/\tau \end{array} \end{array}$$

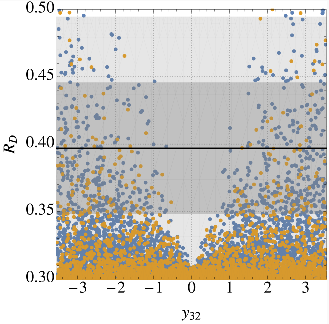
$$C_V^{NP} = \frac{1}{4\sqrt{2}G_F V_{cb}} \frac{x_{33}(x_{32}^* V_{cs} + x_{33}^* V_{ts})}{m_\phi^2}$$

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

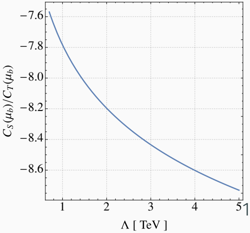
Charged current processes: R_D and R_{D^*} (4)

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





sizable RH coupling y_{32}



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

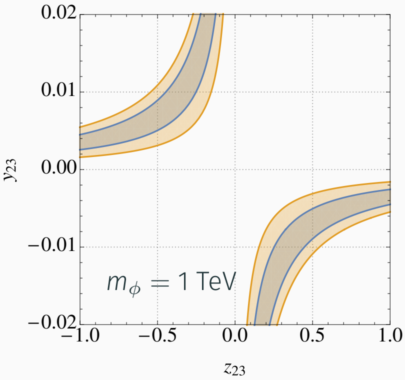
$$C_{S,T}^{NP}(\mu_b) = \begin{Bmatrix} 1 \\ -1/7.8 \end{Bmatrix} \frac{1.65}{4\sqrt{2}G_F V_{cb}} \frac{x_{33} y_{32}}{m_\phi^2} \qquad \text{for } m_\phi = 1 \text{ TeV}$$

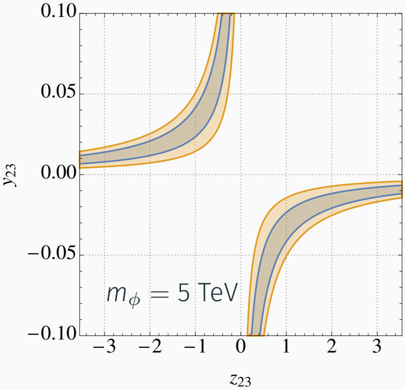
Anomalous magnetic moment of the muon: $(g-2)_\mu$

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

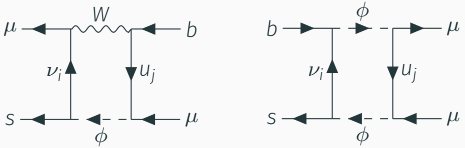
$$O^{\mu}_{LL,LR} \equiv \frac{O_9^{\mu} \mp O_{10}^{\mu}}{2} \sim (\bar{s}\gamma^{\mu} P_L b)(\bar{\mu}\gamma_{\mu} P_{L,R}\mu)$$

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

Effective Lagrangian

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

$$\mathrm{y} = \begin{array}{cc} & \begin{array}{ccc} u & c & t \end{array} \\ & \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{32} & 0 \end{pmatrix} \begin{array}{c} e \\ \mu \\ \tau \end{array} \end{array}$$

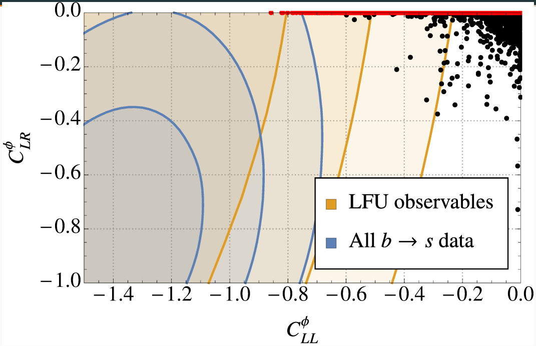


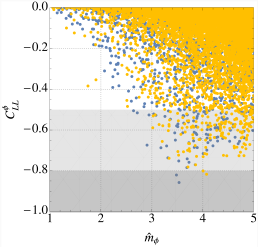
$$C^{\phi,\mu}_{LL} = \overbrace{\frac{m_t^2}{8\pi\alpha m_\phi^2}|z_{23}|^2}\;\overbrace{-\frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb}V_{ts}^*}\sum_i x_{i3}x_{i2}^*\sum_j |z_{2j}|^2} \approx -1.2$$

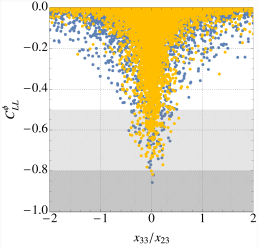
$$C^{\phi,\mu}_{LR} = \frac{m_t^2}{8\pi\alpha m_\phi^2}|y_{23}|^2\left[\ln\frac{m_\phi^2}{m_t^2} - 0.47\right] - \frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb}V_{ts}^*}\sum_i x_{i3}x_{i2}^*\sum_j |y_{2j}|^2 \approx 0$$

$\Rightarrow$ 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)





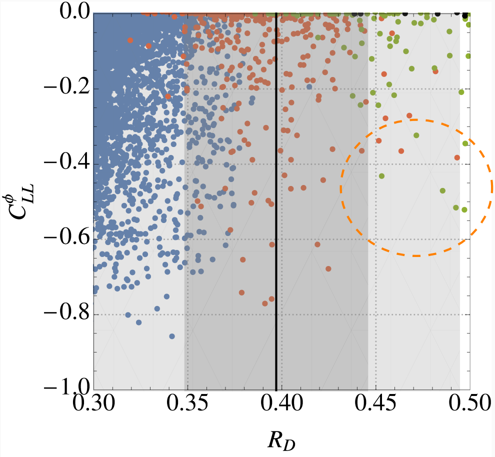


$D^0 \to \mu\mu \Rightarrow |z_{22}| < 0.48 m_\phi/\mathrm{TeV}$ for $y_{ij} = 0$, model prefers large $|z_{23}|$

LFU respected in ratios $R_{D^{(*)}}^{\mu/e}$, 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: $|x_{23}| \gg |x_{33}|$



R_{D^*} fit: 1σ, 2σ, 3σ, $> 3\sigma$

Points in the region of interest look like

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

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

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

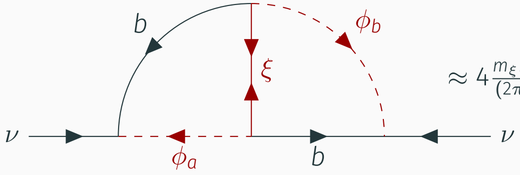
Connection to neutrino mass

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 $\phi \sim (3, 1, -1/3)$ and Majorana fermion $\xi \sim (8, 1, 0)$

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



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

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

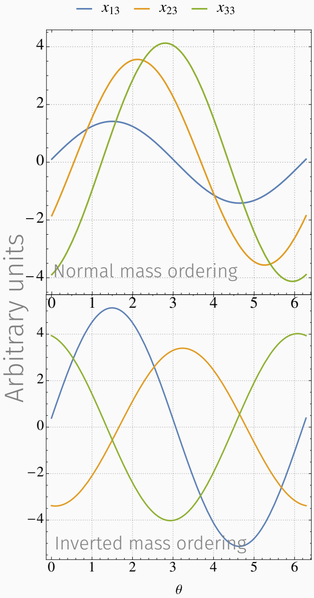
$$\mathrm{R} = \begin{pmatrix} 0 & 0 \\ \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad \mathrm{x} = \begin{pmatrix} 0 & 0 & x_{13} \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix}$$

- 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

Summary and conclusions

One leptoquark solution with S_1 leptoquark $(3, 1, -\frac{1}{3})$

- can seperately explain $R_{K^{(*)}}$ or $R_{D^{(*)}}$ to 1σ along with $(g-2)_\mu$
- provides fit to $R_{D^{(*)}}$ inconsistent with vanishing RH coupling y_{32}
- $R_{K^{(*)}}$ requires large $b-\mu$ coupling x_{23} and LQ mass ~ 3 TeV
- S_1 can accommodate $R_{K^{(*)}}$ and $R_{D^{(*)}}$ together to 2σ

Radiative neutrino mass generation interesting possibility, particularly in connection to other new physics

- S_1 leptoquark naturally part of radiative neutrino mass models
- two-loop scenario considered can explain $R_{D^{(*)}}$ and $(g-2)_\mu$ well

Summary and conclusions

One leptoquark solution with S_1 leptoquark $(3, 1, -\frac{1}{3})$

- can seperately explain $R_{K^{(*)}}$ or $R_{D^{(*)}}$ to 1σ along with $(g-2)_\mu$
- provides fit to $R_{D^{(*)}}$ inconsistent with vanishing RH coupling y_{32}
- $R_{K^{(*)}}$ requires large $b-\mu$ coupling x_{23} and LQ mass ~ 3 TeV
- S_1 can accommodate $R_{K^{(*)}}$ and $R_{D^{(*)}}$ together to 2σ

Radiative neutrino mass generation interesting possibility, particularly in connection to other new physics

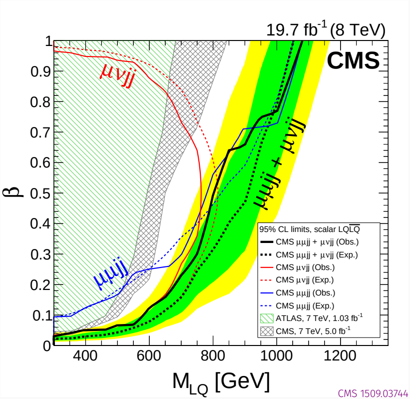
- S_1 leptoquark naturally part of radiative neutrino mass models
- two-loop scenario considered can explain $R_{D^{(*)}}$ and $(g-2)_\mu$ well

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 $\phi \sim (3, 1, -1/3)$

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

Rotate into the mass basis (except for neutrinos)

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

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

Anomalous magnetic moment of the muon

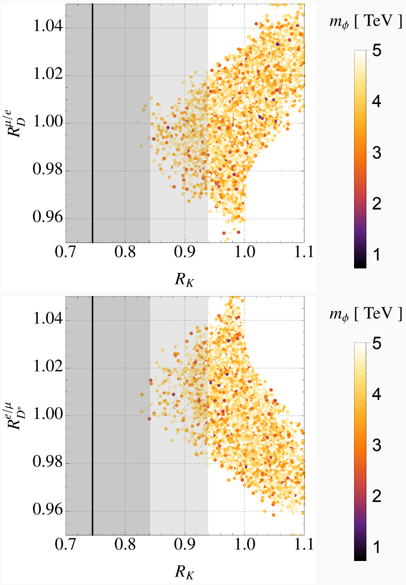
Measured values of $a_\mu = (g-2)_\mu/2$ in $\gtrsim 3\sigma$ tension with hte SM

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

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 $R^{\mu/e}_{D^{(*)}}$



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

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

Belle 1510.03657 1702.01521

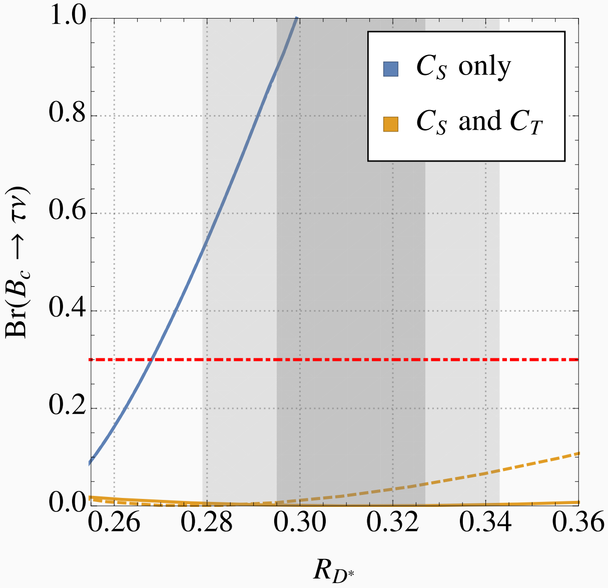
$$C_{LL}^{\phi} \sim \frac{x^4}{m_\phi^2}$$

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

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

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

Comments on $B_c \to \tau\nu$



Numerical scans

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

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

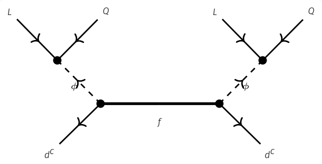
$\to$ $\sim 5 \cdot 10^3$ pass all of the constraints.

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

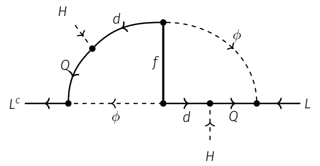
- $B \to K\nu\nu$: $-0.05 \lesssim \frac{[x^\dagger x]_{23}}{\hat{m}_\phi^2} \lesssim 0.1$
- $\hat{m}_\phi \in [0.6, 5]$,
- $|x_{ij}| \leq \sqrt{4\pi}$ for $i, j \neq 1$,
- $|y_{23}| \leq 0.05$, $|y_{32}| \leq \sqrt{4\pi}$,
- All other couplings, including y_{22}, are set to zero.

$\to$ $\sim 4 \cdot 10^4$ 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

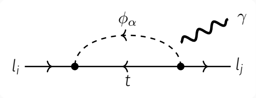
$$-\Delta\mathcal{L} = m^2_{\phi_\alpha}\,\phi^\dagger_\alpha\,\phi_\alpha + \frac{1}{2}\,m_f\,\overline{f}^c f + \lambda^{LQ}_{ij\alpha}\,\overline{L}^c_i\,Q_j\,\phi_\alpha + \lambda^{df}_{i\alpha}\,\overline{d}_i\,f\,\phi^*_\alpha$$
$$-\lambda^{eu}_{ij\alpha}\,\overline{e}^c_i\,u_j\,\phi_\alpha + \lambda^{QQ}_{ij\alpha}\,\overline{Q}_i\,Q^c_j\,\phi_\alpha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

- Large hierarchy in the down quark sector

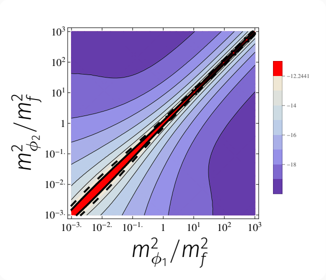
$$(M_\nu)_{ij} \simeq 4\frac{m_f V^2_{tb} m^2_b}{(2\pi)^8}\sum_{\alpha,\beta=1}^{N_\phi}\left(\lambda^{LQ}_{i3\alpha}\lambda^{df}_{3\alpha}\right)(I_{\alpha\beta})\left(\lambda^{LQ}_{j3\beta}\lambda^{df}_{3\beta}\right)$$

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

Angelic model: flavour physics



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



$m_f = 1\mathrm{TeV}$

Large hierarchy in eigenvalues of I.

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

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

Parameter Choice

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

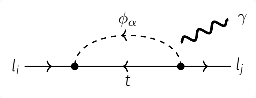
		Other
$\mathrm{Br}(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$	MEG	$6 \cdot 10^{-14}$

Flavour Constraints

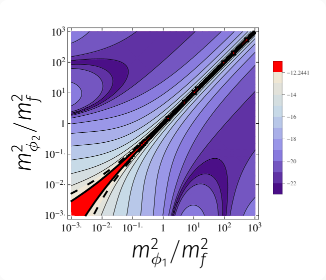
Top decay, meson mixing, $b \to s$ transition and more

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

Angelic model: flavour physics



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



$m_f = 10\mathrm{TeV}$

Large hierarchy in eigenvalues of I.

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

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

Parameter Choice

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

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

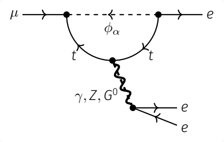
Other

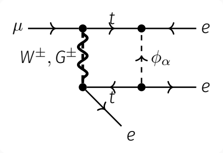
Flavour Constraints

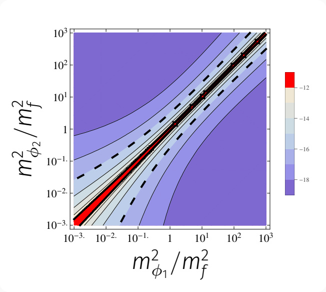
Top decay, meson mixing, $b \to s$ transition and more

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

Angelic model: flavour physics







$m_f = 1\mathrm{TeV}$

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 $\hat{M}_\nu = V^T_\nu M_\nu V_\nu, \hat{I} = S^T I S$ 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}

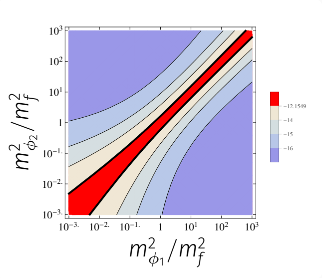
Other

Flavour Constraints

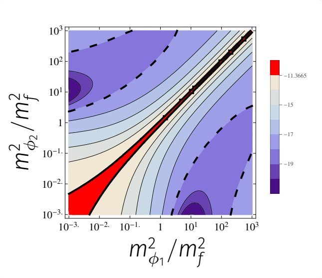
Top decay, meson mixing, $b \to s$ transition and more

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

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`