From the trees to the forest

the search for the origin of neutrino mass

Michael A. Schmidt

14 September 2017

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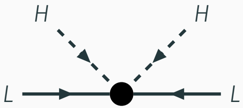
THE UNIVERSITY OF SYDNEY

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Origin of neutrino mass: Neutrino mass generation mechanisms

- Dirac vs. Majorana neutrinos

⇒ Majorana mass generated by Weinberg operator



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

- Effective operator *LHLH* suppressed by $\Lambda \gg \langle H \rangle \simeq 100\mathrm{GeV} \gg m_\nu$
- Can be generated via seesaw mechanisms, minimal UV completions

Minkowski; Yanagida; Glashow;Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic.

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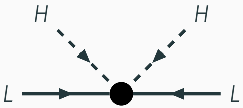

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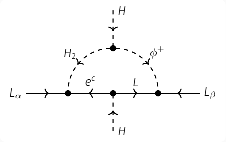
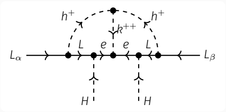
- However not the only possibility to generate neutrino mass



Zee (1980)



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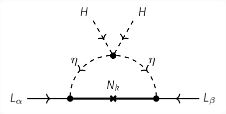

Ma hep-ph/0601225

- among many other possibilities

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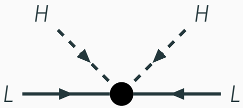

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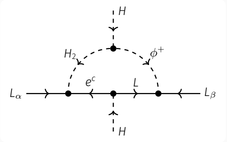

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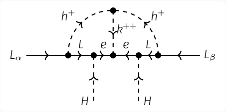

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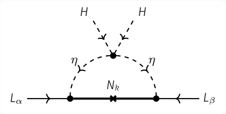

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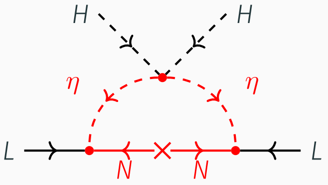
Why should I be interested in anything beyond the seesaw mechanisms?

Connection to other physics: Dark matter (DM)

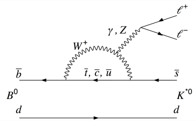


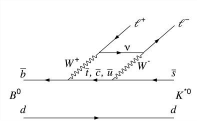
$N \sim (1, 1, 0) \qquad \eta \sim (1, 2, \frac{1}{2})$

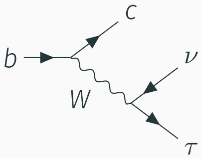
- Scotogenic model Ma hep-ph/0601225
- Discrete symmetry $N \to -N$, $\eta \to -\eta$ to forbid tree-level contribution
- Lightest new particle is a DM candidate
  - Scalar DM:
    very similar to same as inert doublet model Lopez-Honorez, Nezri, Oliver, Tytgat hep-ph/0612275
  - Fermionic WIMP DM:
    close connection with neutrino mass due to bounds from lepton flavour violation recent study: Vicente, Yaguna 1412.2545; Lindner, Platscher, Yaguna, Merle 1608.00577
  - Fermionic FIMP DM:
    one neutrino (almost) massless. Otherwise DM phenomenology mostly decoupled from neutrino physics Molinaro, Yaguna, Zapata 1405.1259

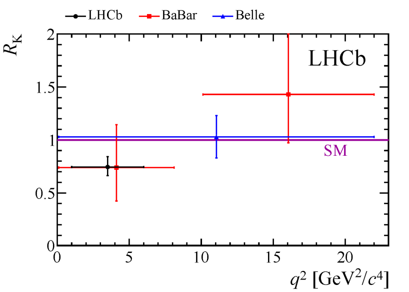
Hints for violations of LFU in $R_{K(*)}$ and $R_{D(*)}$

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









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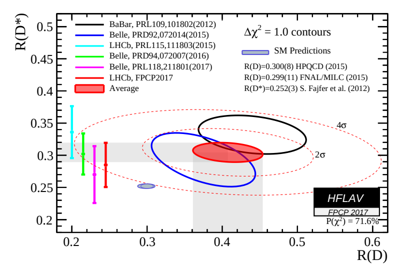

Connection to other physics: B physics anomalies (1)

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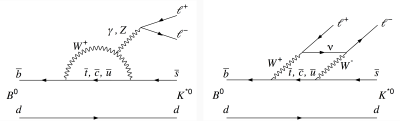

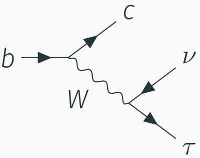

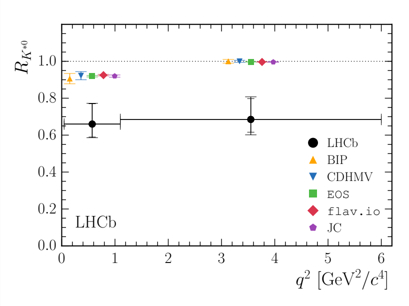

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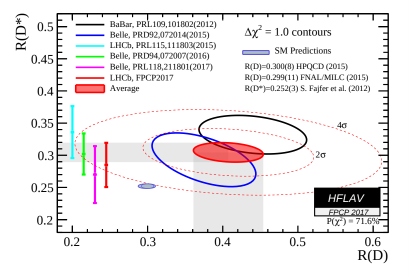
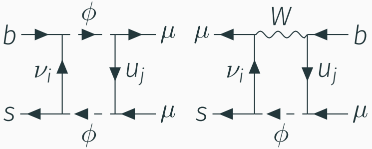
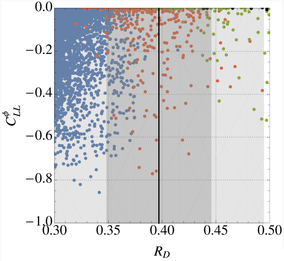


Connection to other physics: B-physics anomalies (2)

One leptoquark [$\phi \sim (3, 1, -1/3)$] 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

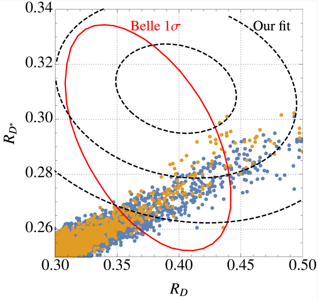


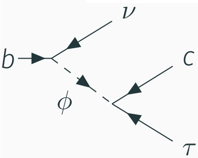


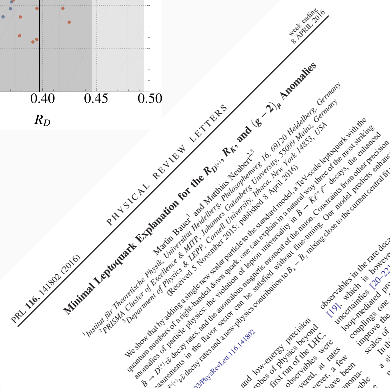
R_{D^*} fit: 1σ, 2σ, 3σ, $> 3\sigma$

Cai, Gargalionis, MS, Volkas 1704.05849

$C_{LL} \sim -1$





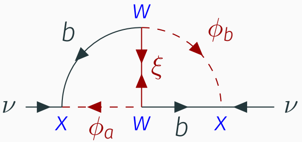


Orange points keep $b \to s$ observables SM-like; Scan II results

Cai, Gargalionis, MS, Volkas 1704.05849

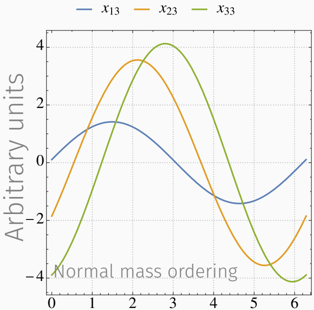
based on dimension-9 operator $\mathcal{O}_{11} = LLQd^cQd^c$ Angel, Cai, Rodd, MS, Volkas 1308.0463

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



$$\mathbf{x} = \begin{pmatrix} 0 & 0 & x_{13} \\ 0 & x_{22} & x_{23} \\ 0 & x_{32} & x_{33} \end{pmatrix}$$

Minimal scenario: only necessary to consider non-negligible w_{3a} (scale factor)



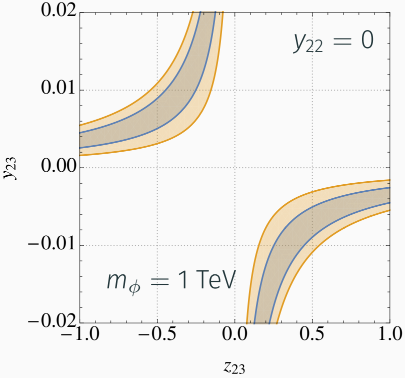
Cai, Gargalionis, MS, Volkas 1704.05849

Important points:

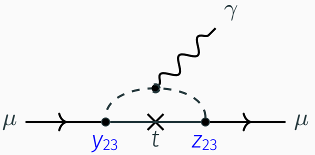
- x_{13} cannot be turned off *ad libitum* $\Rightarrow \mu N \to eN$ serious constraint
- inconsistent with hierarchy $|x_{23}| \gg |x_{33}|$ needed for $R_{K(*)}$ and $\tau \to \mu$ constraints

Connections to other physics

- Anomalous magnetic moment $(g-2)_\mu$
- New scalars can induce strong electroweak phase transition
- New bosons help with stability of electroweak vacuum
- baryogenesis, leptogenesis
- ...



$$\mathcal{L} \supset -z_{ij} e_L^i u_L^j \phi^\dagger + y_{ij} e_R^i u_R^j \phi + \mathrm{h.c.}$$



$$\mathrm{Re}(y_{23} z_{23}) \approx \frac{-0.0039 \frac{m_\phi}{\mathrm{TeV}}}{1 + 1.06 \ln \frac{m_\phi}{\mathrm{TeV}}}$$

1σ and 2σ contours

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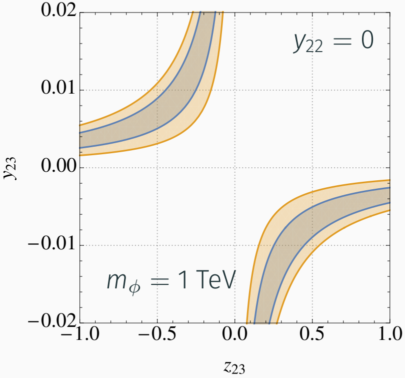

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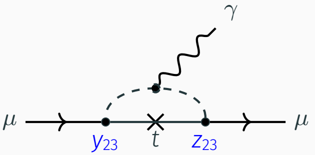

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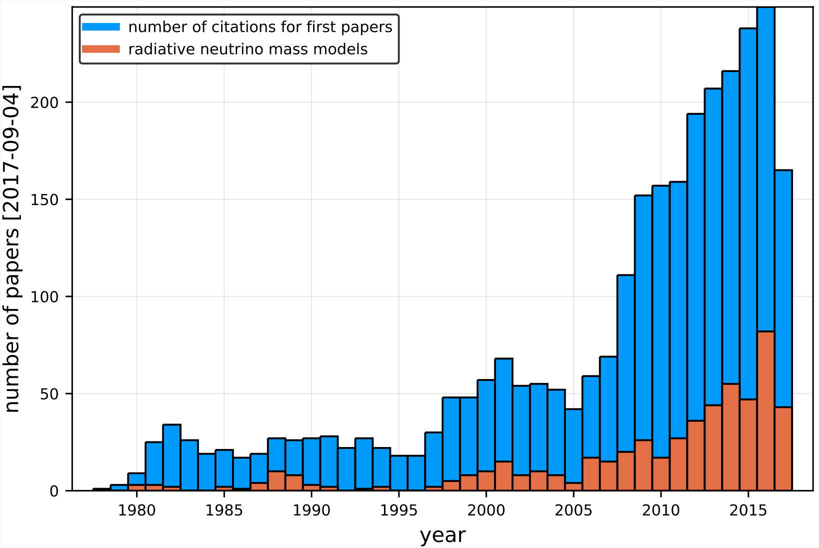
1σ and 2σ contours

Interesting phenomenology testable in current/future experiments

Papers on radiative neutrino mass generation



Radiative neutrino mass at the MPI für Kernphysik

Physics Letters B 680 (2009) 476–479

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Radiative transmission of lepton flavor hierarchies

Adisorn Adulpravitchai [a], Manfred Lindner [a], Alexander Merle [a], Rabindra N. Mohapatra [b,*]

[a] Max-Planck-Inst

[b] Maryland Cente

A R T I C L

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1. Introducti

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PHYSICAL REVIEW D **80,** 055031 (2009)

Confronting flavor symmetries and extended scalar sectors with lepton flavor violation bounds

Adisorn Adulpravitchai,* Manfred Lindner,† and Alexander Merle‡

PHYSICAL REVIEW D **87,** 033006 (2013)

Lepton flavor at the electroweak scale: A complete A_4 model

Martin Holthausen,[1,*] Manfred Lindner,[1,†] and Michael A. Schmidt[2,‡]

PHYSICAL REVIEW D **89,** 013007 (2014)

Dark matter and $U(1)'$ symmetry for the right-handed neutrinos

Manfred Lindner,* Daniel Schmidt,† and Atsushi Watanabe‡

PHYSICAL REVIEW D **94,** 115027 (2016)

Fermionic WIMPs and vacuum stability in the scotogenic model

Manfred Lindner,* Moritz Platscher,† and Carlos E. Yaguna‡

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Alexander Merle§

20 (76) papers from Max-Planck Institut für Kernphysik since 2006

A systematic approach: generalized Weinberg operator

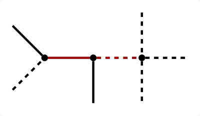
Consider operators of type

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

possibly with multiple Higgs fields

Bonnet, Hernandez, Ota, Winter 0907.3143

dimension-7 operator at tree-level

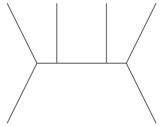


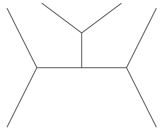
electroweak
triplet fermion
quadruplet scalar

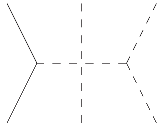
Babu, Nandi, Tavartkiladze 0905.2710

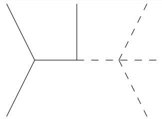
Construct all possible topologies:

- 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.

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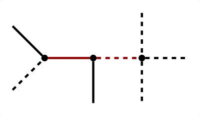

electroweak triplet fermion quadruplet scalar

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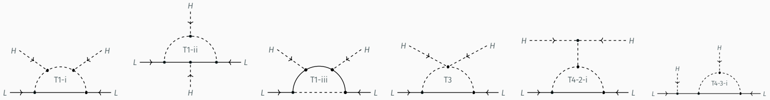

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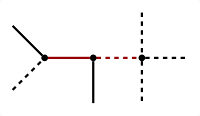

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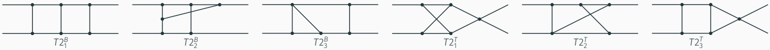

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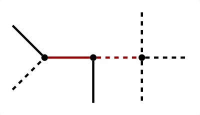

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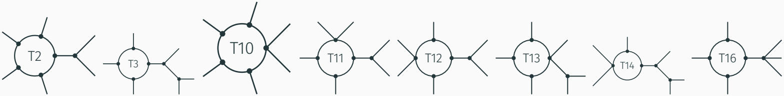

A systematic approach: $\Delta L = 2$ operators

- Black box theorem: Every $\Delta L = 2$ operator 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

- Consider all possible $\Delta L = 2$ operators Babu, Leung hep-ph/0106054; de Gouvea, Jenkins 0708.1344
- UV completions Angel, Rodd, Volkas 1212.6111
- Also describes other $\Delta L = 2$ violating processes: neutrinoless double beta decay, LNV processes at a collider
- Indication of quantum numbers of new particles

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[2]includes hermitean conjugates

- Consider all possible $\Delta L = 2$ operators Babu, Leung hep-ph/0106054; de Gouvea, Jenkins 0708.1344
- UV completions Angel, Rodd, Volkas 1212.6111
- Also describes other $\Delta L = 2$ violating processes: neutrinoless double beta decay, LNV processes at a collider
- Indication of quantum numbers of new particles

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

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

See review for more details …

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]

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juan.herrero-garcia@adelaide.edu.au, avelino.vicente@ific.uv.es,

Minimal UV completions of $\Delta L = 2$ 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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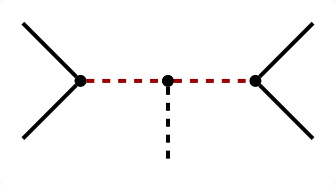

Scalars: leptoquarks, singly charged scalars, EW doublets and quartets

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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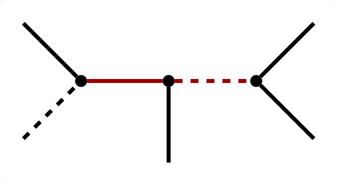

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Dirac fermion	Scalar	Operator
$(1, 2, -\frac{3}{2})$	$(1, 1, 1)$	$\mathcal{O}_2$
$(3, 2, -\frac{5}{6})$	$(1, 1, 1)$	$\mathcal{O}_3$
$(3, 1, \frac{2}{3})$	$(1, 1, 1)$	$\mathcal{O}_3$
$(3, 1, \frac{2}{3})$	$(3, 2, \frac{1}{6})$	$\mathcal{O}_3$
$(3, 2,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

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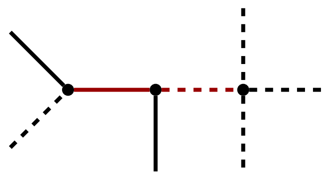

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Fermions: vector-like quarks/charged leptons mixing with third generation

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

New particles at the LHC: (scalar) leptoquarks

Decay channels

$$\phi \to \ell q \qquad \phi \to \nu q$$

Assuming 100% branching ratio

- first generation LQ (e): $m_{LQ} \gtrsim 1130$ GeV CMS-PAS-EXO-16-043
- second generation LQ (μ): $m_{LQ} \gtrsim 1165$ GeV CMS-PAS-EXO-16-007
- third generation LQ (τ): $m_{LQ} \gtrsim 900$ GeV CMS-PAS-EXO-16-023

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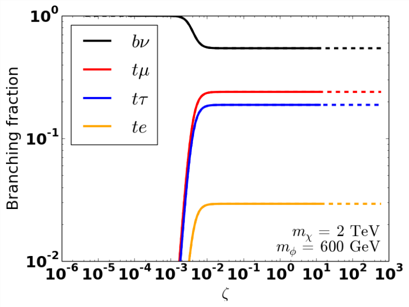

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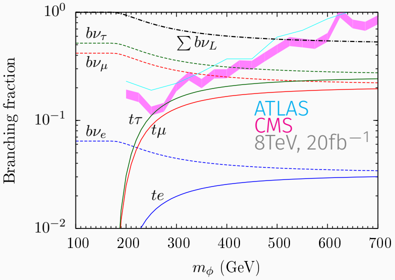

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1-loop model (O_{3b}): ζ controls relative size of Yukawa couplings (like Casas-Ibarra parameter)

New particles at the LHC: vector-like quarks

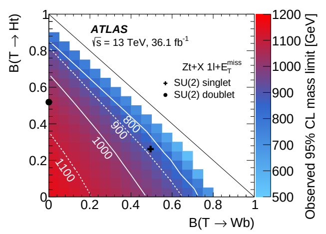
B	T	(BY)	(XT)	(XTB)
$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,-\frac{5}{6})$	$(3,2,\frac{7}{6})$	$(3,3,\frac{2}{3})$

- Searched for at LHC looking using pair production
- Main decay channels to EW gauge bosons and Higgs

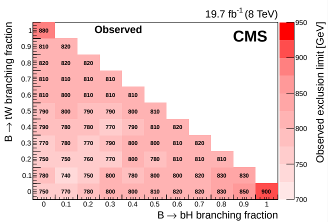
$$B: \quad B \to W^- t, \quad B \to Zb, \quad B \to Hb\,,$$
$$T: \quad T \to W^+ b, \quad T \to Zt, \quad T \to Ht\,,$$

$m_T \gtrsim 0.5 - 1.2$ TeV

$m_B \gtrsim 0.8 - 0.9$ TeV



ATLAS 1705.10751



CMS 1507.07129

ATLAS 1504.04605 1409.5500 1505.04306 1705.10751 1606.03903 1509.04261 ATLAS-CONF-2016-032 CMS 1509.04177 1706.03408 1311.7667 1507.07129

New particles at the LHC: uncolored particles

Vector-like leptons

E	(NE)	(ED)	(NED)
$(1, 1, -1)$	$(1, 2, -\frac{1}{2})$	$(1, 2, -\frac{3}{2})$	$(1, 3, -1)$

currently no dedicated search at LHC

Uncolored scalars

- Charged scalars
  - doubly charged scalar: like-sign dilepton pairs (LNV)
  - singly charged scalar: similar to slepton pair production search
- Higher-dimensional EW multiplets (doublet, quadruplet, ...)
  - Drell-Yan production of charged scalar
  - possibly long lifetime, if small mass splitting
  - disappearing track signature

Conclusions

radiative neutrino mass interesting possibility

current experiments probe theory space

$\Rightarrow$ clear phenomenological signatures required

plethora of models

$\Rightarrow$ systematic approach needed

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Thank you!