Minimal $B-L$ models

with total L conservation

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Focus on

In collaboration with
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Motivation

Lepton number

- Lepton number (L) is an accidental discret or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violates individual L are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes of total $L = L_e + L_\mu + L_\tau$ violation, like neutrino less doublet beta decay (NLDBD) or its collider equivalent at the LHC for example.
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.

NLDBD prospects for Majorana models with a massless neutrino

with M.Reig, J.W.F Vale, O. Zapata, arXiv:806.09977

Total lepton number conservation

In the near future lepton number conservation could be established.

- If L is a conserved quantum number, it must be related to a gauge symmetry
- Z' must be massive and consequently it must be an spontaneously broken gauge symmetry
- An accidental global symmetry for L is left after symmetry breaking.

What is the minimal model with Lepton number as a gauge symmetry?

$$\text{SM} \times \mathrm{U}(1)_{B-L} \underbrace{\longrightarrow}_{\langle S \rangle} \text{SM + Total Lepton number conservation} \tag{1}$$

where B is the *total baryon number.*

Exotic $B - L$

SM-like $B - L$ model

Field	$\mathrm{U}(1)_{B-L}$
L	-1
H	0
S	s
$(\psi_R)^\dagger_\alpha$	r_α [1]

Massless Majorana fermions ($n = 0, 1$)

$$L\left[(\psi_R)^\dagger_\alpha\,(\psi_R)^\dagger_\beta\,S^n\right] \Longrightarrow r_\alpha + r_\beta + nS \neq 0\,, \qquad \text{example: } r \neq 1\text{, if } s = -2\,.$$

$\mathrm{U}(1)_{B-L}$ with 3+α zero Majorana Masses $\Longleftrightarrow$ SM with 3 zero Majorana masses

For $\alpha \leq 2$: $(\psi_R)^\dagger_\alpha \to (\nu_R)^\dagger_\alpha$ $\qquad r_\alpha \to \nu_\alpha$

[1] Weyl notation with only left-handed fields defined; r_α restricted by anomaly cancellation

(Dirac) Neutrino masses

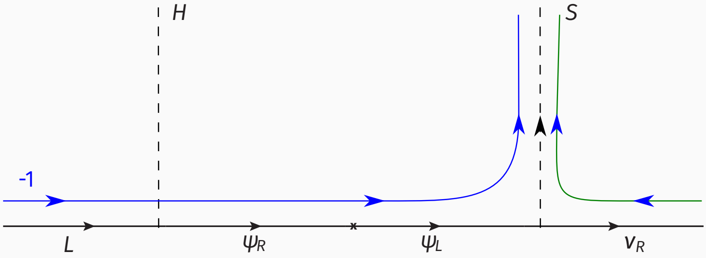
For Dirac neutrino masses: we require to introduce at least one SM-singlet heavy Dirac fermión (Weyl fermion notation)

$$\mathcal{L} = i\,(\psi_L)^\dagger\,\overline{\sigma}^\mu\partial_\mu\psi_L - m\,(\psi_R)^\dagger\,\psi_L + \text{h.c}\,. \tag{2}$$

Field	$\mathrm{U}(1)_{B-L}$
L	-1
H	0
S	s
$(\nu_R)_i^\dagger$	ν_i
$(\psi_R)^\dagger$	r
ψ_L	$-r$

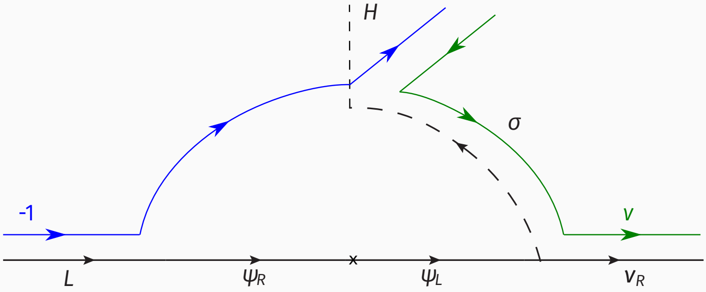
If $(\psi_R)_\alpha^\dagger$ can couple with $(\psi_R)_\beta^\dagger$, then $(\psi_R)_\beta^\dagger \to \psi_{L\alpha}$,

tree-level $r = 1$, $s \neq -2$

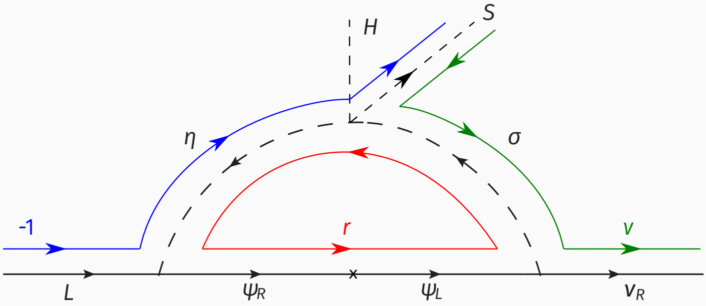


E. Ma, R. Srivastava arXiv:1411.5042 [PLB]

$\nu \neq -1$



Radiative Dirac seesaw

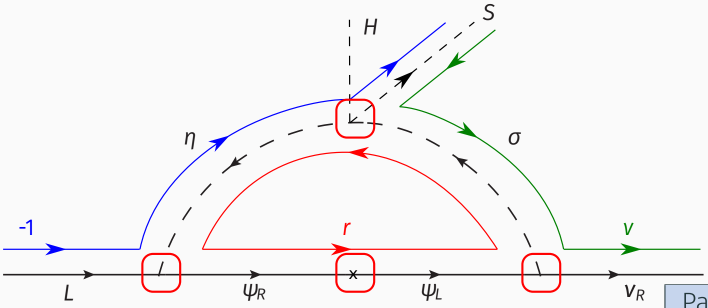


Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^\dagger H \,,$$

where $\kappa = \lambda \langle S \rangle$.

Exotic $(\nu_R)^\dagger$ with $\nu \neq -1$, and vector-like Dirac fermion with $r \neq 1$



$$-1 + \eta = -r$$

$$-r = -r$$

$$-r = -\nu + \sigma$$

$$\sigma = \eta + S$$

$$N_c = 1\,.$$

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$(\psi_R)^\dagger$	r	$(N_c,1)_0$
σ_a	$\nu - r$	$(N_c,1)_0$
η_a	$1 - r$	$(N_c,2)_{1/2}$
S	$\nu - 1$	$(N_c,2)_{1/2}$

Systematic study

Dimension-5 operator

SM+Majorana neutrinos

$$\mathcal{L}_5 = \frac{y_{i\alpha}}{\Lambda}\epsilon_{ab}L_i^a H^b \epsilon_{cd} L_i^c H^d + \text{h.c.}\,,$$

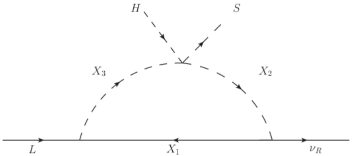
- Tree-level+one-loop+two-loops with DM, three-loops
- Dimension-7, Dimension-5 genuine topologies

Dirac

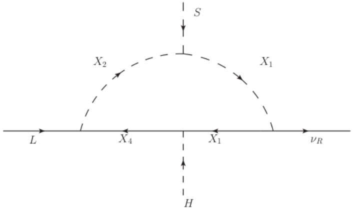
$$\mathcal{L}_5 = \frac{y_{i\alpha}}{\Lambda}\epsilon_{ab}L_i^a H^b \left(\nu_R\right)^\dagger_\alpha S + \text{h.c.}\,,$$

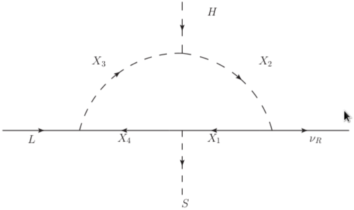
- Three-level+One-loop with DM but extra Z_2 and Z_2' for DM: Y., Chang-Yuan and D. Gui-Jun", arXiv:1802.05231 [PRD]
-

One-loop dimension-5 main Topologies



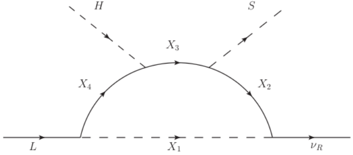
T3-1-A

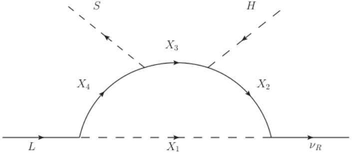




T1-3-D

T1-3-E

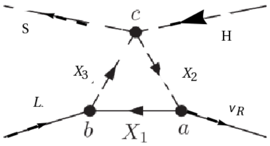




T1-2-A

T1-2-A

T3-1-A




```
In[1]:= sol = Solve[{-ν + X1 == X2, X3 == X1 + l,
      X2 + S == X3 + H}, {X3, X2, S}];
  Print["Y: ", (sol /. {l → -1, ν → 0, H → 1}) /. X1 → α]
  Print["L: ", (sol /. {l → -1, H → 0}) /. X1 → r]
  Print["Full sltn: L: ", (((sol /. {l → -1, H → 0}) /. X1 → r) /. ν → 4) /. {X3 → η, X2 → σ}]
```

Y: $\{\{X_3 \to -1+\alpha,\ X_2 \to \alpha,\ S \to 0\}\}$

L: $\{\{X_3 \to -1+r,\ X_2 \to r-\nu,\ S \to -1+\nu\}\}$

Full sltn: L: $\{\{\eta \to -1+r,\ \sigma \to -4+r,\ S \to 3\}\}$

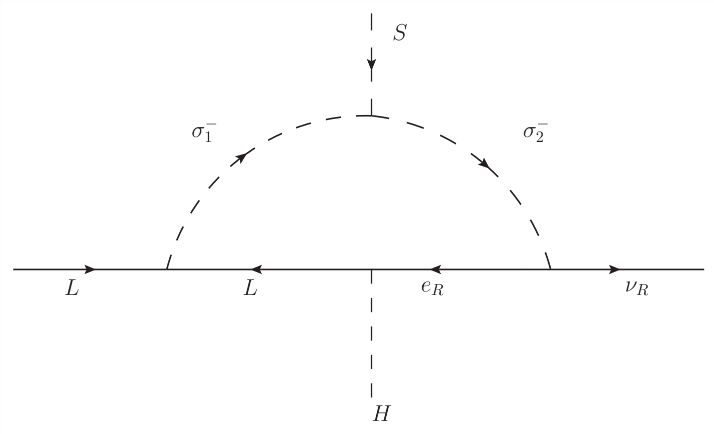
T3-1-A

TABLE V. The finite one-loop diagrams generated from the topology T3. We show the possible quantum numbers of the messenger fields, the predictions for neutrino masses, and the dark matter candidates. The absence of tree level Dirac seesaw excludes certain values of α, where $\varnothing$ and $\mathbb{U}$ denote empty set and universal set respectively. The dark matter Z_2' symmetry can prevent tree level contributions to neutrino masses, such that the excluded α values become admissible and they are underlined.

					Excluded α			
Topology	Solution	X_1^F	X_2^S	X_3^S	Z_2^I	Z_2^{II}	Dark matter	Exotic charges
T3-1-A	I	$\mathbf{1}_\alpha^\mp$	$\mathbf{1}_\alpha^\pm$	$\mathbf{2}_{\alpha-1}^\mp$	$\underline{0, 2}$	$\underline{0}$	$[X_1, X_2, X_3]_0$, $[X_3]_2$	✗
	II	$\mathbf{2}_\alpha^\mp$	$\mathbf{2}_\alpha^\pm$	$\mathbf{1}_{\alpha-1}^\mp$	$\underline{\pm 1}$	$\underline{\pm 1}$	$[X_2]_{-1}$, $[X_2, X_3]_1$	✗
	III	$\mathbf{2}_\alpha^\mp$	$\mathbf{2}_\alpha^\pm$	$\mathbf{3}_{\alpha-1}^\mp$	$\underline{\pm 1}$	$\underline{\pm 1}$	$[X_2, X_3]_{-1}$	✓
							$[X_2, X_3]_1$	✗
	IV	$\mathbf{3}_\alpha^\mp$	$\mathbf{3}_\alpha^\pm$	$\mathbf{2}_{\alpha-1}^\mp$	$\underline{0, 2}$	$\varnothing$	$[X_1, X_2, X_3]_0$	✗
							$[X_2, X_3]_2$	✓

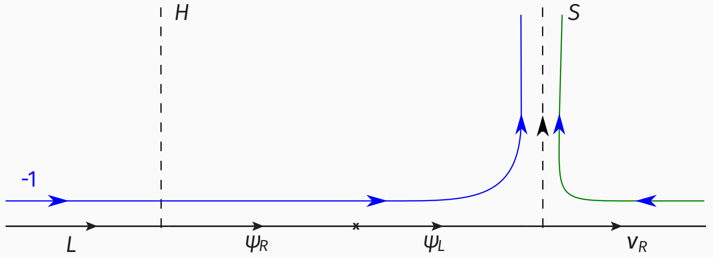
$$(m_\nu)_{\alpha\beta}/(\langle H\rangle\langle S\rangle) = M_{X_1}^{(i)} a_{\alpha i} b_{i\beta} c I_3(M_{X_2}, M_{X_3}, M_{X_1}^{(i)})$$

Zee Dirac



Model	$\overline{\nu_{R_1}}$	$\overline{\nu_{R_2}}$	$\overline{\nu_{R_3}}$	σ_1^-	σ_2^-	S	$\sigma_1'^-$	$\sigma_2'^-$	S'
Dirac Zee	$+4$	$+4$	-5	-2	-5	-3	$\times$	$\times$	$\times$
Dirac Zee	-6	$+\frac{10}{3}$	$+\frac{17}{3}$	-2	$+5$	$+7$	-2	$-\frac{13}{3}$	$-\frac{7}{3}$

tree-level $r = 1$, $s \neq -2$



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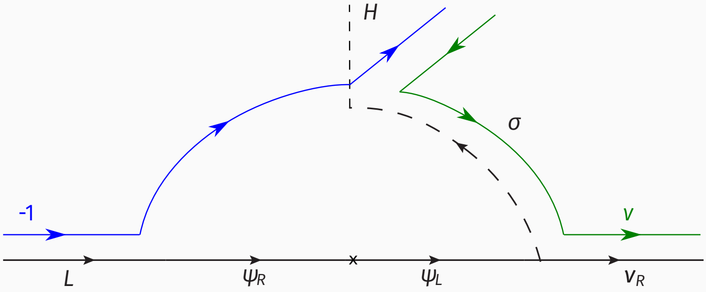

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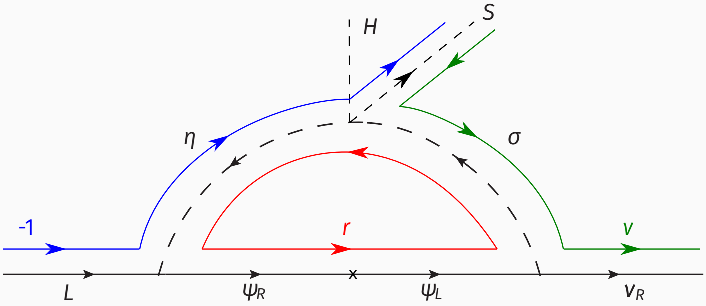

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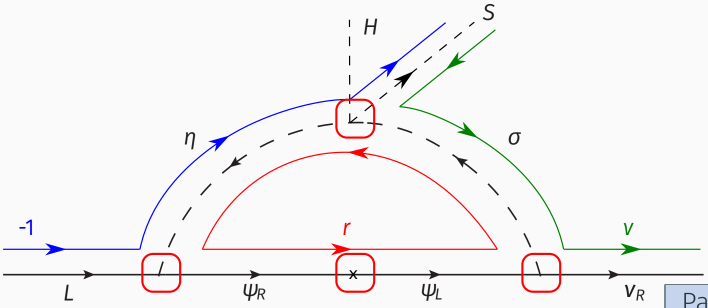

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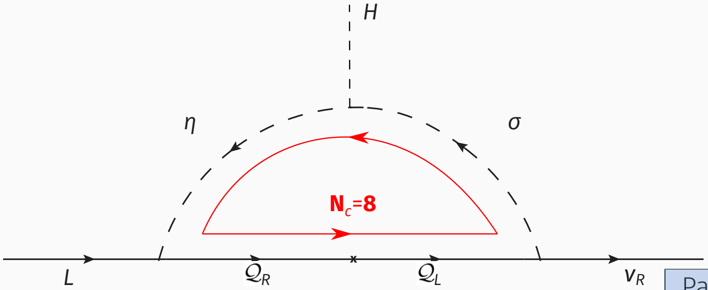
The model: *colored scotogenic*



$$-1 + \eta = - r$$

$$-r = - r$$

$$-r = - \nu + \sigma$$

$$\sigma = \eta + s$$

$$N_c = 8 \, .$$

Soft breaking term induced:

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Particles	$U(1)_{B-L}$	$(SU(3)_c, SU(2)_L)_Y$
L_i	-1	$(1,2)_{-1/2}$
H	0	$(1,2)_{1/2}$
$(\nu_{Ri})^\dagger$	ν	$(1,1)_0$
$\mathcal{Q}_L$	$-r$	$(\mathbf{N}_c,1)_0$
$(\mathcal{Q}_R)^\dagger$	r	$(\mathbf{N}_c,1)_0$
σ_a	$\nu - r$	$(\mathbf{N}_c,1)_0$
η_a	$1 - r$	$(\mathbf{N}_c,2)_{1/2}$

Neutrino masses and mixings

- ν_i are free parameter and could be fixed if we impose $\mathrm{U}(1)_{B-L}$ to be local

$$r \neq 1\,, \qquad \sum_i \nu_i = 3\,, \qquad \sum_i \nu_i^3 = 3$$

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$\mathrm{U}(1)_{B-L}$	$+4$	$+4$	-5
$\mathrm{U}(1)_{B-L}$	-6	$+\frac{10}{3}$	$+\frac{17}{3}$

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- To have at least a rank 2 neutrino mass matrix we need either:
  - At least two heavy Dirac fermions $\mathcal{Q}_a$, $a = 1, 2, \ldots$
  - At least two sets of scalars η_a, σ_a

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-

$$\mathcal{L} \supset \left[M_{\mathcal{Q}} \, (\mathcal{Q}_R)^\dagger \, \mathcal{Q}_L + h_i^a \, (\mathcal{Q}_R)^\dagger \, \widetilde{\eta}_a^\dagger L_i + y_i^a \overline{\nu_{Ri}} \, \sigma_a^* \mathcal{Q}_L + \mathrm{h.c} \right] + \kappa^{ab} \, \sigma_a \eta_b^\dagger H + \ldots$$

Neutrino masses and mixings

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_{\mathcal{Q}}}{64\pi^2} \sum_{a=1}^{2} h_i^a y_j^a \frac{\sqrt{2}\kappa_{aa} v}{m^2_{S^a_{2R}} - m^2_{S^a_{1R}}} \left[F\left(\frac{m^2_{S^a_{2R}}}{M^2_{\mathcal{Q}}}\right) - F\left(\frac{m^2_{S^a_{1R}}}{M^2_{\mathcal{Q}}}\right)\right] + (R \to I) \tag{3}$$

where $F(m^2_{S_\beta}/M^2_Q) = m^2_{S_\beta} \log(m^2_{S_\beta}/M^2_Q)/(m^2_{S_\beta} - M^2_Q)$. The four CP-even mass eigenstates are denoted as $S^1_{1R}, S^1_{2R}, S^2_{1R}, S^2_{2R}$, with a similar notation for the CP-odd ones.

If $(\mu_\eta^{aa})^2 \gg M^2_{\mathcal{Q}}$ one has

$$\begin{aligned}(\mathcal{M}_\nu)_{ij} &= N_c \frac{M_{\mathcal{Q}}}{32\pi^2} \sqrt{2} v \sum_{a=1}^{2} \kappa^{aa} \frac{h_i^a y_j^a}{(\mu_\eta^{aa})^2} \\ &\sim 0.03\,\text{eV} \left(\frac{M_{\mathcal{Q}}}{9.5\,\text{TeV}}\right) \left(\frac{\kappa^{aa}}{1\,\text{GeV}}\right) \left(\frac{50\,\text{TeV}}{\mu_\eta^{aa}}\right)^2 \left(\frac{h_i^a y_j^a}{10^{-6}}\right).\end{aligned} \tag{4}$$

Dark matter

$U(1)_{B\text{-}L} \rightarrow \mathbb{Z}_N$

SM

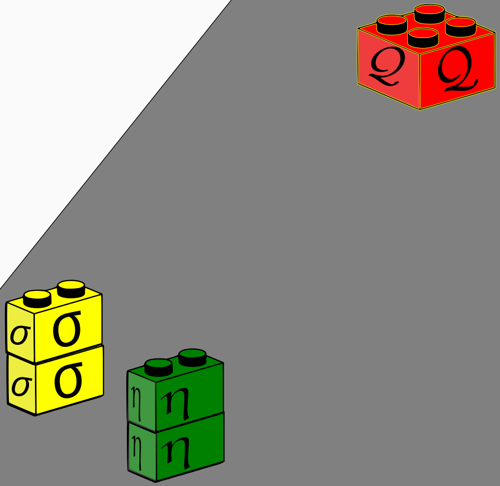
$+\ \nu_R$

if $r \neq 0$ (even with $N_c = 8$)

SM

+

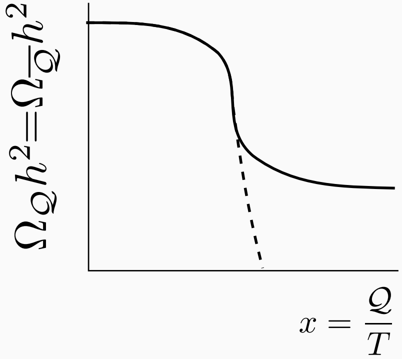
$(\nu_R)_i^\dagger$



(Switch to Dirac fermions)

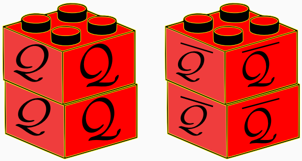
Because $\mathcal{Q}$ is a Dirac fermion, $\mathcal{Q}\mathcal{Q}$ is also stable

$$\mathcal{Q}\mathcal{Q} \not\to g\,, \qquad \overline{\mathcal{Q}\mathcal{Q}} \not\to g\,.$$



Step one

$\mathcal{Q}$-onlyum

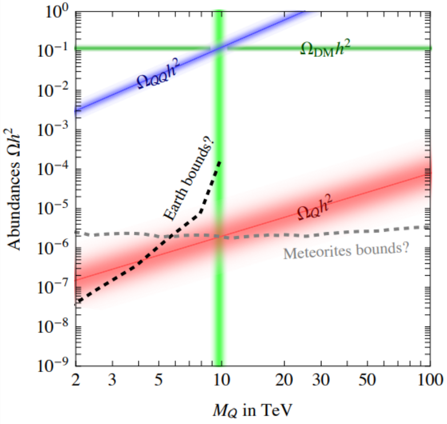


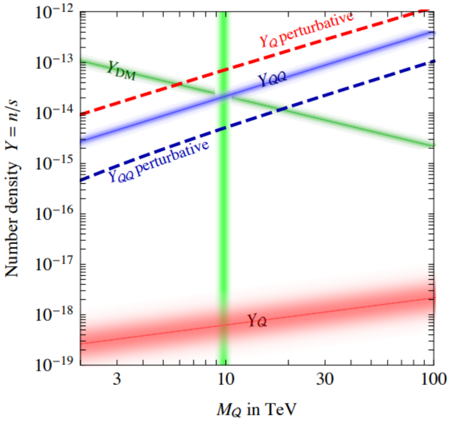
Step two

Relic abundance. From: `http://bit.ly/Mitridate_53d_53rd_Rencontres_de_Moriond`

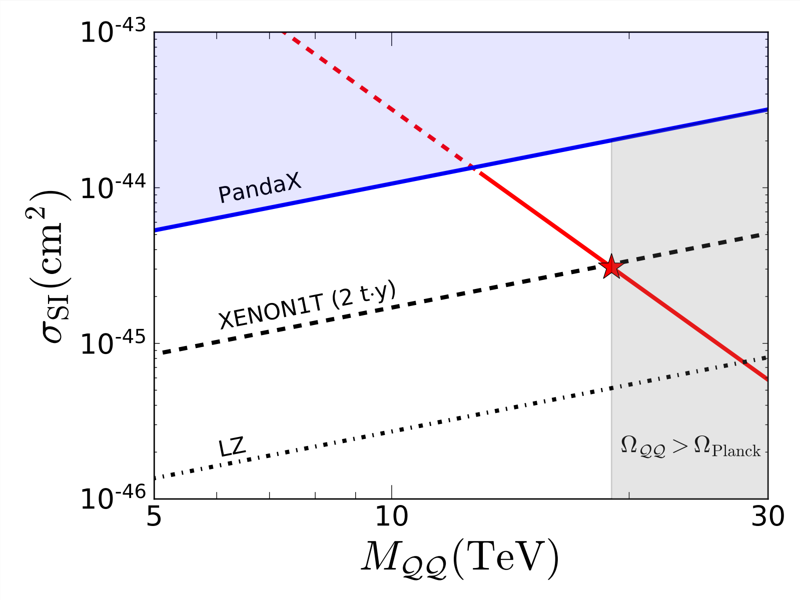
$M_Q \simeq 9.5\,\mathrm{TeV}$

$\Omega_{\rm hyb} \sim 10^{-5}\Omega_{\rm DM}$





Direct detection



The Daily

Sunday, June 30, 2018

Dark matter discovered by

Lorem ipsum dolor sit amet, arcu eget et facilisis ac pede. Quia justo per eros sapien amet feugiat, aliquet in senectus curabitur vivamus, vel consectetuer mi quam scelerisque suspendisse, lorem nostra nunc sapien mauris. Est fusce in faucibus tristique, pretium sagittis turpis rutrum eget, cras mauris, cras enim posuere phasellus risus consectetuer massa. Praesent metus aliquet convallis, etiam dapibus aliquet, eu massa, inceptos sodales dolor, risus ligula in lectus adipiscing non. Ac et justo, libero odio leo diam orci in, ultrices nascetur mauris. Dolor eu.

The New Y

Sunday June 24, 2029

Quonlyum disovered at the

Lorem ipsum dolor sit amet, arcu eget et facilisis ac pede. Quia justo per eros sapien amet feugiat, aliquet in senectus curabitur vivamus, vel consectetuer mi quam scelerisque suspendisse, lorem nostra nunc sapien mauris. Est fusce in faucibus tristique, pretium sagittis turpis rutrum eget,

cras mauris, cras enim posuere phasellus risus consectetuer massa. Praesent metus aliquet convallis, etiam dapibus aliquet, eu massa, inceptos sodales dolor, risus ligula in lectus adipiscing non. Ac et justo, libero odio leo diam orci in, ultrices nascetur mauris. Dolor eu.

Long lived hadrons

$$p + p \longrightarrow \mathcal{Q} + \overline{\mathcal{Q}}$$

$$\Downarrow$$

$$\mathcal{Q} \to \mathcal{Q}g \qquad \mathcal{Q} \to \mathcal{Q}q\bar{q}$$

$\sqrt{s} = 65$ TeV needed to discover $M_{\mathcal{Q}} = 9.5$ TeV .

Conclusions

Standard Model with right-handed neutrinos of exotic $B - L$ charges

Conclusions

Standard Model with right-handed neutrinos of exotic $B-L$ charges

Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac Type-I seesaw.
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- If color is also circulating the loop, the colored dark matter scenario can be realized

DM is made of two color octets with mass around 9.5 TeV

- For standard cosmology:
    - A single point to be discovered in Direct Detection.
    - Crosscheck at future colliders possible.