Leptoquarks: neutrino masses and collider signals

Diego Aristizabal

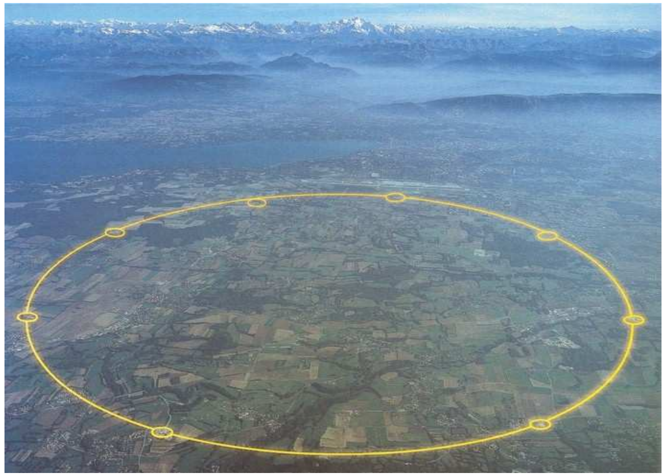
INFN, Laboratori Nazionali di Frascati

Based on: Leptoquarks: neutrino masses and related accelerator phenomenology PRD, 77, 055011 [arXiv:0710.5699]

In collaboration with M. Hirsch and S. G. Kovalenko

Outline

- Motivation:



Neutrino oscillation experiments have well established that neutrinos have non-zero masses. The upcoming operation of LHC will allow to test neutrino mass models that can explain the origin of neutrino masses at the EW scale.

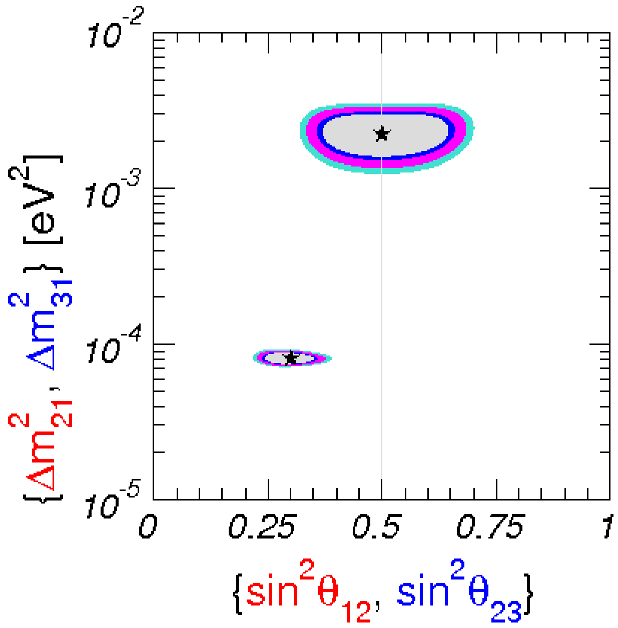
- A model for neutrino masses induced by scalar Leptoquark (LQ) interactions
  - The model
  - Neutrino mass generation
- Scalar LQs accelerator phenomenology
  - Fermionic LQ decays
  - LQ decays to Higgs and gauge bosons final states.
- Conclusions

Experimental and theoretical results

Present status of ν data

Present values of neutrino mixing angles as well as of the solar and the atmospheric mass-squared differences are derived from global fits of current experimental data.

M. Maltoni *et. al*, New J. Phys. **6**, 122 (2004). Updated version V5 (2006)



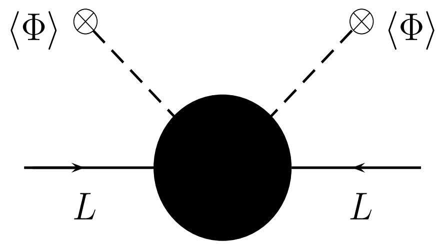
parameter	3σ
$\Delta m^2_{21}\ [10^{-5}]$ eV	7.1–8.9
$\Delta m^2_{31}\ [10^{-3}]$ eV	2.0–3.2
$\sin^2\theta_{12}$	0.24–0.40
$\sin^2\theta_{23}$	0.34–0.68
$\sin^2\theta_{13}$	0.040

Neutrino oscillations experiments have firmly established that neutrinos have non-zero mass and mixing angles among the different generations

Neutrino mass generation

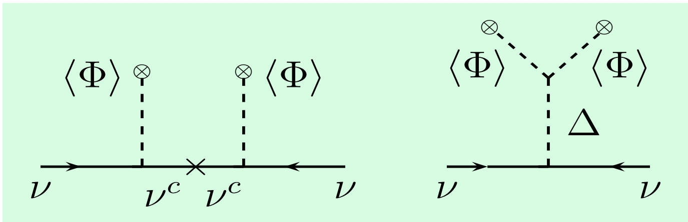
An effective dimension-five operator $L\Phi L\Phi$ can be added to the SM. Once the EW symmetry breaks through the vev of Φ neutrino Majorana masses are induced

S. Weinberg, Phys. Rev. D **22**, 1694 (1980)

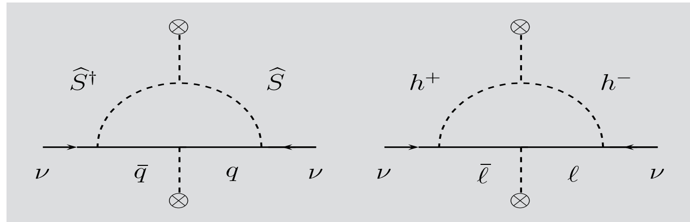


Several realizations of this operator exist

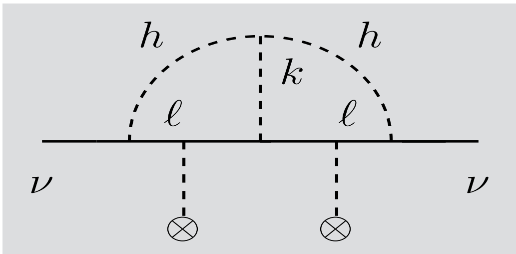
Seesaw mechanism



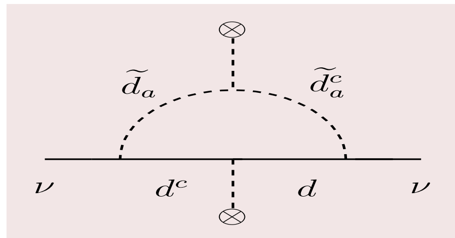
One-loop radiative mechanism



Two-loop radiative mechanism



R-parity violating SUSY



Scalar LQs and neutrino masses

LQ interactions and ν masses

LQ interactions are determined by renormalizability and gauge invariance. The SM symmetries allow five scalar LQs.

LQ	$SU(3)_c$	$SU(2)_L$	Y	Q_{em}
S_0	$\mathbf{3}$	$\mathbf{1}$	-2/3	-1/3
$\widetilde{S}_0$	$\mathbf{3}$	$\mathbf{1}$	-8/3	-4/3
$S_{1/2}$	$\mathbf{3}^*$	$\mathbf{2}$	-7/3	(-2/3,-5/3)
$\widetilde{S}_{1/2}$	$\mathbf{3}^*$	$\mathbf{2}$	-1/3	(1/3,-2/3)
S_1	$\mathbf{3}$	$\mathbf{3}$	-2/3	(2/3,-1/3,-4/3)

Possible fermionic bilinears in the SM are: singlets, doublets or triplets.

$$\mathcal{L}_{LQ-l-q} = \lambda^{(R)}_{S_0}\, \overline{u^c} P_R e\; S_0^{R\dagger} + \lambda^{(R)}_{\tilde{S}_0}\, \overline{d^c} P_R e\; \widetilde{S}_0^{R\dagger} + \lambda^{(R)}_{S_{1/2}}\, \overline{u} P_L l\; S_{1/2}^{R\dagger} + \lambda^{(R)}_{\tilde{S}_{1/2}}\, \overline{d} P_L l\; \tilde{S}^{\dagger}_{1/2}$$
$$+\lambda^{(R)}_{S_{1/2}}\, \overline{u} P_L l\; S^{R\dagger}_{1/2} \quad + \lambda^{(L)}_{S_{1/2}}\, \overline{q} P_R i\tau_2 e\; S^{L\dagger}_{1/2} + \lambda^{(L)}_{S_1}\, \overline{q^c} P_L i\tau_2\; \widehat{S}_1^{\dagger}\; l + \text{h.c.}$$

LQ fields also induce scalar interactions. The most general scalar potential is given

$$V = h^{(i)}_{S_0} H i\tau_2\, \widetilde{S}_{1/2}\, S_0^i + h^{(i)}_{S_1} H i\tau_2\, \widehat{S}_1\, \widetilde{S}_{1/2} + Y^{(i)}_{S_{1/2}} \left(H i\tau_2 S^i_{1/2}\right) \left(\widetilde{S}^{\dagger}_{1/2} H\right) + Y_{S_1} \left(H i\tau_2 \widehat{S}_1^{\dagger} H\right) \widetilde{S}_0$$
$$+\kappa^{(i)}_S \left(H^{\dagger} \widehat{S}_1 H\right) S_0^{i\dagger} - \left(M_\Phi^2 - g_\Phi^{(i_1 i_2)} H^{\dagger} H\right) \Phi^{i_1\dagger} \Phi^{i_2} + \text{h.c.}$$

M. Hirsch, *et. al*, Phys. Lett. B **378**, 17 (1996)

LQ mixing

Lepton number is explicitly broken in the scalar potential by scalar trilinear couplings. Mass matrices for scalar LQs are non-diagonal. This induces a lepton number violating mixing among members from different multiplets.

$$\widehat{S}_Q = R^Q S_Q$$

The rotation matrix R^Q diagonalize the corresponding LQ mass matrix

$$\left(\mathcal{M}_Q^2\right)_{\text{diag}} = R^Q \mathcal{M}_Q^2 (R^Q)^T$$

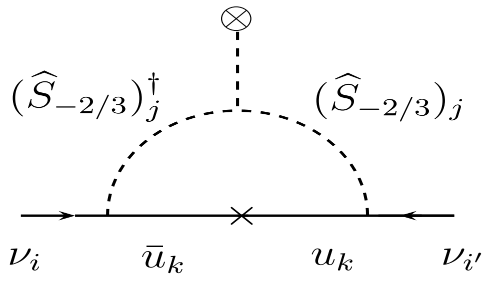
Leptoquark-lepton-quark Yukawa interactions and $Q = 2/3, 1/3$
LQ mixing induce neutrino masses at the one-loop level

U. Mahanta, Phys. Rev. D **62**, 073009 (2000)
D.A.S, M. Hirsch and S. Kovalenko arXiv:0710.5699

Neutrino mass matrices

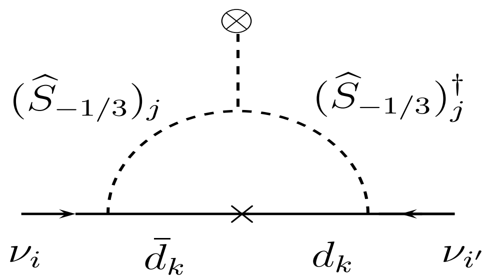
The neutrino mass matrix receives contributions from diagrams which involve u-type as well as d-type quarks.

u-type quark loops



$$(\mathcal{M}_\nu^{\rm up})_{ir} \propto m_k R^{2/3}_{j3} R^{2/3}_{j4} \left[(\lambda^R_{S_{1/2}})_{ik}(\lambda^L_{S_1})_{rk} + (\lambda^R_{S_{1/2}})_{rk}(\lambda^L_{S_1})_{ik}\right]$$

d-type quark loops



$$(\mathcal{M}_\nu^{\rm down})_{ir} \propto m_k R^{1/3}_{j3} \Big\{ R^{1/3}_{j4} \left[(\lambda^R_{\tilde{S}_{1/2}})_{ik}(\lambda^L_{S_1})_{rk} + (\lambda^R_{\tilde{S}_{1/2}})_{rk}(\lambda^L_{S_1})_{ik}\right] + R^{1/3}_{j1} \left[(\lambda^R_{\tilde{S}_{1/2}})_{ik}(\lambda^L_{S_0})_{rk} + (\lambda^R_{\tilde{S}_{1/2}})_{rk}(\lambda^L_{S_0})_{ik}\right] \Big\}$$

Due to the hierarchy $m_{t,b} \gg m_{c,s} \gg m_{u,d}$ in general, both, $\mathcal{M}_\nu^{\rm up}$ and $\mathcal{M}_\nu^{\rm down}$ are dominated by t and b loops

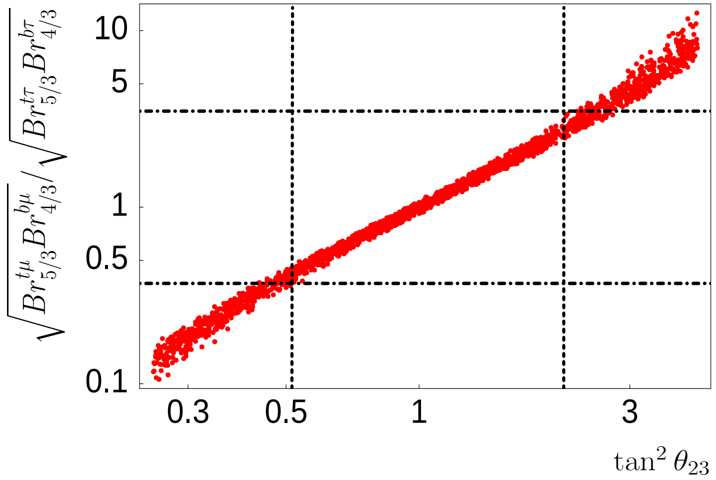
det$(\mathcal{M}_\nu^{t,b}) \simeq 0$

One neutrino remain massless

LQ fermionic decays

Collider signals: numerical results I

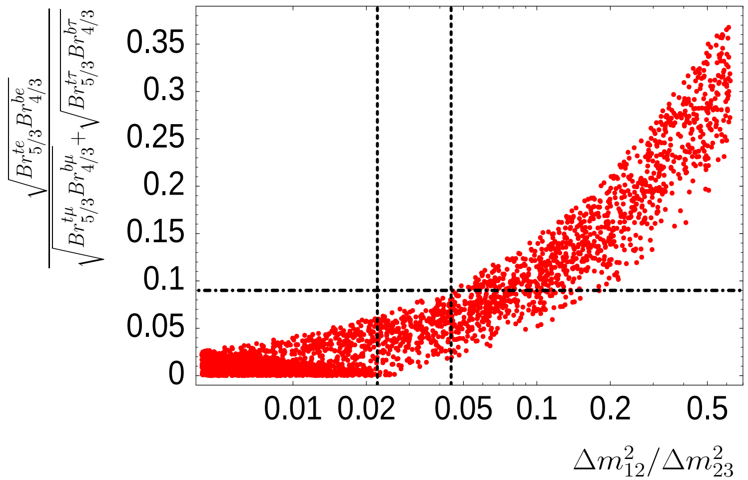
Approximate correlations, based on a numerical study of the model, can be found and can be used to test the model.



Best fit point value $\tan^2\theta_{23} = 1$
$\Rightarrow \; Br^{t\mu}_{5/3}Br^{b\mu}_{4/3} \simeq Br^{t\tau}_{5/3}Br^{b\tau}_{4/3}$

Current 3σ range for the atmospheric mixing angle indicates that this observable must be in [0.4,4.7]

A correlation between the observable $O \equiv \dfrac{\sqrt{Br^{te}_{5/3}Br^{be}_{4/3}}}{\sqrt{Br^{t\mu}_{5/3}Br^{b\mu}_{4/3}}+\sqrt{Br^{t\tau}_{5/3}Br^{b\tau}_{4/3}}}$ and $R = \Delta m^2_{12}/\Delta m^2_{23}$ exist $\Rightarrow$ upper bound on O

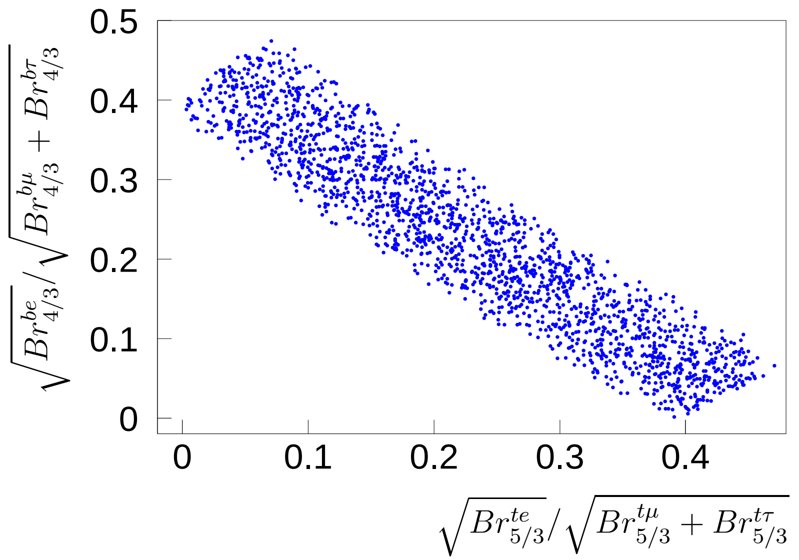


$$\frac{\sqrt{Br^{te}_{5/3}Br^{be}_{4/3}}}{\sqrt{Br^{t\mu}_{5/3}Br^{b\mu}_{4/3}}+\sqrt{Br^{t\tau}_{5/3}Br^{b\tau}_{4/3}}} \lesssim 9\times 10^{-2}$$

Due to the constraints from $\tan^2\theta_{23}$ $Br^{te}_{5/3}Br^{be}_{4/3} \sim$ two orders of magnitude smaller than $Br^{t(\mu\tau)}_{5/3}Br^{b(\mu\tau)}_{4/3}$

Collider signals: numerical results II

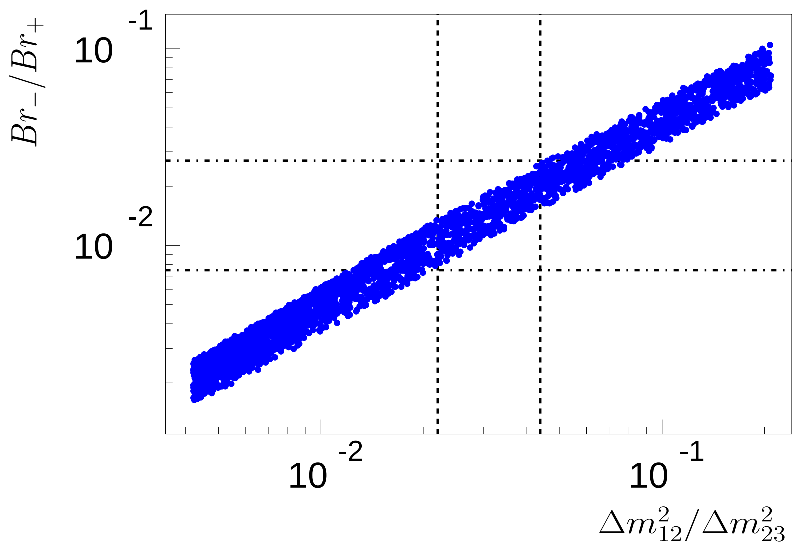
The smallness of $Br^{te}_{5/3}Br^{be}_{4/3}$ is due to the smallness of either $Br^{te}_{5/3}$ or $Br^{be}_{4/3}$



For one of the decaying LQs e^- final states
could be sizeable

$$R = \frac{Br'_-}{Br'_+} \equiv \frac{\sum_{i=e,\mu\tau}\sqrt{Br^{ti}_{5/3}Br^{bi}_{4/3}} - \sqrt{\sum_{i,j=e,\mu\tau} Br^{ti}_{5/3}Br^{bj}_{4/3}}}{\sum_{i=e,\mu\tau}\sqrt{Br^{ti}_{5/3}Br^{bi}_{4/3}} + \sqrt{\sum_{i,j=e,\mu\tau} Br^{ti}_{5/3}Br^{bj}_{4/3}}}$$

Neglecting e^- final states BRs this observable is predicted to lie $[7.5\times10^{-3}$,$2.9\times10^{-2}]$ with an spread of $\sim 25\%$



Higgs and gauge bosons final states

Higgs + LQ final states

Outline

Experimental and theoretical results

Scalar LQs and neutrino masses

LQ fermionic decays

Higgs and gauge bosons final states

Higgs + LQ final states

W + LQ final states

Z + LQ final states

Numerical estimates

Conclusions

The interactions given in the scalar potential are responsible for the processes

$$(\widehat{S}_Q)_j \to h^0 + (\widehat{S}_Q)_i$$

$$r_{ij} \equiv m^2_{S_i}/m^2_{S_j}$$

$$\Gamma[(\widehat{S}_Q)_j \to h^0 + (\widehat{S}_Q)_i] = \frac{1}{16\pi}\widetilde{g}^2_Q\, m_{S_j}\lambda^{1/2}(1, r_{ij}, r_h)$$

$$r_h \equiv m^2_{h^0}/m^2_{S_j}$$

The effective coupling $\widetilde{g}_Q$ involve LQ rotation matrices R^Q as well as the same parameters which induce neutrino masses due to LQ mixing (off-diagonal elements of LQs mass matrices):

$$\widetilde{g}_{-4/3} = \frac{Y_{S_1}}{\sqrt{2}}\frac{v}{m_{S_j}} R^{4/3}_{j1} R^{4/3}_{i2} \qquad \mathcal{M}^2_{-4/3} = \begin{pmatrix} \overline{M}^2_{\tilde{S}_0} & \sqrt{2} Y_{S_1} v^2 \\ \cdot & \overline{M}^2_{S_1} \end{pmatrix}$$

h^0 final states are possible for non-zero LQ mixing

W + LQ final states

These processes are determined by the kinematic terms for the different LQ states.

$W^\pm$ + LQ

These processes $S_Q \to W + S_{Q'}$ involve transitions from members of the same doublet (triplet). These processes exist even in the absence of LQ mixing. Possible decays are:

$$\underbrace{(\widehat{S}_{-5/3})_j \to W^- + (\widehat{S}_{-2/3})_i,}_{Y=-7/3 \text{ doublet}, \; S_{1/2}} \quad \underbrace{(\widehat{S}_{-2/3})_j \to W^- + (\widehat{S}_{-1/3})_i^\dagger,}_{Y=-1/3 \text{ doublet}, \; \widetilde{S}_{1/2}} \quad \underbrace{(\widehat{S}_{-4/3})_j \to W^- + (\widehat{S}_{-1/3})_i}_{\text{Triplet}, \; \widehat{S}_1}$$

$$\Gamma[(\widehat{S}_Q)_j \to W^\pm + (\widehat{S}_{Q'})_i] = \frac{g^2 \theta_Q{}^2}{32\pi} \frac{m^3_{S_j}}{M^2_W} \lambda^{3/2}(1, r_{ij}, r_W) \qquad r_W \equiv M^2_W / m^2_{S_j}$$

The mixing factors θ_Q are determined by the rotation matrices that relate the interaction and mass LQ eigenstate bases.

Higgs + LQ final states kinematically allowed do not necessarily imply W + LQ final states open

Z + LQ final states

For any given set of LQs of charge Q the couplings with the Z^0 can be written as

$$\frac{ig}{\cos\theta_W} Z^\mu \sum_l \left(T_3^l - Q\ \sin^2\theta_W\right) S_Q^l \overleftrightarrow{\partial}_\mu (S_Q^l)^\dagger$$

Non-diagonal couplings of the Z^0 gauge boson to different LQ states of the same Q, but different T_3 appear, after rotation to the mass eigenstate basis.

$$S_{-5/3} = (\underbrace{S_{1/2}^L}_{T_3=-1/2}, \underbrace{S_{1/2}^R}_{T_3=-1/2})$$

$Q = -5/3$ LQs-Z^0 interactions are diagonal

$$S_{-4/3} = (\underbrace{\widetilde{S}_0}_{T_3=0}, \underbrace{S_1}_{T_3=-1})$$

$Q = -4/3$ LQs-Z^0 interactions are non-diagonal

$$\Gamma[(\widehat{S}_Q)_j \to Z^0 + (\widehat{S}_Q)_i] = \frac{1}{16\pi}\frac{g^2}{\cos\theta_W^2}{\theta_Q}^2 \frac{M_{S_j}^3}{M_Z^2}\lambda^{3/2}(1, r_{ij}, r_Z)$$

$$r_Z \equiv M_Z^2/m_{S_j}^2$$

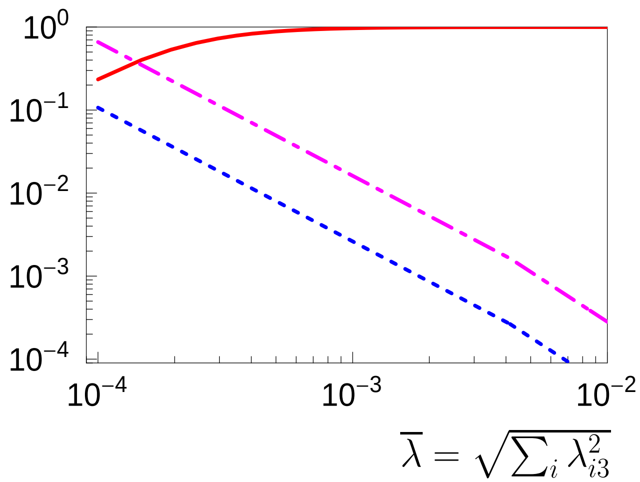
Decays to Z^0 states can occur only if LQ mixing is non-zero

Observation of Z^0 states
will be a prove of LQ mixing

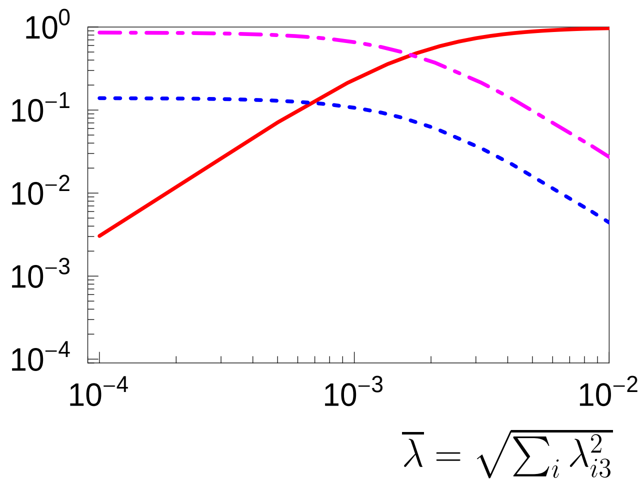
Numerical estimates

For LQs with $Q = 4/3$, assuming the decay to $Q = 1/3$ LQs plus $W^\pm$ is kinematically closed and fixing $m_1^{Q=4/3} = 250$ GeV and $m_{h^0} = 115$ GeV

$Y_{S_1} = 10^{-2}$
$m_2^{Q=4/3} = 400$ GeV



$Y_{S_1} = 10^{-1}$
$m_2^{Q=4/3} = 800$ GeV



For Yukawa couplings $\mathcal{O}(\bar{\lambda}) \sim 10^{-3}$ values of Y_{S_1} as small as $Y_{S_1} \simeq 10^{-2}$ can lead to observable BRs into bosonic final states

Conclusions

Final remarks

- LQ fields with baryon number conserving Yukawa interactions can have masses at or near the electro-weak scale. If these LQ fields couple to the SM Higgs, the resulting model generates neutrino masses at the one-loop level.
- In this work we have explored the phenomenological consequences of LQs as the origin of the observed neutrino masses for future accelerator experiments, such as the LHC.
- Certain ratios of fermionic decay branching ratios can be predicted from current neutrino data. If LQs are pair produced at LHC they are expected to decay with sizeable flavour violation.
- Heavy LQs can also decay to light LQs + h^0(Z^0 or $W^{\pm}$), if kinematically possible. An important test of the hypothesis that LQs can generate Majorana neutrino masses, is the observation of these decays.
- Experiments at the LHC might be able to exclude the LQ mechanism as explanation of neutrino data.