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)

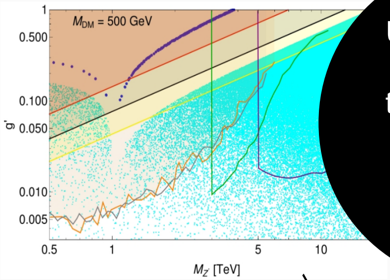
Electroweak baryogenesis

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 😀



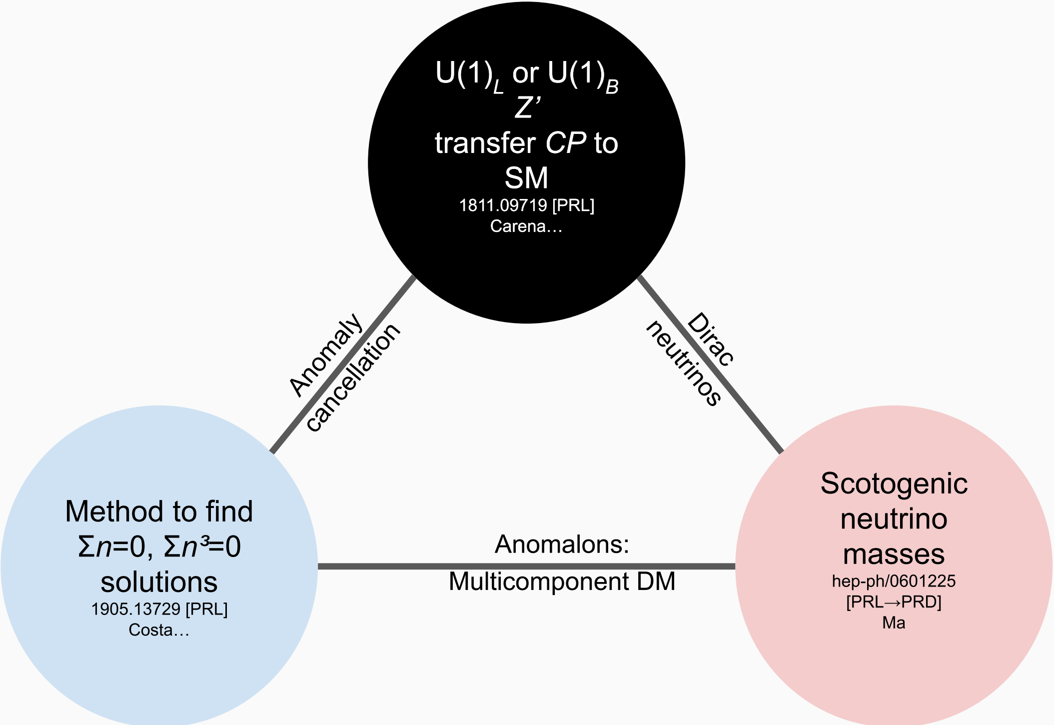
U(1)$_L$ or U(1)$_B$
Z'
transfer *CP* to SM
1811.09719 [PRL]
Carena…

Anomaly cancellation

Dirac neutrinos

Anomalons:

DM


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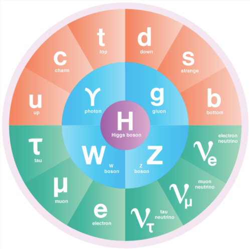
Carena…
Anomaly cancellation
Dirac neutrinos
Method to find Σn=0, Σn^3=0 solutions
1905.13729 [PRL]
Costa…
Anomalons:
Multicomponent DM
Scotogenic neutrino masses
hep-ph/0601225
[PRL→PRD]
Ma

Dark sectors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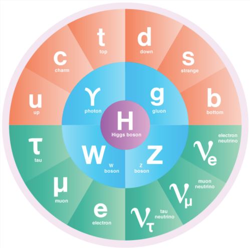
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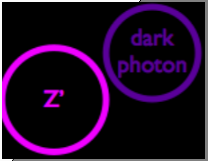
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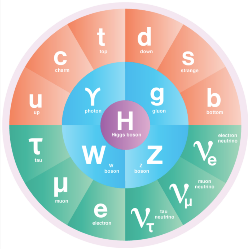


$F_{\mu\nu}$ $V^{\mu\nu}$

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

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

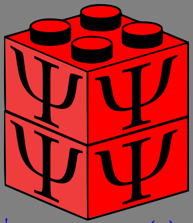
Anomalons: SM-singlet Dirac fermion

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

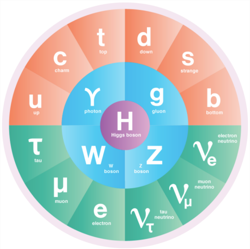
LHC production:

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

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



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



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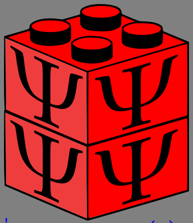

multi-component
dark matter

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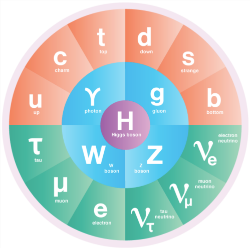

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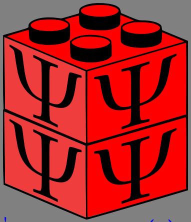

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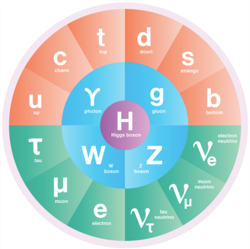

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CP violation Yukawa y

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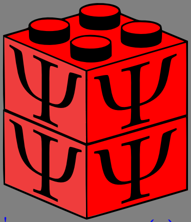

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Standard model extended with $\mathrm{U}(1)_{\mathcal{X}=L \text{ or } B}$ gauge symmetry

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

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

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

$\rightarrow$

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

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

https://doi.org/10.5281/zenodo.5526707

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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: $\phi = -\nu = -5$

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

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- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
  $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1,\ x'' = 6$

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

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- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \to z_3 = -3,\ z_4 = -2$

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U(1)$_B$ selection

- $L = 0$
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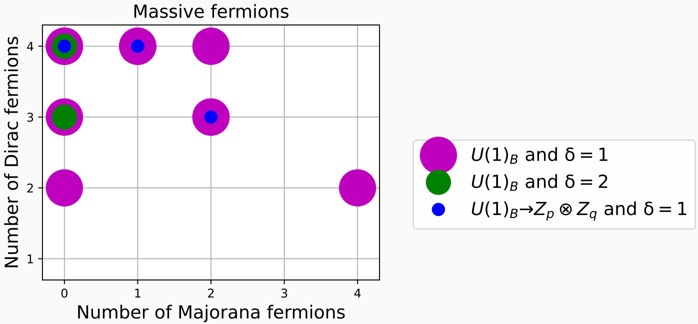
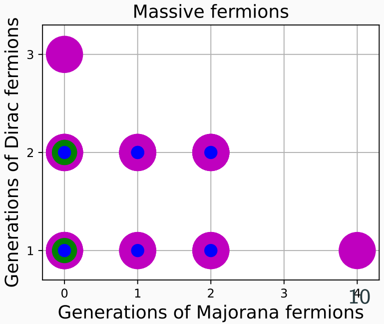
959 solutions from $\sim 400,000$

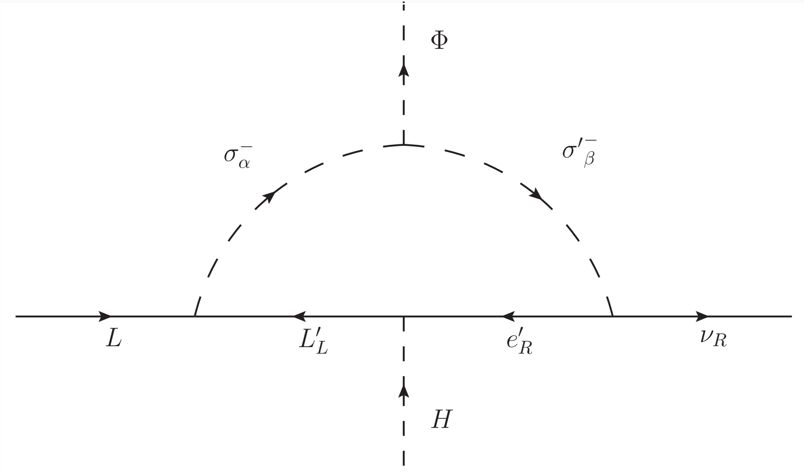
$$(5, 5, -3, -2, 1, -6)$$





Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



Full $\mathrm{U}(1)_B$ model

Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	$\mathbf{1}$	$2/3$	$u = -5/9$
d_{Ri}	$\mathbf{1}$	$-1/3$	$d = -5/9$
$(Q_i)^\dagger$	$\mathbf{2}$	$-1/6$	$Q = 5/9$
$(L_i)^\dagger$	$\mathbf{2}$	$1/2$	$L = 0$
e_R	$\mathbf{1}$	-1	$e = 0$
$\left(L'_L\right)^\dagger$	$\mathbf{2}$	$1/2$	$-x' = 1$
e'_R	$\mathbf{1}$	-1	$x' = -1$
L''_R	$\mathbf{2}$	$-1/2$	$x'' = -6$
$\left(e''_L\right)^\dagger$	$\mathbf{1}$	1	$-x'' = 6$
$\nu_{R,1}$	$\mathbf{1}$	0	5
$\nu_{R,2}$	$\mathbf{1}$	0	5
χ_R	$\mathbf{1}$	0	-2
$(\chi_L)^\dagger$	$\mathbf{1}$	0	-3
H	$\mathbf{2}$	$1/2$	0
S	$\mathbf{1}$	0	-5
Φ	$\mathbf{1}$	0	-5
σ^-_α	$\mathbf{1}$	1	-1
σ'^-_α	$\mathbf{1}$	-1	4

Table 2: Fermion (top) and scalar (bottom) content and its quantum numbers, $i = 1, 2, 3$, $\alpha = 1, 2$.

Baryogenesis

CP violation occurs in the dark sector and is transmited to SM sector by the new Z' gauge boson.

- High scale fields: Φ , $(\langle\Phi\rangle \to L'_L, L''_R, e'_L, e''_R$: vector-like anomalons)
- Electroweak scale fields: $\boxed{Z'_\mu, S, \chi_L, \chi_R}$
- CP-violation

$$
\begin{aligned}
\mathcal{L}_{\text{Dirac DM}} =& h\,(\chi_L)^\dagger\,\chi_R\Phi^* + y\,(\chi_L)^\dagger\,\chi_R S^* + \text{h.c}\,, \qquad\qquad y \in\mathbb{C}\\
\supset& \left(m_\chi + |y|\,\mathrm{e}^{i\theta}\,|S|\right)(\chi_L)^\dagger\,\chi_R + \text{h.c}\,.
\end{aligned}
$$

- CP-violation Portal

$$
\mathcal{L}_{\text{anomalous}} \supset g'\,Z'_\mu\left[3\bar{\chi}_L\gamma^\mu\chi_L - 2\bar{\chi}_R\gamma^\mu\chi_R + \bar{L}_i\gamma^\mu L_i + \bar{\ell}_{Ri}\gamma^\mu\ell_{Ri}\right]
$$

- Strong electroweak phase transition (EWPT) portal

$$
\mathcal{L}_{\text{first order EWPT}} \supset -\lambda_{SH} H^\dagger H\,S^* S\,.
$$

First-order phase transition i

$T = 0$: $h = H/\sqrt{2}$, $s = |S|$

$$V(h,s) \;=\; \frac{\lambda_H}{4}\left(h^2 - v^2\right)^2 + \frac{\lambda_S}{4}\left(s^2 - w^2\right)^2 + \frac{\lambda_{SH}}{2} h^2 s^2\,, \tag{10}$$

$v = v_{\mathrm{EW}}$ and $w = 0$ if

$$\lambda_{SH} > 0, \quad \lambda_H \lambda_S - \frac{1}{4}\lambda_{SH}^2 < -\frac{\lambda_{SH} m_s^2}{2v^2}\,. \tag{11}$$

$T \neq 0$:

$$V_T(h,s) = \frac{\lambda_H v_c^4}{4}\left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1\right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_c^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2)\,, \tag{12}$$

where

$$c_h = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}\right) , \quad c_s = \frac{1}{12}\left(3\lambda_S + 2\lambda_{HS}\right) . \tag{13}$$

An additional condition, to ensure that the global minimum for this potential is the broken one when $T = 0$, is

$$\frac{c_h}{c_s} > \sqrt{\frac{\lambda_h}{\lambda_s}}. \tag{14}$$

$T \gg T_c$: $v(T) = 0$ and $w(T) \neq 0$

$T = T_c$: $v(T_c) = v_c$ and $w(T_c) = w_c = v_c$

First-order phase transition iii

Using the thin wall approximantion for the nucleation bubbles, we use the ansatz in which the space dependence of the fields is given by

$$h(z) = \frac{1}{2}v(T_n)\left(1-\tanh\left(z/L_w\right)\right)\,, \qquad s(z) = \frac{1}{2}s_0\left(1+\tanh\left(z/L_w\right)\right)\,, \tag{15}$$

where z is the direction normal to the wall and L_w is the wall width.

The nucleation temperature, T_n, is defined by the condition [**?**]

$$\exp\left(-S_3/T_n\right) = \frac{3}{4\pi}\left(\frac{H(T_n)}{T_n}\right)^4\left(\frac{2\pi T_n}{S_3}\right)^{\frac{3}{2}}\,, \tag{16}$$

where S_3 is the Euclidean action of the bubble and $H(T)$ is the Hubble rate.

The CP violating phase, θ from

$$M_\chi = m_\chi + |y|\, e^{i\theta}\, |S|\,, \tag{17}$$

will lead to opposite signs in the perturbations of particles and antiparticles, resulting in a net asymmetry in the interior of the bubble. Imposing the condition $v(T_n)/T_n > 1$ avoids the asymmetry washout inside the bubble.

The evolution of the particle and anti-particle distribution functions is obtained from the Boltzmann equations, which are recast as the diffusion equation for the rescaled chemical potential, $\xi_i(z) \equiv \mu_i(z)/T = 6\,(n_i - \overline{n}_i)\,/T^3$,

$$-D_L\xi''_{\chi_L} - v_w\xi'_{\chi_L} + \Gamma_L(\xi_{\chi_L} - \xi_{\chi_R}) = S_{\not{CP}}\,, \tag{18}$$

where D_L is the diffusion constant for χ_L, which is related to the scattering rate Γ_L by $D_L = \langle v_{p_z}^2\rangle/3\Gamma_L$. Here, $\langle\,\rangle$ means thermal average. $S_{\not{CP}}$ is CP-violating source that results from the variation of θ [**?**],

$$S_{\not{CP}} = -\frac{\lambda}{2}\frac{v_w D_h}{\langle v_{p_z}^2\rangle T}\left\langle\frac{|p_z|}{\omega^2}\right\rangle\left(M_\chi^2\,\theta'\right)''\,, \tag{19}$$

where

$$\langle v_{p_z}^2 \rangle = \frac{3x+2}{x^2+3x+2}\,, \quad \left\langle \frac{|p_z|}{\omega^2} \right\rangle = \frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)}\,, \quad x \equiv m_\chi/T\,,$$

$$\left(M_\chi^2 \theta'\right)'' = \frac{m_\chi s_0 |y| \left(-2 + \cosh\left(\frac{2z}{L_w}\right)\right) \sin\theta}{L_w^3 \cosh^4\left(\frac{z}{L_w}\right)}\,. \tag{20}$$

The chiral particle give rise to a non-zero $\mathrm{U}(1)_B$ charge density in the proximity of the wall. This results in a Z' background that couples to the SM fields with $\mathrm{U}(1)_B$ charge,

$$\langle Z_0' \rangle = \frac{g_B\,(q_{\chi_L} - q_{\chi_R})\,T_n^3}{6M_{Z'}} \int_{-\infty}^{\infty} \mathrm{d}\,z_1\, \xi_{\chi_L}(z')\, e^{-M_{Z'}|z-z'|}\,, \tag{21}$$

which generates a chemical potential for the SM quarks,

$$\mu_Q(z) = \mu_{d_R,u_R}(z) = 3 \times \frac{5}{9} \times g_B \langle Z_0'(z) \rangle. \tag{22}$$

This chemical potential sources a thermal-equilibrium asymmetry in the quarks [**?**], $\Delta n_Q^{\mathrm{EQ}}(z) \sim T_n^2\,\mu_Q(z)$.

Finally, the baryon-number asymmetry is then given by

$$n_B = \frac{\Gamma_{\rm sph}}{v_w} \int_0^\infty \mathrm{d}\, z \, n_Q^{\rm EQ}(z) \exp\left(-\frac{\Gamma_{\rm sph}}{v_w} z\right) , \tag{23}$$

where $\Gamma_{\rm sph}$ is the sphaleron rate. The baryon-to-photon-number ratio is then obtained by

$$\eta_B = \frac{n_B}{s(T_n)}, \quad s(T) \equiv \frac{2\pi^2}{45} g_{*S}(T)\, T^3 , \tag{24}$$

where $g_{*S}(T)$ is the effective number of relativistic degrees of freedom.

Results

We vary the typical Dirac-fermion DM parameter space and for each point that satisfy neutrino oscillation data, relic density and DM direct detection constraints. For each point we ...

Parameter	Range
θ	$(-\pi/2\,,\pi/2)$
s_0/GeV	$100-500$
T_n/GeV	$100-200$
L_w/GeV^{-1}	$1/T_n-10/T_n$
v_w	$0.05-0.5$

Table 3: Scan ranges for the free parameters that are involved in the baryogenesis mechanism.