THE UNIVERSITY OF MELBOURNE

RADIATIVE NEUTRINO MASS GENERATION: Models, Flavour & the LHC

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1. Intro: see-saw vs radiative ν mass
2. Models: opening up d=7 operators
3. LHC: constraints from Run 1 (on a new model)
4. Flavour: bounds and prospects
5. Final remarks

1. Intro: see-saw vs radiative ν mass

ΔL=2 SM effective operators can be used to systematically study models of Majorana neutrino mass generation.

These have mass dimension d = 5, 7, 9, …

At d = 5, there is only the Weinberg operator: LLHH

It gives neutrino mass directly, via the see-saw formula $m_\nu \sim \langle H \rangle^2/M$

Underlying renormalisable theories yielding LLHH are constructed by "opening up" the operator. The type-1,2,3 see-saw models are the minimal, tree-level ways to open up LLHH.

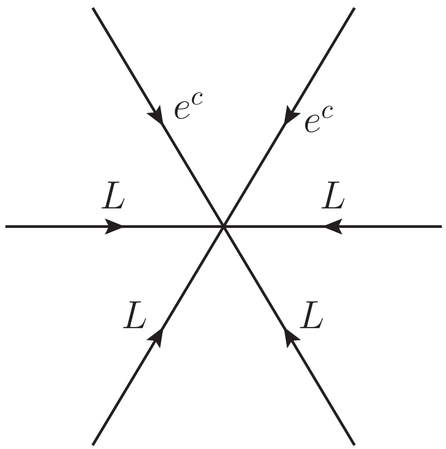
Other ΔL=2 SM effective operators require external legs (quarks, additional leptons) to be closed off in loops to give neutrino mass: radiative neutrino mass generation.

The effective operator is still minimally opened up at tree-level.

Historic example: Zee-Babu model

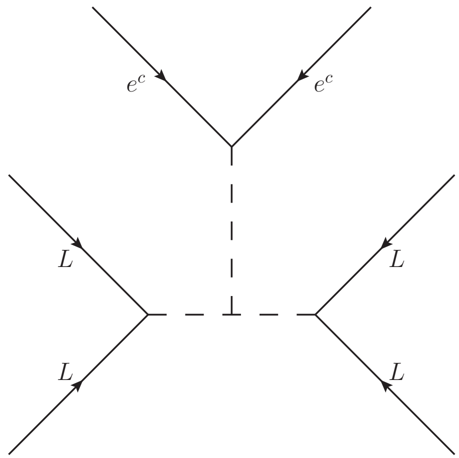
Doubly-charged scalar k

Singly-charged scalar h

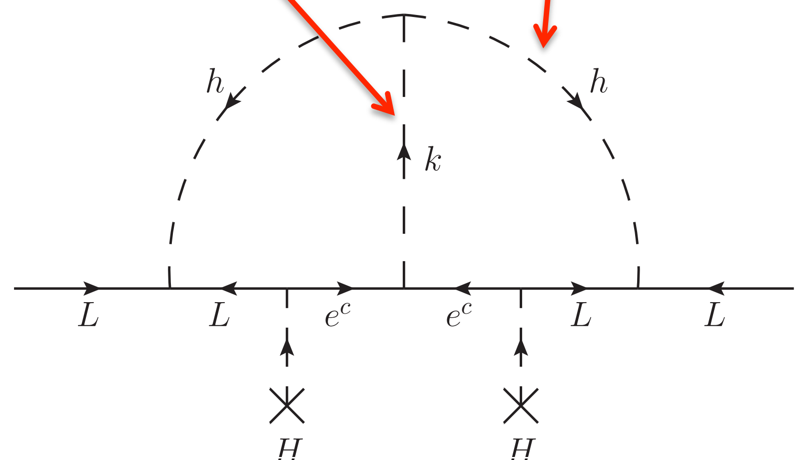


$$O_9 = LLLe^cLe^c$$

Effective op

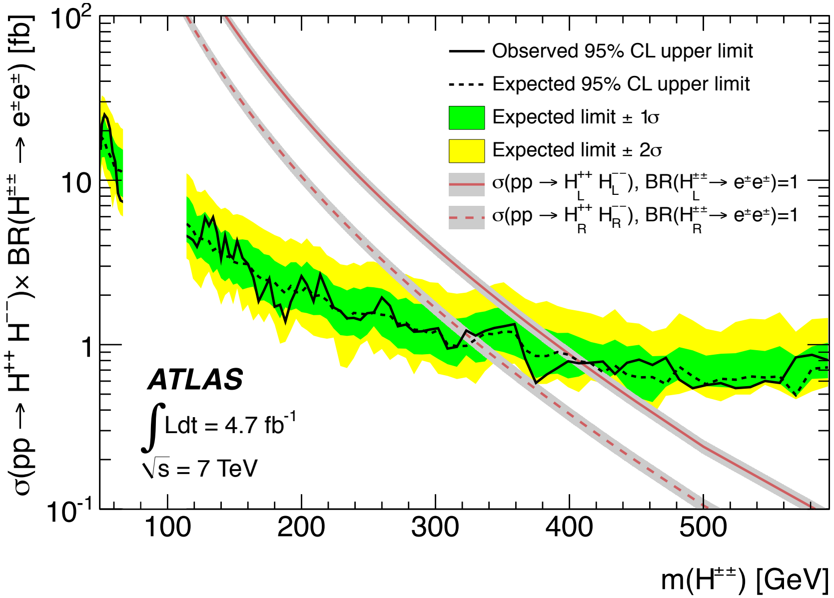


Opening it up

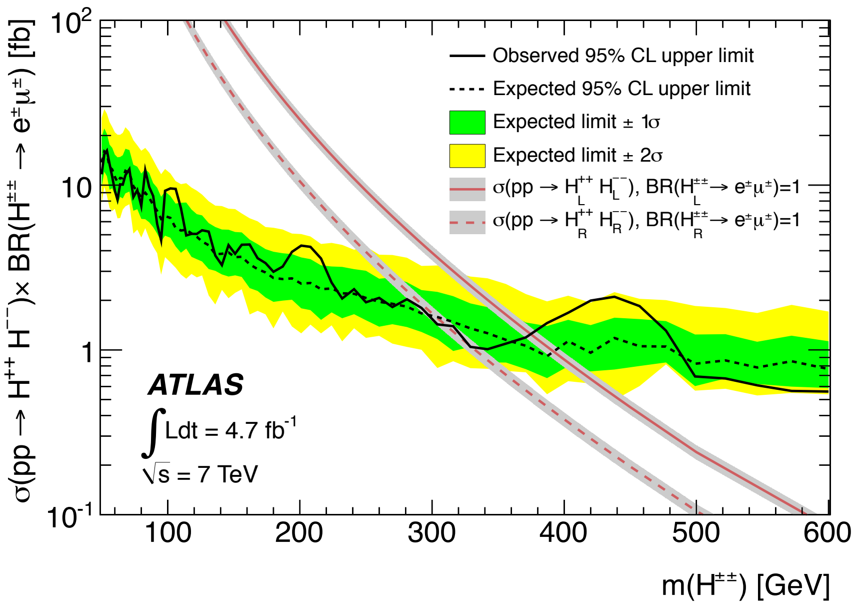


2-loop nu mass diagram

The exotics (k, h in this case) can be searched for at the LHC.



Mass limits on charge-2 scalar. Depends on BR assumption. Early Run 1 data.



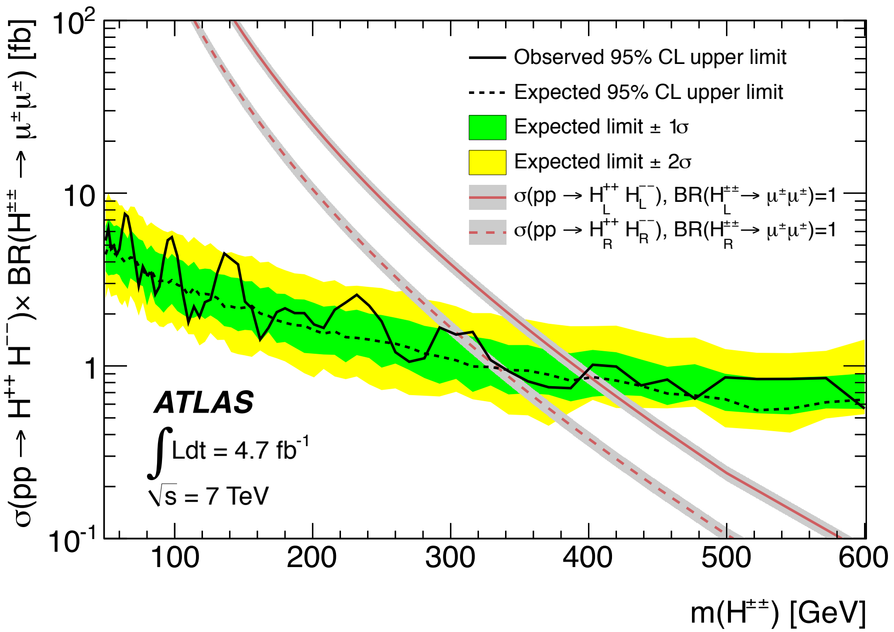
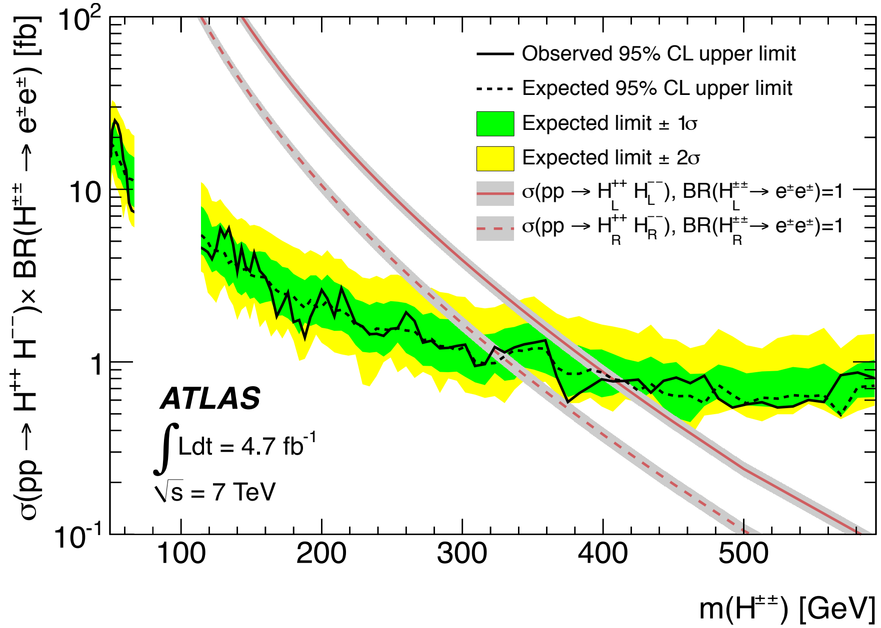


Table 1 Lower mass limits at 95% CL on $H^{\pm\pm}$ bosons decaying to $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, or $e^{\pm}\mu^{\pm}$ pairs. Mass limits are derived assuming branching ratios to a given decay mode of 100%, 33%, 22%, or 11%. Both expected and observed limits are given.

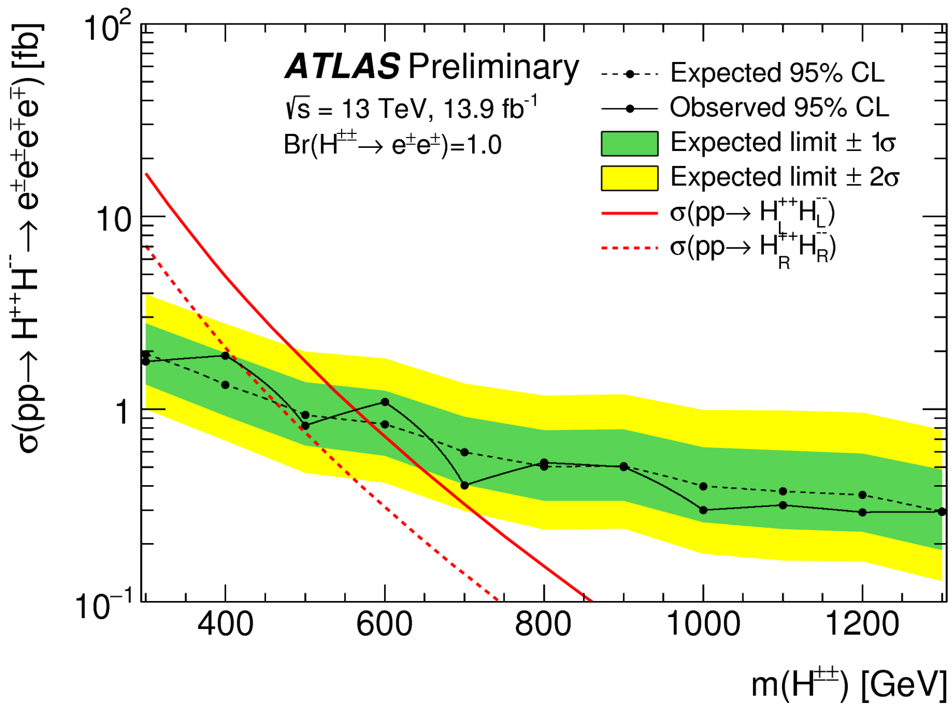
$\mathrm{BR}(H_L^{\pm\pm} \to \ell^{\pm}\ell'^{\pm})$	95% CL lower limit on $m(H_L^{\pm\pm})$ [GeV]					
	$e^{\pm}e^{\pm}$		$\mu^{\pm}\mu^{\pm}$		$e^{\pm}\mu^{\pm}$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	407	409	401	398	392	375
33%	318	317	317	290	279	276
22%	274	258	282	282	250	253
11%	228	212	234	216	206	190

$\mathrm{BR}(H_R^{\pm\pm} \to \ell^{\pm}\ell'^{\pm})$	95% CL lower limit on $m(H_R^{\pm\pm})$ [GeV]					
	$e^{\pm}e^{\pm}$		$\mu^{\pm}\mu^{\pm}$		$e^{\pm}\mu^{\pm}$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	329	322	335	306	303	310
33%	241	214	247	222	220	195
22%	203	199	223	212	194	187
11%	160	151	184	176	153	151

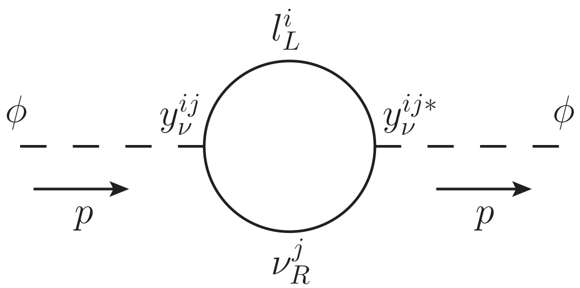
ATLAS mass limits as function of BR



For the 100% BR to ee case, bound increases from about 320 GeV to 450 GeV going to Run 2 data.



Comment on naturalness of the type-1 see-saw model:



Vissani PRD57, 7027 (1998):

$$\delta\mu^2 \simeq \frac{1}{4\pi^2}\frac{1}{\langle\phi\rangle^2} m_\nu M_N^3 < 1\ \mathrm{TeV}^2$$

$$\Rightarrow m_N < 3 \times 10^7\ \mathrm{GeV}$$

Standard hierarchical, thermal leptogenesis:

Bound for N_1 leptogen $m_N > 5 \times 10^8 - 2 \times 10^9$ GeV

Davidson, Ibarra
Giudice et al

What about in the full, three-flavour case, and for N1-, N2- and N3-leptogenesis?

Clarke, Foot, RV: PRD91 (2015) 073009
arXiv:1502.01352

$$\left|\delta\mu^2\right| \approx \frac{1}{4\pi^2}\frac{1}{\langle\phi\rangle^2}\mathrm{Tr}\left[\mathcal{D}_m R \mathcal{D}_M^3 R^\dagger\right].$$

Diag light nu mass matrix

Casas-Ibarra matrix

Diag heavy nu mass matrix

No dependence on PMNS matrix in the appropriate basis.

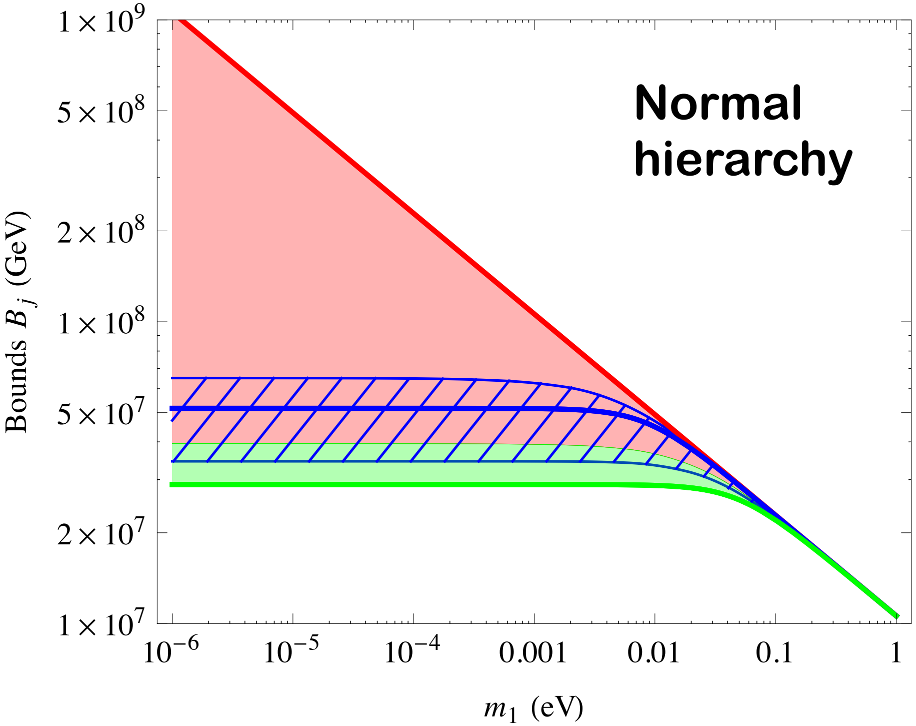
Naturalness criterion:

$$\frac{1}{4\pi^2}\frac{1}{\langle\phi\rangle^2}M_j^3\sum_i m_i|R_{ij}|^2 < 1\ \mathrm{TeV}^2,$$

$$\Rightarrow M_j \lesssim 2.9\times 10^7\ \mathrm{GeV}\left(\frac{0.05\ \mathrm{eV}}{\sum_i m_i|R_{ij}|^2}\right)^{\frac{1}{3}}$$

Vissani

3-flavour effects



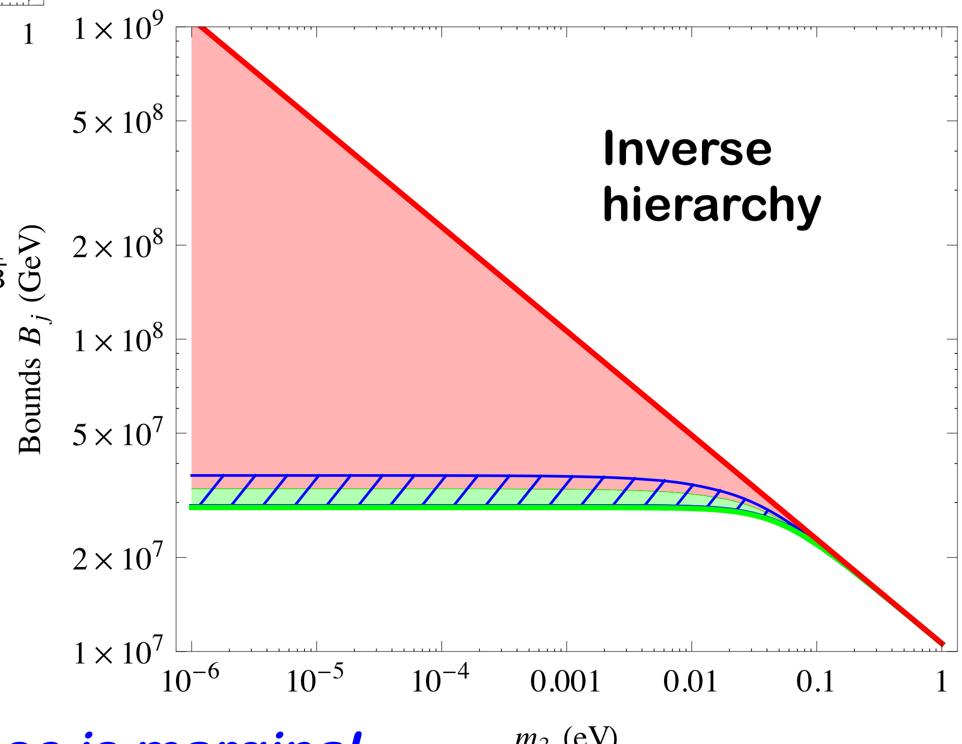
Upper bounds B_j ordered s.t. $B_1 < B_2 < B_3$ (green/blue/red)

Scan over R parameters (real) and absolute nu mass scale

Whether a given B_j applies to N_1, N_2 or N_3 depends on R

$$M_{N_1} \lesssim 4 \times 10^7 \text{ GeV}$$
$$M_{N_2} \lesssim 7 \times 10^7 \text{ GeV}$$
$$M_{N_3} \lesssim 3 \times 10^7 \text{ GeV} \left(\frac{0.05 \text{ eV}}{m_{min}}\right)^{\frac{1}{3}}$$

These are the weakest bounds.
For general R, bounds stronger.

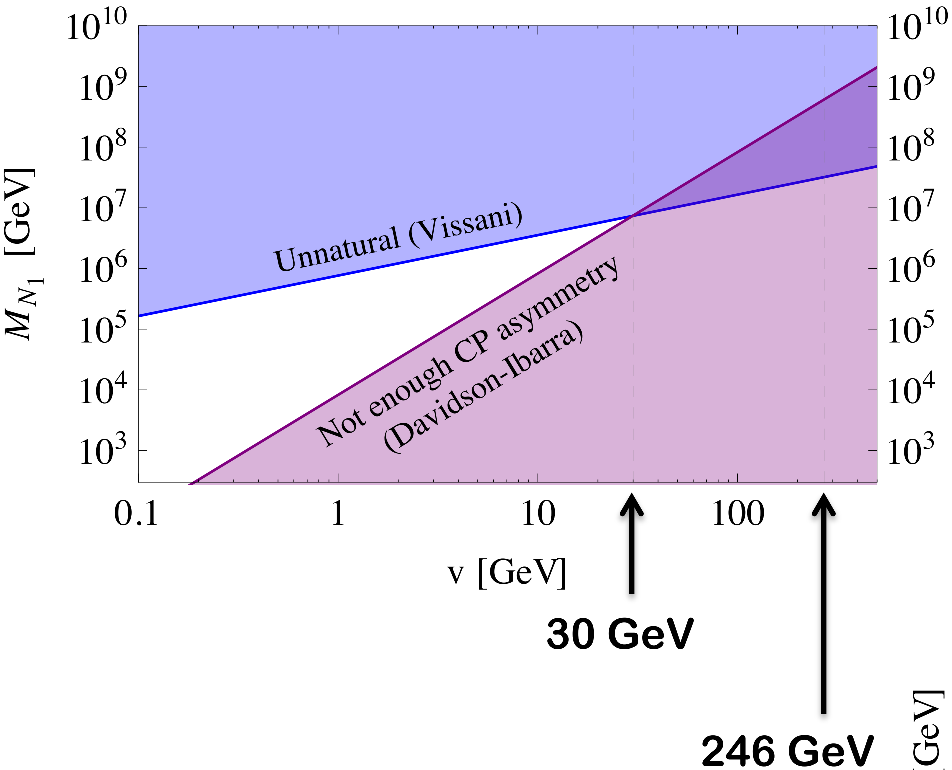


Challenge for all hierarchical, thermal leptogen scenarios.

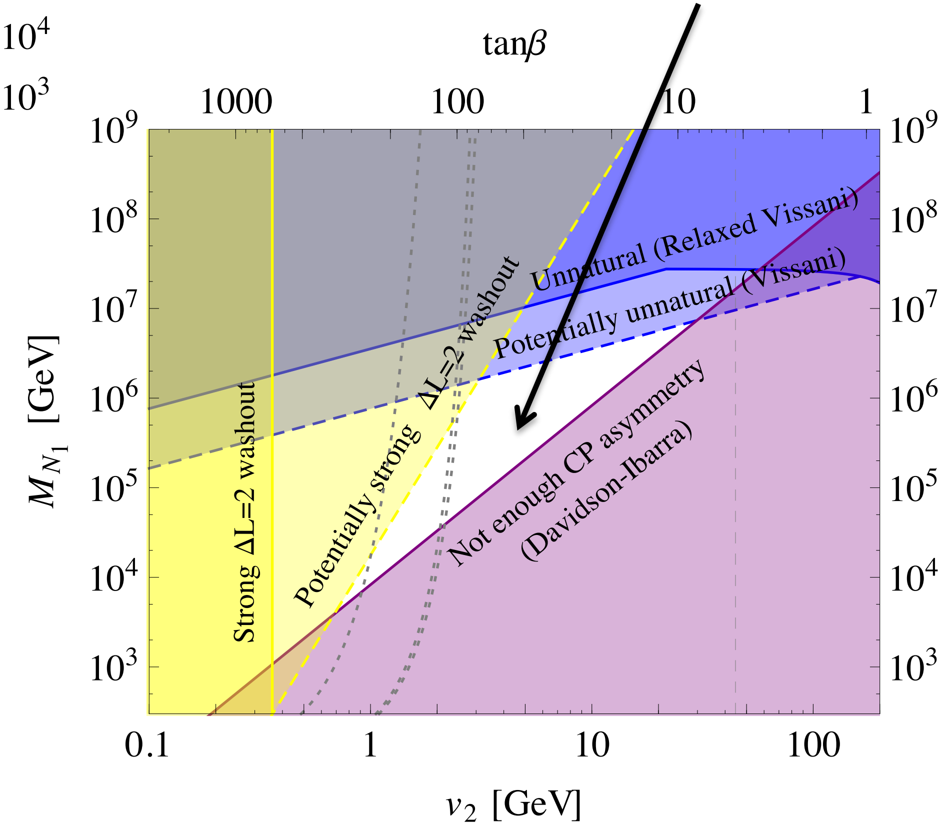
Initial dominant N_1 abundance case is marginal.

One possible minimal modification: 2 Higgs doublets

Clarke, Foot, RV: PRD92 (2015) 033006;
arXiv: 1505.05744



Clearly allowed region



2. Models: opening up d=7 operators

Assumption: SM gauge group and multiplets

Babu & Leung, NPB619, 667 (2001)
de Gouvêa & Jenkins, PRD77, 013008 (2008)
W. Winter et al, recent papers

Classification criteria:

- mass dimension = d
- number of fermion fields = f

Pre-2015 analyses

B=Babu J=Julio L=Leung Z=Zee d=detailed, b=brief

d	f	operator(s)	scale from m_ν (TeV)	model(s)?	comments
7	4	$O_2 = LLLe^cH$	10^7	Z (1980,d)	pure-leptonic,1-loop, ruled out
		$O_3 = LLQd^cH(2)$	$10^{5,8}$	BJ (2012,d) BL (2001,b)	2012 = 2-loop 2001 = 1-loop
		$O_4 = LL\bar{Q}\bar{u}^cH(2)$	$10^{7,9}$	BL (2001,b)	1-loop vector leptoquarks
		$O_8 = L\bar{e}^c\bar{u}^cd^cH$	10^4	BJ (2010,d)	2-loop
9	4	$O_5 = LLQd^cHH\bar{H}$	10^6	BL (2001,b)	1-loop
		$O_6 = LL\bar{Q}\bar{u}^cHH\bar{H}$	10^7		
		$O_7 = LQ\bar{e}^c\bar{Q}HHH$	10^2		
		$O_{61} = (LLHH)(Le^c\bar{H})$	10^5		purely leptonic
		$O_{66} = (LLHH)(Qd^c\bar{H})$	10^6		
		$O_{71} = (LLHH)(Qu^cH)$	10^7	BL (2001,b)	1-loop

A=Angel et al   dGJ=deGouvêa+Jenkins

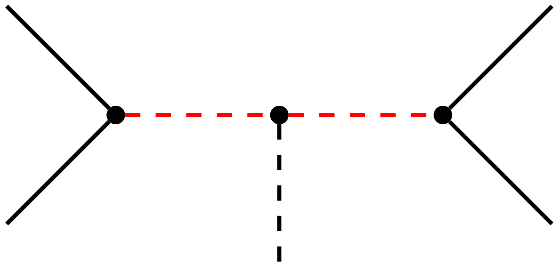
d	f	operator(s)	scale from mν (TeV)	model(s)?	comments
9	6	$O_9 = LLLe^cLe^c$	10^3	BZ (1988,d)	2-loop, purely leptonic
		$O_{10} = LLLe^cQd^c$	10^4	BL (2001,b)	two 2-loop models
		$O_{11} = LLQd^cQd^c(2)$	30, 10^4	BL (2001,b) A (2013,d)	three 2-loop models one 2-loop model
		$O_{12} = LL\bar{Q}\bar{u}^c\bar{Q}\bar{u}^c(2)$	$10^{4,7}$	BL (2001,b)	2-loop
		$O_{13} = LL\bar{Q}\bar{u}^cLe^c$	10^4		
		$O_{14} = LL\bar{Q}\bar{u}^cQd^c(2)$	$10^{3,6}$		
		$O_{15} = LLLd^c\bar{L}\bar{u}^c$	10^3		3-loop
		$O_{16} = LL\bar{e}^cd^c\bar{e}^c\bar{u}^c$	2		3-loop
		$O_{17} = LLd^cd^c\bar{d}^c\bar{u}^c$	2		3-loop
		$O_{18} = LLd^cu^c\bar{u}^c\bar{u}^c$	2		3-loop
		$O_{19} = LQd^cd^c\bar{e}^c\bar{u}^c$	1	dGJ (2008,b)	3-loop
		$O_{20} = Ld^c\bar{Q}\bar{u}^c\bar{e}^c\bar{u}^c$	40		3-loop

In Cai, Clarke, Schmidt, RV JHEP 1502 (2015) 161, arXiv:1410.0689 we constructed all minimal models from d = 7 operators:

$$\mathcal{O}_1' = LL\tilde{H}HHH$$

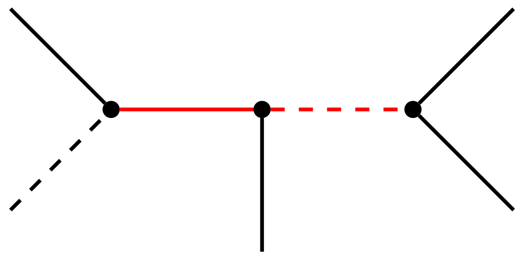
$$\mathcal{O}_2 = LLL\bar{e}H, \quad \mathcal{O}_3 = LLQ\bar{d}H, \quad \mathcal{O}_4 = LLQ^\dagger\bar{u}^\dagger H, \quad \mathcal{O}_8 = L\bar{d}\bar{e}^\dagger\bar{u}^\dagger H$$

Scalar-only extension:



Scalar	Scalar	Operator	
(1,2,1/2)	(1,1,1)	$O_{2,3,4}$	Zee
(3,2,1/6)	(3,1,-1/3)	$O_{3,8}$	Babu, Leung, Julio
(3,2,1/6)	(3,3,-1/3)	O_3	

Scalar + fermion extension:

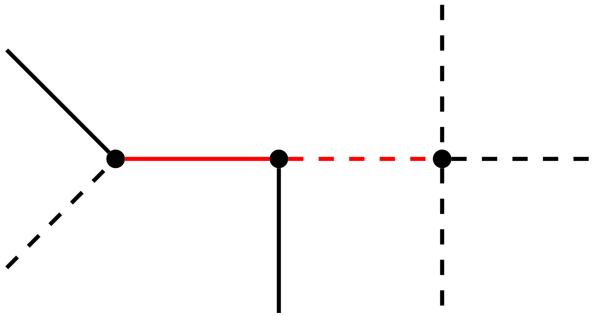


Dirac fermion	Scalar	Operator
(1,2,-3/2)	(1,1,1)	O_2
(3,2,-5/6)	(1,1,1)	O_3
(3,1,2/3)	(1,1,1)	O_3
(3,1,2/3)	(3,2,1/6)	O_3
(3,2,-5/6)	(3,1,-1/3)	$O_{3,8}$
(3,2,-5/6)	(3,3,-1/3)	O_3
(3,3,2/3)	(3,2,1/6)	O_3
(3,2,7/6)	(1,1,1)	O_4
(3,1,-1/3)	(1,1,1)	O_4
(3,2,7/6)	(3,2,1/6)	O_8
(1,2,-1/2)	(3,2,1/6)	O_8

Babu, Julio

Cai, Clarke, Schmidt, RV
- this talk

Scalar + fermion extension:



Dirac fermion	Scalar	Operator
(1,3,-1)	(1,4,3/2)	O'_1

3. LHC: constraints from Run 1 (on a new model)

O_3 = LLQd^{c}H model (subdominant O_8 contribution)

Exotics: $\phi \sim (\bar{3}, 1, 1/3)\,,$ $\chi \sim (3, 2, -5/6)$

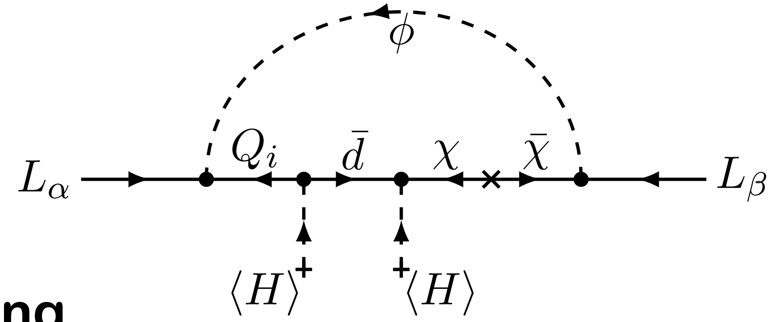
Leptoquark scalar **Vector-like quark**

$$-\mathcal{L} = \mu_\phi^2 \phi^\dagger \phi + m_\chi \bar{\chi}\chi + \left(Y_{ij}^{LQ\phi} L_i Q_j \phi + Y_i^{L\bar{\chi}\phi} L_i \bar{\chi} \phi^\dagger + Y_i^{\bar{d}\chi H} \bar{d}_i \chi H + h.c. \right)$$
$$+ \left(Y_{ij}^{\bar{e}\bar{u}\phi} \bar{e}_i \bar{u}_j \phi^\dagger + h.c. \right)$$

Set to zero for simplicity b/c no role in nu mass gen

Impose B-conservation to forbid proton-decay interactions allowed by the gauge symmetry: $QQ\phi^\dagger$ and $\bar{d}\bar{u}\phi$

Neutrino mass generation:



Prop to down quark masses

- **dominated by b quark**
- **for simplicity, have zero mixing of χ with 1st, 2nd gen quarks**

$$(m_\nu)_{ij} = \frac{3}{16\pi^2}\left(Y_{i3}^{LQ\phi} Y_j^{L\bar{\chi}\phi} + (i \leftrightarrow j)\right) m_{bB} \frac{m_b m_B}{m_\phi^2 - m_B^2} \ln \frac{m_B^2}{m_\phi^2}$$

$$m_{bB} = Y_3^{\bar{d}\chi H} v/\sqrt{2} \qquad (m_b \ll m_B, m_\phi)$$

$$\chi = \begin{pmatrix} B' \\ Y \end{pmatrix}$$

charge -1/3 mixing with b to give B
charge -4/3 massive exotic quark

One almost massless nu, and two massive

$$m_\nu = a_+ a_-^T + a_- a_+^T$$ **outer product of vectors**

$$a_\pm^{\rm NO} = \frac{\zeta^{\pm 1}}{\sqrt{2}} \left(\sqrt{m_2} u_2^* \pm i \sqrt{m_3} u_3^*\right), \qquad a_\pm^{\rm IO} = \frac{\zeta^{\pm 1}}{\sqrt{2}} \left(\sqrt{m_1} u_1^* \pm i \sqrt{m_2} u_2^*\right)$$

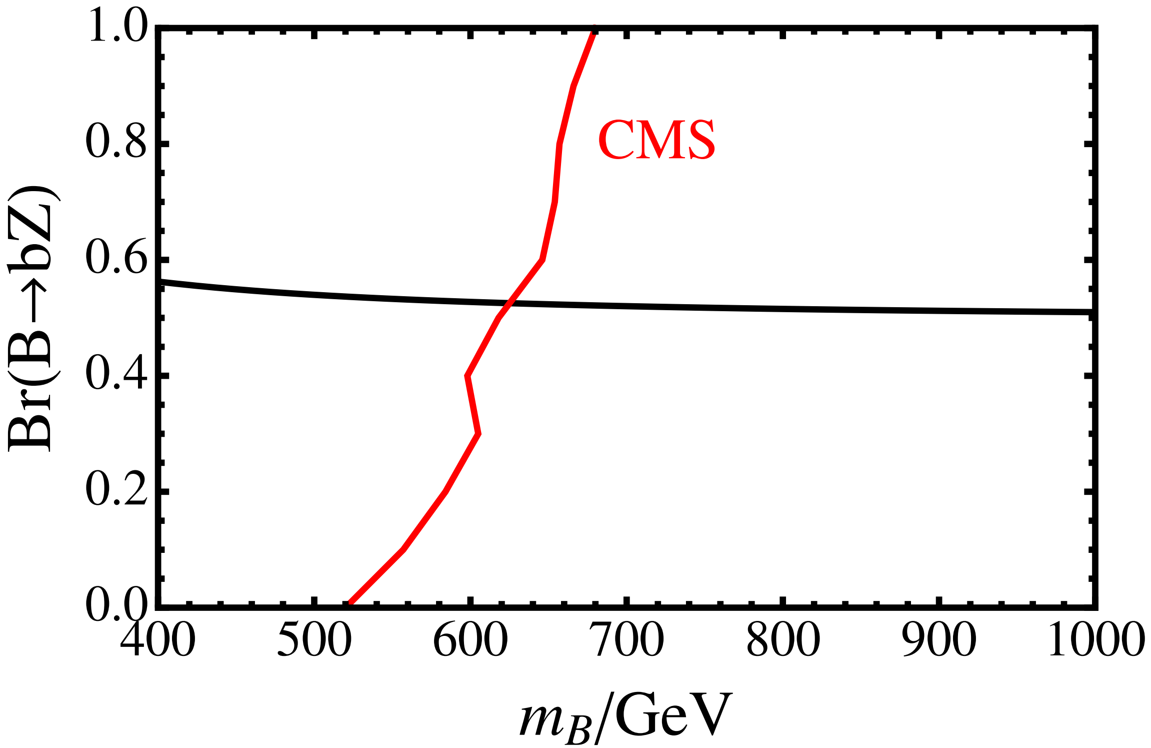
$$U_{\rm PMNS} = (\, u_1 \,,\, u_2 \,,\, u_3 \,)$$

ζ **is a Casas-Ibarra-like, complex parameter not determined by low-energy parameters**

Set lightest nu mass and all PMNS phases to zero.

CMS search for vector-like B quark (no Y search has been done):

$$B \to Zb, \quad B \to Hb \ \text{dominate}$$



$$m_B \geq 620 \ \text{GeV}$$

Leptoquark searches:

Pair production: **gg fusion and q q-bar annihilation.**
Colour charge only, so σ(pp→$\phi\ \phi$) depends on m_ϕ only.
σ(pp→$\phi\ \phi$) = 82 (23.5) fb for m_ϕ = 500 (600) GeV.

Decays: $\phi \longrightarrow Lt, \quad b\nu \qquad\qquad L \equiv (e, \mu, \tau)$

Consider $m_{Y,B}$ >> m_ϕ only, so LY, B υ final states not possible

$$\Gamma(\phi \to Lt) = \frac{m_\phi}{8\pi} \left| Y_{L3}^{LQ\phi} \right|^2 f(m_\phi, m_L, m_t)$$

Also give nu mass

$$\Gamma(\phi \to \nu_L b) \simeq \frac{m_\phi}{8\pi} \left(\left| Y_{L3}^{LQ\phi} c_2 \right|^2 + \left| Y_L^{L\bar{\chi}\phi} s_1 \right|^2 \right) f(m_\phi, m_{\nu_L}, m_b)$$

BRs depend on $|\xi|$. Because of connection to nu mass generation, they are quite constrained.

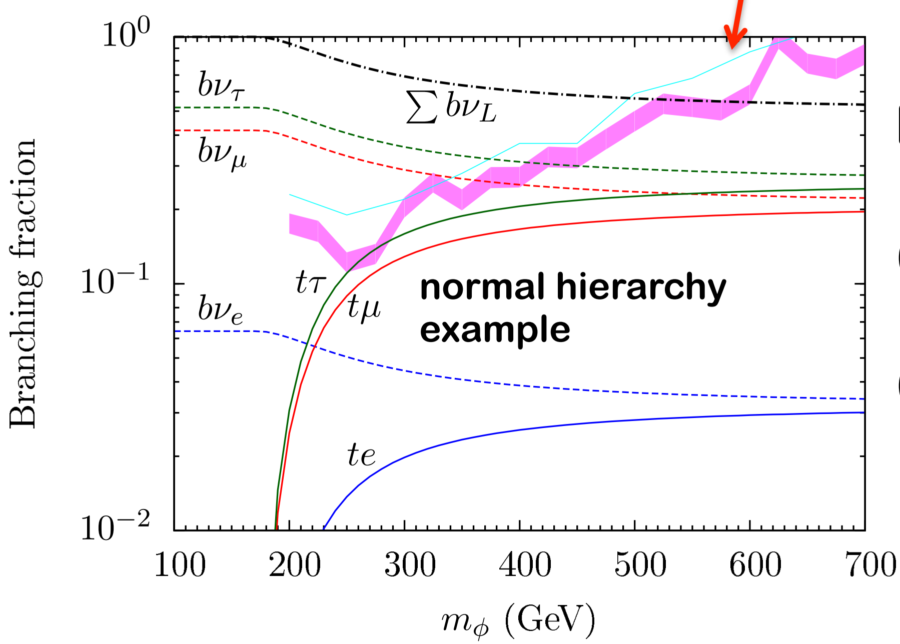
Next slide: region B (Br(ϕ → b υ)≈100%) and region T (Br(ϕ → b υ)<100%)

Region B: $$pp \longrightarrow \phi\phi \longrightarrow bb + \text{missing } E_T$$

sbottom pair searches apply: m_ϕ > 730 GeV at 95% C.L.

Region T:

ATLAS,CMS limits on decays to all b υ final states.



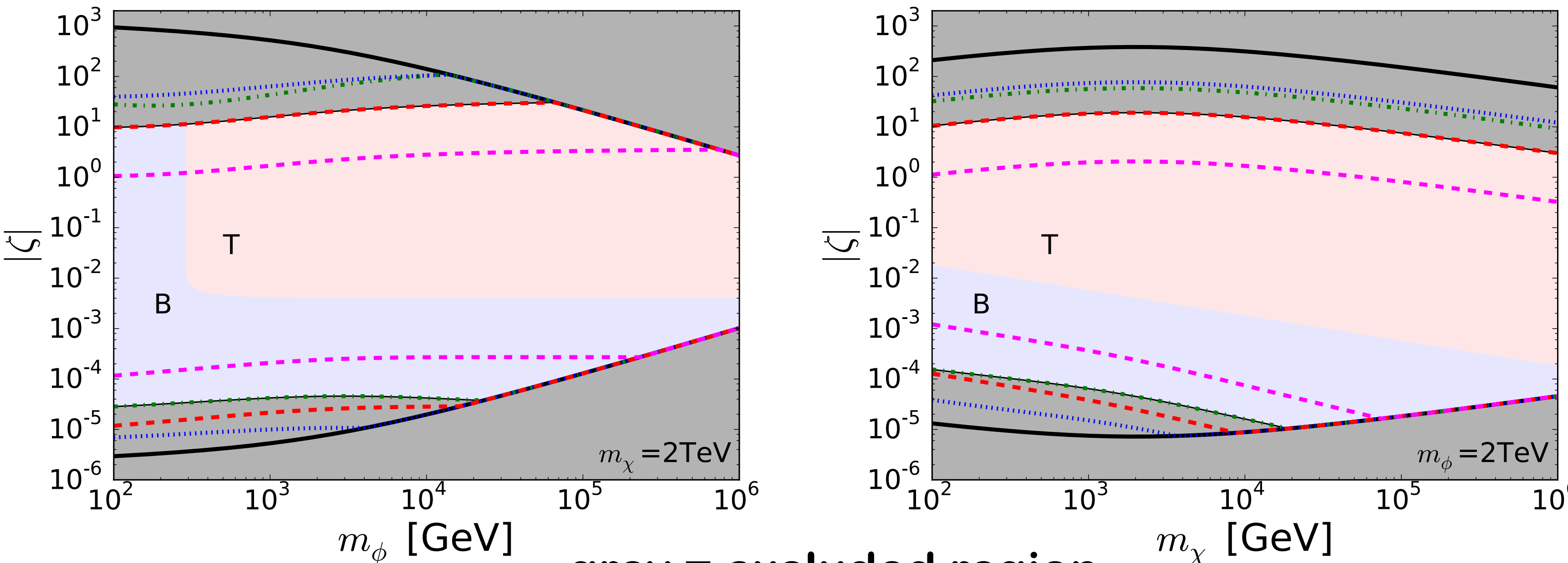
bb + MET: m_ϕ>520-600 GeV

(e, μ) + MET + (b-)jets: m_ϕ>580 GeV

(e, μ)$^+$(e, μ)$^-$ + MET + jets: m_ϕ>600 GeV

4. Flavour: bounds and prospects

Same model, flavour violation constraints: $\mu \to e\gamma, \quad \mu \to eee, \quad \mu N \to eN$



grey = excluded region

Blue (B) allowed region has Br(ϕ →b $\cup$)≈100% **Red (T) allowed region has Br(ϕ →b $\cup$)<100%**

$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

$\mathrm{BR}(\mu \to eee) < 10^{-12}$

$\mathrm{BR}(\mu\mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$

$\mathrm{BR}(\mu\mathrm{Ti} \to e\mathrm{Ti}) \sim 10^{-16}$ **reach of Mu2E, COMET**

Scalar leptoquarks, which abound in radiative nu mass models, are of considerable interest for the following flavour anomalies:

$$R_K \equiv \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)}$$

b → s transition
2.6 σ discrepancy

$$\mathrm{SM}: \;\; 1.0003 \pm 0.0001 \qquad \mathrm{LHCb}: \;\; 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{D^{(*)}} \equiv \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

b → c transition

$$\mathrm{SM}: \;\; R_D \approx 0.30 \pm 0.01, \qquad R_{D^*} = 0.252 \pm 0.003$$

$$\mathrm{BaBar}: \;\; R_D = 0.440 \pm 0.058 \pm 0.042, \qquad R_{D^*} = 0.332 \pm 0.024 \pm 0.018$$

Belle: between BaBar & SM; LHCb R_{D^*} similar to BaBar

For example, the leptoquark used earlier: $\phi \sim (\bar{3}, 1, 1/3)$

has the couplings $d_i \nu_j \phi, \quad u_i \ell_j \phi$

For nu mass, b-quark couplings dominate.

But we can switch on $c\tau\phi$ involving 2nd family.

Needed to fit central value of $R_{D(*)}$ (tree-level process)

Also:

$s\nu_i\phi \quad \mu u_i \phi$

are of relevance to R_K at 1-loop level

See, e.g. Bauer & Neubert, 1511.01900
Bečirević et al, 1608.07583
Deshpande & He, 1608.04817v4

More analysis is needed and underway!

5. Final remarks

1. ΔL=2 effective operators are a useful organising principle for Majorana nu mass models
2. Exotic scalars and fermions are constrained by LHC searches.
3. There is interesting flavour-violation pheno in these models for both leptons and quarks.