Effective Dirac neutrino masses and baryogenesis

with gauged Baryon number

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Focus on
arXiv:¿¿¿¿.?????
In collaboration with
Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

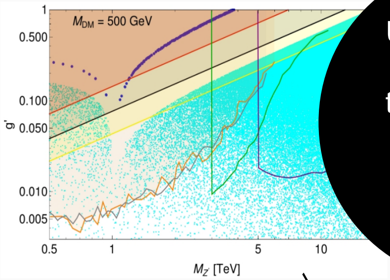
Electroweak baryogenesis

Problems

- Standard model (SM) $m_h \sim 40$ GeV. 😞
- Beyond the SM: Source of CP contains fields charged under SM
  $\rightarrow$ too large electric dipole moments 😩

Dark sectors

- Inert SM-singlet complex scalar field which acquires vev with temperature to have strong electroweak phase transition 😊
- CP violation (CPV) triggered in dark sectors through SM gauge singlets
  $\rightarrow$ CPV Yukawa between SM-singlet complex scalar and SM-singlet quiral fermions 😀



U(1)$_L$ or U(1)$_B$

Z'

transfer *CP* to SM

1811.09719 [PRL]

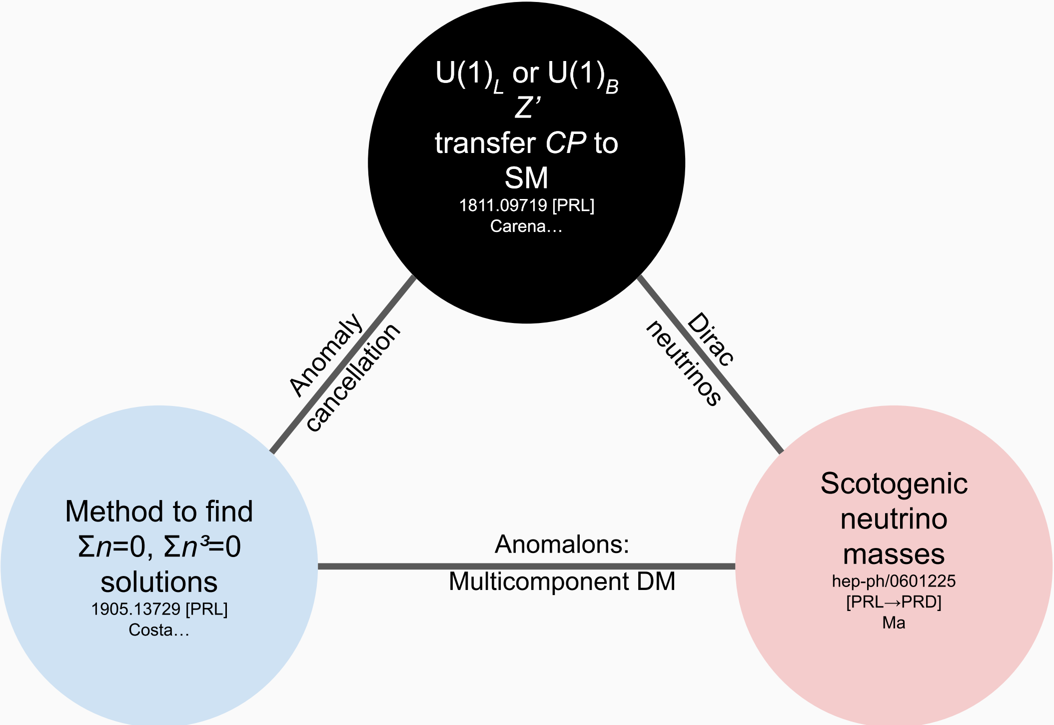
Carena…

Anomaly cancellation

Dirac neutrinos

Anomalons:

DM


U(1)$_L$ or U(1)$_B$
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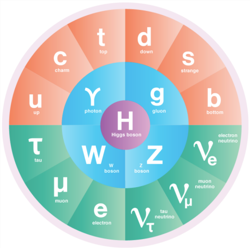
Carena…
Anomaly cancellation
Dirac neutrinos
Method to find Σn=0, Σn^3=0 solutions
1905.13729 [PRL]
Costa…
Anomalons:
Multicomponent DM
Scotogenic neutrino masses
hep-ph/0601225
[PRL→PRD]
Ma

Dark sectors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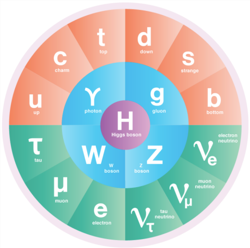
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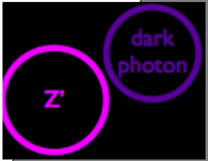
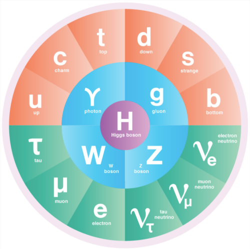

Z'
dark
photon



Local $U(1)\chi$

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\sum_i \chi_i^{\dagger}\not{\mathcal{D}}\chi_i$$

$$-h\left(\chi_1\chi_2\Phi + \text{h.c}\right)$$

Anomalons: SM-singlet Dirac fermion

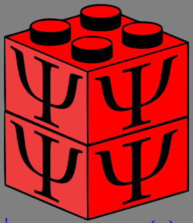
dark matter $m_\Psi = h\langle\Phi\rangle$

LHC production:

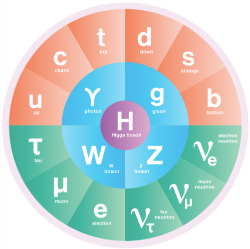
$F_{\mu\nu}$ $V^{\mu\nu}$

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

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



$\overline{\Psi}\Psi = \chi_1\chi_2 + \chi_1^{\dagger}\chi_2^{\dagger} \to \chi_\alpha\chi_\beta\Phi^{(*)}$, $\alpha = 1, \ldots N' \to N' > 4$



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

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^{\dagger} \not{\mathcal{D}} \chi_i$$

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

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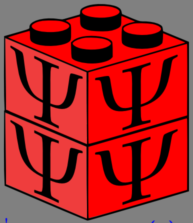

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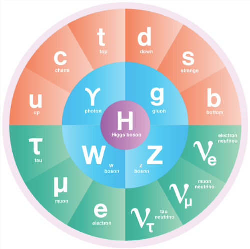

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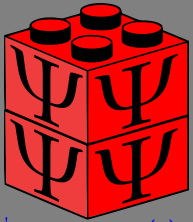

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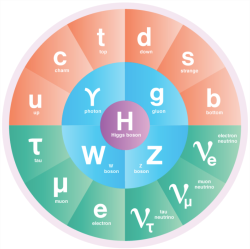


$F_{\mu\nu}$ $V^{\mu\nu}$

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

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i\sum_i \chi_i^\dagger \not{\mathcal{D}} \chi_i$$
$$-y(\chi_1 \chi_2 S + \text{h.c})$$

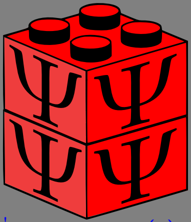
Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

LHC production:

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

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



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Standard model extended with $\mathrm{U}(1)_{\mathcal{X}}$ gauge symmetry

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

Table 1: $L=e=0$ for $\mathcal{X}=B$. Or $Q=u=d=0$ for $\mathcal{X}=L$. $i=1,2,3$, $\alpha=1,2,\ldots,N'$

Effective Dirac neutrino mass operator

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,, \tag{1}$$

$$\mathcal{L}_{\text{eff}} = h_\nu^{\alpha i}\, (\nu_{R\alpha})^\dagger\, \epsilon_{ab}\, L_i^a\, H^b \left(\frac{\Phi^*}{\Lambda}\right)^\delta + \text{H.c.}, \qquad \text{with } i = 1, 2, 3\,,$$

S is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry with D or X-charge

$$\phi = -(\nu + L)/\delta\,, \tag{2}$$

Anomaly cancellation I

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

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

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

$$(e + L)(x' - x'') = 0\,. \tag{4}$$

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

$$e = -L\,, \tag{5}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{6}$$

If $L = 0 \to \mathrm{U}(1)_B$

Anomaly cancellation II

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,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{7}$$

where $N = N' + 5$ and

$$z_{N'+1} = -x'\,, \qquad z_{N'+2} = x''\,,$$
$$z_{N'+2+i} = L\,, \quad i = 1,2,3 \tag{8}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=N'+1}^{N'+5} z_\alpha = -x' + x'' + L + L + L\,, \tag{9}$$

If $Q = 0 \not\rightarrow \mathrm{U}(1)_L$

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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 hte 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')
>>> 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:

390074 solutions with $5 \leq N \leq 12$ integers until `|32|` [JSON]

Publication date:
September 24, 2021

DOI:
DOI 10.5281/zenodo.5526707

Keyword(s):
Anomaly free Diophantine equations Abelian symmetry Gauge Symmetry

Versions

Version 1 Sep 24, 2021
10.5281/zenodo.5526707

$\mathrm{U}(1)_B$ selection

- $L = 0$

$$(5, 5, -3, -2, 1, -6)$$

$\mathrm{U}(1)_B$ selection

- $L = 0$
- Effective neutrino mass $\phi = \nu = -5$

$$(5, 5, -3, -2, 1, -6)$$

$\mathrm{U}(1)_B$ selection

- $L = 0$
- Effective neutrino mass $\phi = \nu = -5$
- $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$

$$(5, 5, -3, -2, 1, -6)$$

$\mathrm{U}(1)_B$ selection

- $L = 0$
- Effective neutrino mass $\phi = \nu = -5$
- $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$
- $(\chi_L)^\dagger \chi''_R \Phi^* \to z_3 = -3,\ z_4 = -2$

959 solutions from $\sim 400,000$

$$(5, 5, -3, -2, 1, -6)$$