

Gauged Lepton number

with *dark* matter and *dark* baryogenesis



UNIVERSIDAD DE ANTIOQUIA
1803

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Focus on

...

In collaboration with

Leonardo Leite, Orlando Peres, William Novelo (UNICAMP), David Suárez (UdeA)

Dark sectors







$$F_{\mu\nu} \text{ } V^{\mu\nu}$$

Local $U(1)_{\mathcal{X}}$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \psi_i^\dagger \not{D} \psi_i - h(\psi_1 \psi_2 \Phi + \text{h.c.})$$

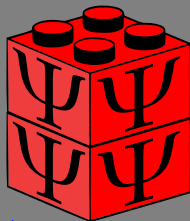
SSB: SM-singlet Dirac fermion

dark matter $m_\Psi = h\langle\Phi\rangle$

LHC production:

Gauged Symmetry: $\mathcal{X} \rightarrow D$:

Gauged Symmetry: $\mathcal{X} \rightarrow X$:



$$\bar{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \rightarrow \psi_\alpha\psi_\beta\Phi^{(*)},$$

$$\alpha = 1, \dots N \rightarrow N > 4$$



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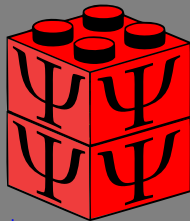
dark matter $m_\Psi = h\langle\Phi\rangle$

LHC production:

Gauged Symmetry: $\mathcal{X} \rightarrow B: q\bar{q} \rightarrow Z' \rightarrow \text{jets}$

Gauged Symmetry: $\mathcal{X} \rightarrow L:$

$$F_{\mu\nu} \quad V^{\mu\nu}$$



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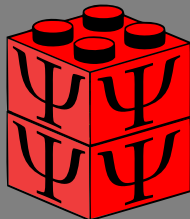
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LHC production:

$$F_{\mu\nu} V^{\mu\nu}$$

Gauged Symmetry: $\mathcal{X} \rightarrow B: q\bar{q} \rightarrow Z' \rightarrow \text{jets}$

Gauged Symmetry: $\mathcal{X} \rightarrow L:$



multi-component
dark matter

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$$\alpha = 1, \dots, N \rightarrow N > 4$$



$$F_{\mu\nu} \mathcal{V}^{\mu\nu}$$

Local $U(1)_{\mathcal{X}}$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \psi_i^\dagger \not{D} \psi_i - y(\psi_1 \psi_2 S + \text{h.c.})$$

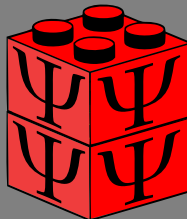
SSB: SM-singlet Dirac fermion

CP violation Yukawa y

LHC production:

Gauged Symmetry: $\mathcal{X} \rightarrow B: q\bar{q} \rightarrow Z' \rightarrow \text{jets}$

Gauged Symmetry: $\mathcal{X} \rightarrow L:$



multi-component
dark matter

$$\bar{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \rightarrow \psi_\alpha\psi_\beta\Phi^{(*)},$$

$$\alpha = 1, \dots, N \rightarrow N > 4$$

Any *universal* local Abelian extension of the Standard Model can be reduced to a set of integers which must satisfy the gravitational anomaly, $[SO(1, 3)]^2 U(1)_Y$, and the cubic anomaly, $[U(1)_X]^3$ conditions:

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (1)$$

- From a list of $N - 2$ integers, e.g., for N even

$$\mathbf{q} = [l_1, l_2, \dots, l_n, k_1, k_2, \dots, k_n], \quad n = (N - 2)/2. \quad (2)$$

in the range $[-m, m]$, build two vector-like solutions of N integers,

$$\mathbf{x} = [l_1, k_1, \dots, k_n, -l_1, -k_1, \dots, -k_n], \quad \mathbf{y} = [0, 0, l_1, \dots, l_n, -l_1, \dots, -l_n] \quad (3)$$

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- Obtain a (some times) non vector-like solution with $z_{\max} = 2m$

$$\mathbf{z} = \mathbf{x} \oplus \mathbf{y} = \left(\sum_{i=1}^N x_i y_i^2 \right) \mathbf{x} + \left(\sum_{i=1}^N x_i^2 y_i \right) \mathbf{y}, \quad (4)$$

- From a list of $N - 2$ integers, e.g., for N even

$$\mathbf{q} = [l_1, l_2, \dots, l_n, k_1, k_2, \dots, k_n], \quad n = (N - 2)/2. \quad (2)$$

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- Obtain a (some times) **non vector-like** solution with $z_{\max} = 2m$

$$\mathbf{z} = \mathbf{x} \oplus \mathbf{y} = \left(\sum_{i=1}^N x_i y_i^2 \right) \mathbf{x} + \left(\sum_{i=1}^N x_i^2 y_i \right) \mathbf{y}, \quad (4)$$

The parameter space to be explored with $z_{\max} = 20$ ($m = 10$) has **96 153 non vector-like** solutions

$$\# \text{ of } \mathbf{q} \text{ lists} = (2m + 1)^{N-2} = \begin{cases} 9261 \rightarrow 3 & N = 5 \\ 194841 \rightarrow 38 & N = 6 \\ \vdots & \vdots \\ 1.6 \times 10^{13} \rightarrow 65910 & N = 12, \quad \text{instead } 10^{19} \end{cases} \quad (5)$$

- From a list of $N - 2$ integers, e.g., for N even

$$\mathbf{q} = [2, 3, -1, -3], \quad n = 6. \quad (2)$$

in the range $[-3, 3]$, build two vector-like solutions of 6 integers,

$$\mathbf{x} = [2, -1, -3, -2, 1, 3], \quad \mathbf{y} = [0, 0, 2, \dots, 3, -2, \dots, -3] \quad (3)$$

- Obtain a (some times) **non vector-like** solution with $z_{\max} = 2 \times 3 = 6$

$$\mathbf{z} = \mathbf{x} \oplus \mathbf{y} = \left(\sum_{i=1}^N x_i y_i^2 \right) \mathbf{x} + \left(\sum_{i=1}^N x_i^2 y_i \right) \mathbf{y}, \quad (4)$$

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restrepo ▾

anomalies 0.2.5

`pip install anomalies`



Latest version

Released: Sep 6, 2022

Anomaly cancellation

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GitHub statistics:

Stars 0

Project description

Anomalies

Python package passing Upload Python Package passing DOI [10.5281/zenodo.5526558](https://doi.org/10.5281/zenodo.5526558)

Implement the anomaly free solution of [arXiv:1905.13729](https://arxiv.org/abs/1905.13729) [PRL]:

Obtain a numpy array \mathbf{z} of N integers which satisfy the Diophantine equations

```
>>> z.sum()  
0  
>>> (z**3).sum()  
0
```

The input is two lists \mathbf{l} and \mathbf{k} with any $(N-3)/2$ and $(N-1)/2$ integers for N odd, or $N/2-1$ and $N/2-1$ for N even ($N \geq 4$). The function is implemented below under the name: `free(l,k)`

September 24, 2021

Dataset

Open Access

Set of N integers between -30 and 30 with sum and cubic sum up to zero for $4 < N < 13$

Diego Restrepo

Anomalies

Solutions obtained with the python package: [anomalies](#) based on the method to find anomaly free solutions of the standard model extended with an Abelian Dark Symmetry with N right-handed singlet chiral fields described in [arXiv:1905.13729](#) [PRL]:

Data scheme

- 'l': integer lists → input to obtain the 'solution' by using the [anomalies](#) package
- 'k': integer lists → input to obtain the 'solution' by using the [anomalies](#) package
- 'solution': list → of integers, z_i which satisfy $\sum_{i=1}^N z_i = 0$ and $\sum_{i=1}^N z_i^3 = 0$.
- 'n': integer → number of integers in 'solution', N .

USAGE

```
#Example of JSON file usage in Python with pandas (see also json module)
>>> import pandas as pd
>>> df=pd.read_json('solutions.json.gz')
>>> df[:2]
   l          k          solution  gcd  n
0  [1, 2]  [0, -3]  [1, 5, -7, -8, 9]    1  5
1  [-2, -1] [0, -1]  [2, 4, -7, -9, 10]    1  5
```

Data:

2 296 615 solutions with $5 \leq N \leq 12$ integers until 'j32' [JSON]

141

views

351

downloads

[See more details...](#)

Indexed in

OpenAIRE

Publication date:

September 24, 2021

DOI:

DOI [10.5281/zenodo.7380817](#)

Keyword(s):

Anomaly free Diophantine equations Abelian symmetry Gauge Symmetry

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Versions

Version v2

Sep 24, 2021

[10.5281/zenodo.7380817](#)

$$\mathcal{L} = i\bar{\psi}_i^\dagger \not{D} \psi_i - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{i < j} h_{ij} \bar{\psi}_i \psi_j \phi^{(*)} + \text{h.c} \quad (6)$$

96 153 \rightarrow 5 196 multi-component DM ($N = 8, 12$) \rightarrow 142 with three Dirac-fermion DM

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96 153 \rightarrow 5 196 **multi-component DM** ($N = 8, 12$) \rightarrow 142 with three Dirac-fermion DM

$$\mathbf{z} = [1, -2, -2, 4, 5, -7, -7, 8] \rightarrow \phi = 9 \rightarrow [(1, 8), (-2, -7), (4, 5)] \quad (7)$$

Minimal secluded model with SM-singlet massive chiral fermions from SSB: $U(1)_D$

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{i < j} h_{ij} \psi_i \psi_j \phi^{(*)} + \text{h.c.} \quad (6)$$

96 153 \rightarrow 5 196 **multi-component DM** ($N = 8, 12$) \rightarrow 142 with three Dirac-fermion DM

$$\mathbf{z} = [1, -2, -2, 4, 5, -7, -7, 8] \rightarrow \phi = 9 \rightarrow [(1, 8), (-2, -7), (4, 5)] \quad (7)$$

$$\mathcal{L} \subset h_{(1,8)} \psi_1 \psi_8 \phi^* \phi^{(*)} + \underbrace{\sum_{a,b=1}^2 h_{(-2a,-7b)} \psi_4 \psi_{-7\phi}}_{\text{multi-flavor DM}} + h_{(4,5)} \psi_4 \psi_5 \phi^* \phi^{(*)} + \text{h.c.} \quad (8)$$

Simplest secluded model with SM-singlet massive chiral fermions from SSB: $U(1)_D$

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \quad (9)$$

96 153 \rightarrow 5 196 **multi-component DM** ($N = 8, 12$) \rightarrow 41 with two Dirac-fermion DM

Simplest secluded model with SM-singlet massive chiral fermions from SSB: $U(1)_D$

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96 153 \rightarrow 5 196 **multi-component DM** ($N=8,12$) \rightarrow 41 with two Dirac-fermion DM

$$\mathbf{z} = [1, 2, 2, 4, -5, -5, -7, 8] \rightarrow \phi = 3 \rightarrow [(1, 2), (2, -5), (-5, 8), (4, -7)] \quad (10)$$

Simplest secluded model with SM-singlet massive chiral fermions from SSB: $U(1)_D$

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \quad (9)$$

96 153 \rightarrow 5 196 **multi-component DM** ($N = 8, 12$) \rightarrow 41 with two Dirac-fermion DM

$$\mathbf{z} = [1, 2, 2, 4, -5, -5, -7, 8] \rightarrow \phi = 3 \rightarrow [(1, 2), (2, -5), (-5, 8), (4, -7)] \quad (10)$$

$$\mathcal{L} \subset \Psi^T \begin{bmatrix} & 1 & 2 & 2 & -5 & -5 & 8 \\ 1 & 0 & h_{(1,2)} & h'_{(1,2)} & 0 & 0 & 0 \\ 2 & h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ 2 & h'_{(1,2)} & 0 & 0 & 0 & 0 & 0 \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h'_{(-5,8)} \\ 8 & 0 & 0 & 0 & h_{(-5,8)} & h'_{(-5,8)} & 0 \end{bmatrix} \Psi \phi^{(*)} + h_{(4,-7)}\psi_4\psi_{-7}\phi^*$$

Standard model extended with $U(1)_{\mathcal{X}=\textcolor{blue}{X} \text{ or } \textcolor{red}{D}}$ gauge symmetry

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=\textcolor{red}{D} \text{ or } \textcolor{blue}{X}}$
Q_i^\dagger	2	$-1/6$	$\textcolor{red}{Q}$
d_{Ri}	1	$-1/2$	$\textcolor{red}{d}$
u_{Ri}	1	$+2/3$	$\textcolor{red}{u}$
L_i^\dagger	2	$+1/2$	$\textcolor{blue}{L}$
e_{Ri}	1	-1	$\textcolor{blue}{e}$
H	2	$1/2$	h
χ_α	1	0	z_α

Φ	1	0	ϕ
--------	----------	-----	--------

Table 1:

$i = 1, 2, 3, \alpha = 1, 2, \dots, N'$

Standard model extended with $U(1)_{\mathcal{X}=L \text{ or } B}$ gauge symmetry

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=B \text{ or } L}$
Q_i^\dagger	2	$-1/6$	Q
d_{Ri}	1	$-1/2$	d
u_{Ri}	1	$+2/3$	u
L_i^\dagger	2	$+1/2$	L
e_{Ri}	1	-1	e
H	2	$1/2$	$h = 0$
χ_α	1	0	z_α
$(L'_L)^\dagger$	2	$1/2$	$-\mathcal{X}'$
L''_R	2	$-1/2$	\mathcal{X}''
e'_R	1	-1	\mathcal{X}'
$(e''_L)^\dagger$	1	1	$-\mathcal{X}''$
Φ	1	0	ϕ
S	1	0	s

Table 1: minimal set of new fermion content: $L = e = 0$ for $\mathcal{X} = B$. Or $Q = u = d = 0$ for $\mathcal{X} = L$.
 $i = 1, 2, 3, \alpha = 1, 2, \dots, N'$

Anomaly cancellation: $\mathcal{X} = L$ or B

The anomaly-cancellation conditions on $[\mathrm{SU}(3)_c]^2 \mathrm{U}(1)_X$, $[\mathrm{SU}(2)_L]^2 \mathrm{U}(1)_X$, $[\mathrm{U}(1)_Y]^2 \mathrm{U}(1)_X$, allow us to express three of the X -charges in terms of the others

$$u = -e - \frac{2}{3}L - \frac{1}{9}(x' - x''), \quad d = e + \frac{4}{3}L - \frac{1}{9}(x' - x''), \quad Q = -\frac{1}{3}L + \frac{1}{9}(x' - x''), \quad (12)$$

while the $[\mathrm{U}(1)_X]^2 \mathrm{U}(1)_Y$ anomaly condition reduces to

$$(e + L)(x' - x'') = 0. \quad (13)$$

- Previously: $x' = x''$
- We choose instead ($h = 0$):

$$e = -L, \quad (14)$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}(x' - x''). \quad (15)$$

If $B = 0 \rightarrow \mathrm{U}(1)_L$

Anomaly cancellation: $\mathcal{X} = L$

The gravitational anomaly, $[\mathrm{SO}(1,3)]^2 \mathrm{U}(1)_Y$, and the cubic anomaly, $[\mathrm{U}(1)_X]^3$, can be written as the following system of Diophantine equations, respectively,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (16)$$

where

$$\begin{aligned} z_1 &= -x', & z_2 &= x'', \\ z_{2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (17)$$

\rightarrow

$$9Q = -\sum_{\alpha=1}^5 z_{\alpha} = -x' + x'' + L + L + L, \quad (18)$$

$L = 0 \rightarrow \mathrm{U}(1)_B$ but $Q = 0 \not\rightarrow \mathrm{U}(1)_L$

$U(1)_L$ selection

- $B = 0$ with $L = 6$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

$U(1)_L$ selection

- $B = 0$ with $L = 6$
- Electroweak-scale vector-like fermions with $\Phi = 18$:
 $(L'_L)^\dagger L''_R \Phi \rightarrow x' = 8, x'' = -10$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

$U(1)_L$ selection

- $B = 0$ with $L = 6$
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- $L + L + L - x' + x'' = 0$

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$$(L'_L)^\dagger L''_R \Phi \rightarrow x' = 8, \quad x'' = -10$$

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- Dirac-fermionic DM:

$$(\chi_L)^\dagger \chi'_R \Phi^* \rightarrow z_3 = 5, \quad z_4 = 13$$

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$U(1)_L$ selection

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- (Two generations) Majorana-fermionic DM:

$$(\chi''_i)^\dagger \chi''_j \Phi \rightarrow z_5 = -9, z_6 = -9$$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

$U(1)_L$ selection

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$$(L'_L)^\dagger L''_R \Phi \rightarrow x' = 8, \quad x'' = -10$$

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$$(\chi_L)^\dagger \chi'_R \Phi^* \rightarrow z_3 = 5, \quad z_4 = 13$$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

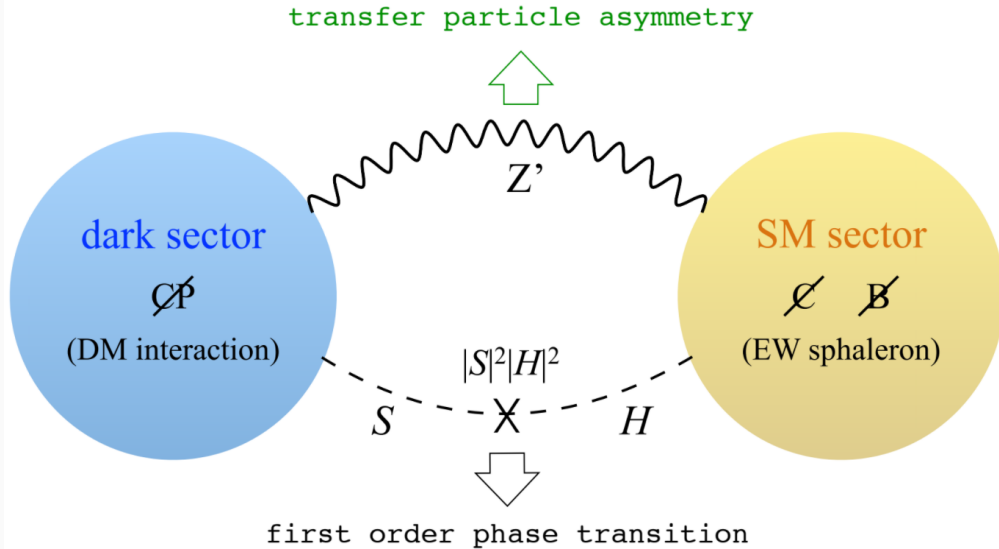
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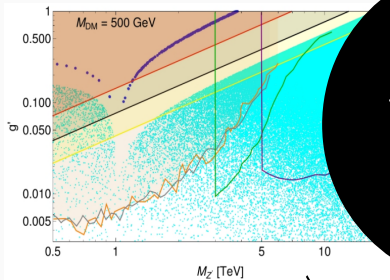
$$(\chi''_i)^\dagger \chi''_j \Phi \rightarrow z_5 = -9, \quad z_6 = -9$$

Only 4 solutions from 96 153

l	k	solution	gcd	n	zmax	hidden
[-2, -3, 0]	[1, 2, 3, 2]	[5, 6, 6, 6, -8, -9, -9, -10, 13]	4	9	13	[{'S': 18, 'psi': [(-9, -9), (-8, -10), (5, 13)]]]
[2, 0, 3]	[-2, 1, -3, -1]	[2, 3, 3, 3, 6, -8, -11, -15, 17]	12	9	17	[{'S': 9, 'psi': [(2, -11), (6, -15), (-8, 17)]]]
[-4, -2, 1]	[2, -4, 4, -2]	[1, -2, 6, 6, 6, -9, -9, -16, 17]	16	9	17	[{'S': 18, 'psi': [(-9, -9), (1, 17), (-2, -16)]]]
[3, -2, -4]	[-2, -1, -2, 3]	[1, 2, 3, -6, -6, -6, 15, 16, -19]	2	9	19	[{'S': 18, 'psi': [(1, -19), (3, 15), (2, 16)]]]

Dark sector baryogenesis





$U(1)_L$ or $U(1)_B$
 Z'
 transfer CP to
 SM

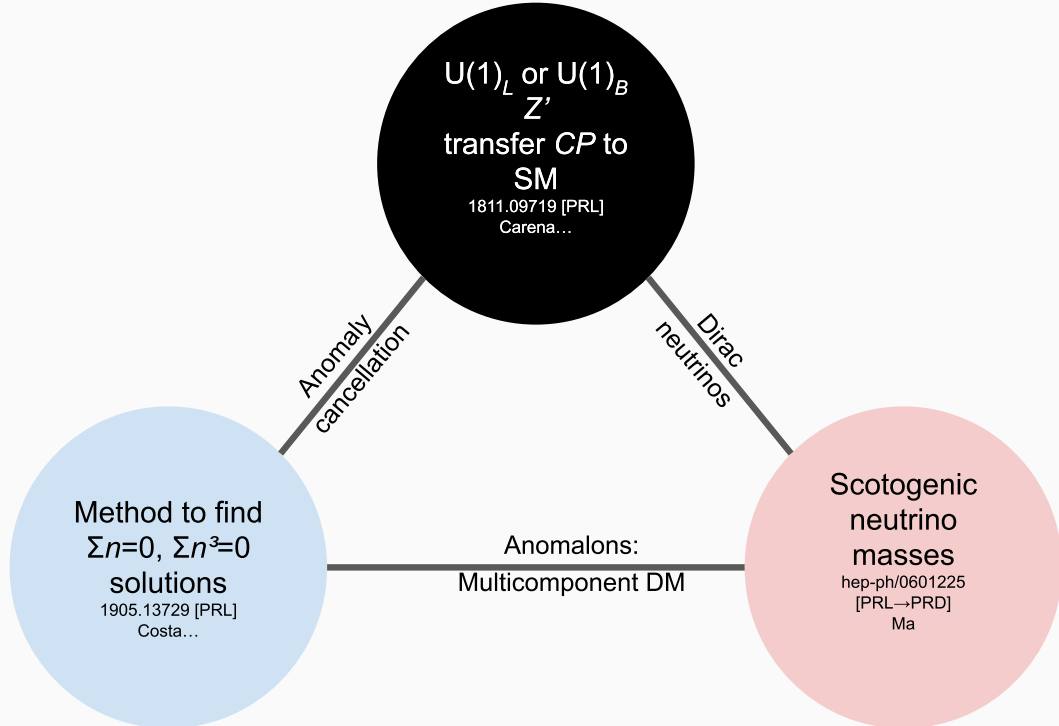
1811.09719 [PRL]
 Carena...

Anomaly
 cancellation

Dirac
 neutrinos

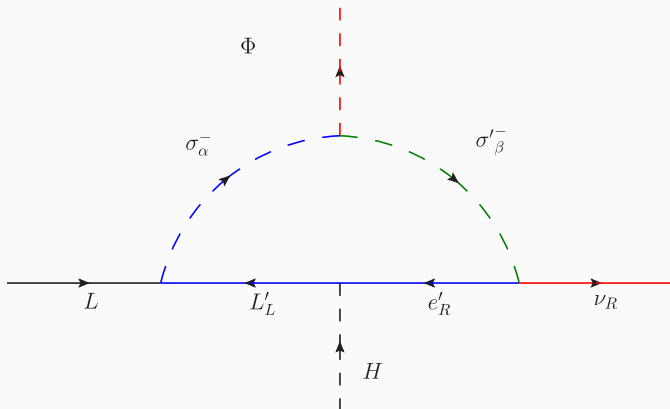
Anomalons:

DM



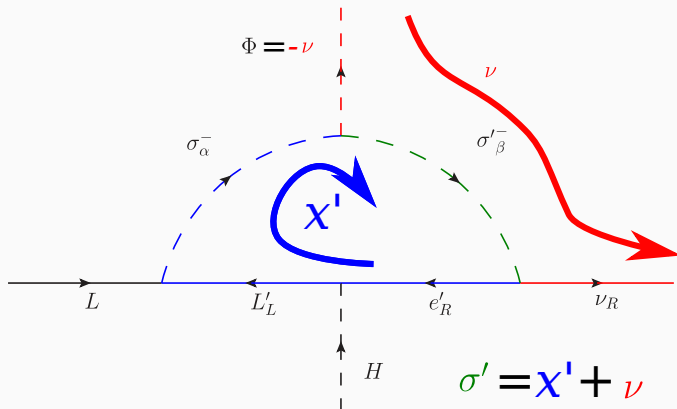
Gauge Baryon number scotogenic realization: arXiv:2205.05762 [PRD]

with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



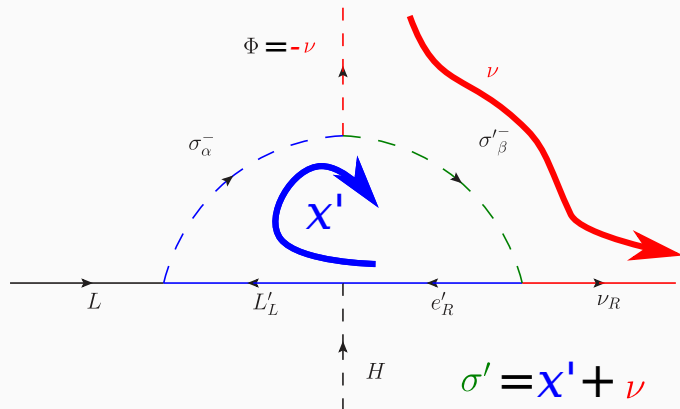
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Gauge Baryon number scotogenic realization: arXiv:2205.05762 [PRD]

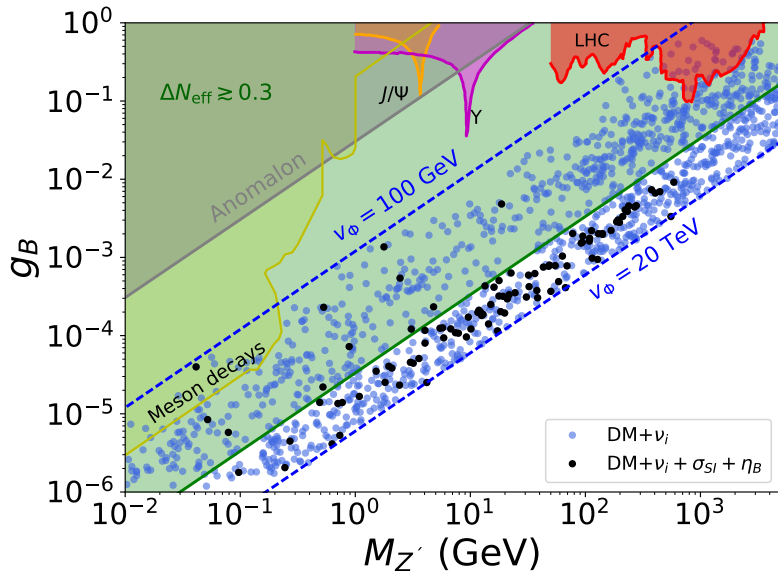
with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	1	2/3	$u = 1/3$
d_{Ri}	1	-1/3	$d = 1/3$
$(Q_i)^\dagger$	2	-1/6	$Q = -1/3$
$(L_i)^\dagger$	2	1/2	$L = 0$
e_R	1	-1	$e = 0$
$(L'_L)^\dagger$	2	1/2	$-x' = -3/5$
e'_R	1	-1	$x' = 3/5$
L''_R	2	-1/2	$x'' = 18/5$
$(e'_L)^\dagger$	1	1	$-x'' = -18/5$
$\nu_{R,1}$	1	0	-3
$\nu_{R,2}$	1	0	-3
χ_R	1	0	6/5
$(\chi_L)^\dagger$	1	0	9/5
H	2	1/2	0
S	1	0	3
Φ	1	0	3
σ_α^-	1	1	3/5
σ'^-_α	1	-1	-12/5

- SARAH→SPheno→MicroMegas
- η_B calculation code
- Python notebook with the scan

Black points: Dirac neutrinos with proper DM and baryon assymetry



A methodology to find all the *universal* Abelian extensions of the standard model is designed

All of the extensions can be reformulated as the solution of

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0,$$

which we fully scan until $N = 12$ and $|z_{\max}| = 20$

Once the physical conditions are established, the full set of self-consistent models are found from a simple data-analysis procedure