EWBG & Dark CPV

Dark Universe Workshop - October 21-25 2019
ICTP-SAIFR Sao Paulo, Brazil

Mariano Quirós

IFAE, BCN

Outline

The outline of this talk is

Outline

- Introduction
- EWBG in the Standard Model (rev.)
- CP violation and EDM
- A model with CPV in the dark sector
- EWBG mediated by Z'
- Phenomenology
- Conclusions

I thank my collaborators in the subject since 1992: A. Brignole, M. Carena, J. Espinosa, T. Konstandin, A. Megevand, J. Moreno, G. Nardini, J.M. No, D. Oaknin, A. Riotto, M. Seco, A. de Simone, C. Wagner, Y. Zhang, F. Zwirner, . . .

Introduction

- One of the great mysteries of our universe is the observed matter (protons+neutrons) antimatter asymmetry
- Since there is good evidence that the universe is mostly made of matter (and no antimatter) the baryon density corresponds to the cosmological matter-antimatter asymmetry.
- This number is determined from consistency with BBN data as (PDG)

$$\eta_{BBN} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = 6.05(7) \times 10^{-10}$$

- Why does this ratio has this value?
- In the SCM starting from an initial symmetric state at high temperatures (after inflation) one would expect a much smaller baryon asymmetry.

There are then two options within the SCM

1. A small baryon-antibaryon asymmetry has to be imposed **by hand** as an **initial condition** (not very satisfactory)
2. Some **dynamical mechanism** has produced a tiny baryon-antibaryon asymmetry in the early universe leading, after $p\bar{p}$ annihilations, to the required baryon asymmetry (advised)

It was suggested by Sakharov in 1967 [1] that a tiny $n_{\Delta B}$ might have been produced in the early universe leading to η_{BBN}. The three necessary ingredients for baryogenesis are:

Sakharov conditions

- B-violation
- C and CP violation
- Departure from thermal equilibrium. The out-of-equilibrium conditions are present e.g. in the bubble wall in a first order phase transition, in particular for ElectroWeak BaryoGenesis (EWBG)

[1] A.D. Sakharov, JETPL 91B (1967) 24

Two conditions for EWBG

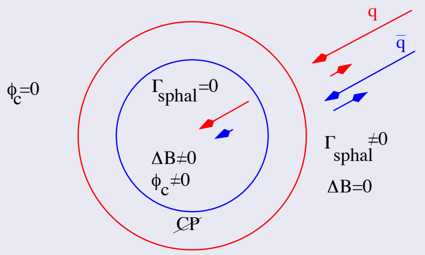
1. Baryon asymmetry has to be generated

If there is not enough *CP*-violation the mechanism for generating the BAU does not work, or does not generate enough baryon asymmetry

2. Baryon asymmetry should not be washed out

If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase

Cartoon of EWBG



EWBG in the Standard Model

- Saharov's conditions are fulfilled in the Standard Model
- In a system at finite temperature baryon number can be sizeably violated by sphaleron solutions

Sphaleron rate at $T > T_c$: in the symmetric phase

The rate of baryon violation per unit time and unit volume Γ does not contain any exponential Boltzmann factor

$$\Gamma = k(\alpha_W T)^4, \quad 0.1 \lesssim k \lesssim 1.0$$

Sphaleron rate at $T < T_c$: in the broken phase

The rate per unit time and unit volume for fluctuations between neighboring minima contains a Boltzmann suppression $\zeta(T) = E_{\rm sph}(T)/T$

$$\Gamma \sim 2.8 \times 10^5 T^4 \left(\frac{\alpha_W}{4\pi}\right)^4 \kappa \frac{\zeta^7}{B^7} e^{-\zeta}, \quad 10^{-4} \lesssim \kappa \lesssim 10^{-1}$$

Out of equilibrium conditions

The out of equilibrium condition can be achieved, if the phase transition is strong enough first order, in the bubble walls. In that case the B-violating interactions are out of equilibrium in the bubble walls and a net B-number can be generated during the phase transition

How strong should the phase transition be to not erase the baryon asymmetry? $\Leftrightarrow$ How much out of equilibrium the sphaleron should be?

- The condition for the sphalerons to be out of equilibrium

$$\frac{E_{\rm sph}(T_c)}{T_c} \gtrsim 45$$

- This translates into a constraint for the value of the Higgs field ϕ

$$\frac{\phi(T_c)}{T_c} \gtrsim 1$$

The SM fails quantitatively to fulfill the out of equilibrium & CPV conditions

CP violation

The SM contains the $\mathcal{O}(1)$ CP-violating CKM phase required for EWBG

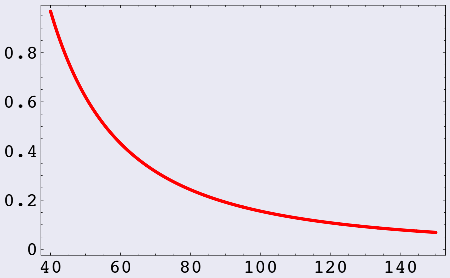
But it was soon realized [a] that the effect was suppressed by the Jarlskog invariant and

$$\frac{n_B}{n_\gamma} < 6 \times 10^{-27} \Longrightarrow \textbf{BSM}$$

Extra CP Violating phases!!!

[a] M.B. Gavela et al., hep-ph/9312215

ϕ_c/T_c Vs m_H/GeV @ one-loop



$\Longrightarrow$ **BSM**

Extra stuff to strengthen PhT!!!

CP-violation and EDM

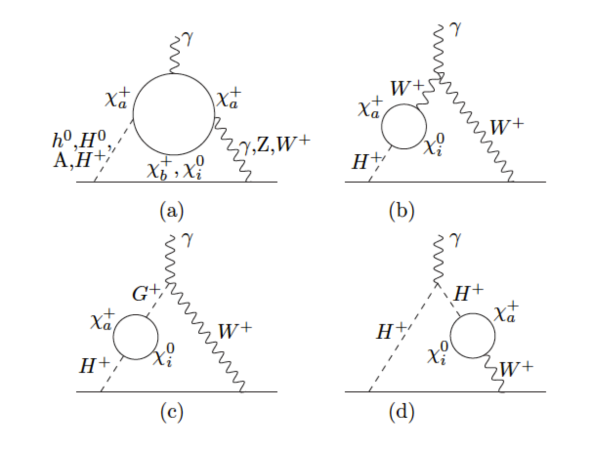
- As we have seen we need extra CP-violating phases to generate baryon asymmetry
- They will also generate EDM which are severely constrained by experimental data
- The most constraining ones are for the electron and the neutron

$$|d_e| < 1.1 \times 10^{-29} e \cdot cm \; (90\% CL), \quad |d_n| < 3.0 \times 10^{-26} e \cdot cm \; (90\% CL)$$

ACME, Nature 562 (2018) 355 J.M. Pendlebury et al., 1509.04411

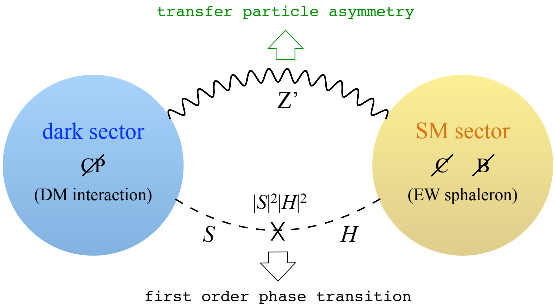
- They generically imply $\sim 10^{-3}$ phases. The statement of the SUSY CP-problem and it is barely at odd with EWBG
- For $\mathcal{O}(1)$ phases, e.g. in the MSSM, the first and second generation squarks must be heavy enough ($\sim 10\ TeV$): pay attention to two-loop contribution to EDM from charginos and neutralinos

- Two loop (Barr-Zee type) diagrams may be competitive or even dominant [2]



[2] Y. Li, S. Profumo and M. Ramsey-Musolf, arXiv:0806.2693 [hep-ph]

- The simplest solution out of this problem is to have models with CP violated in a Dark sector
- The schematic picture of the model we propose contains a dark sector with Dark Matter, a dark $U(1)'$ gauge boson Z' and CP violation
- *Main challenge: to find an efficient mechanism to transfer the CP violation from the dark sector to the visible sector in the early universe, while still keeping contributions to EDMs sufficiently suppressed today*



A model with dark CPV & gauged ℓ

- We consider [3] an extension of the SM with gauged lepton $\ell \equiv L_e + L_\mu + L_\tau$ number: $U(1)_\ell$
- Additional fermions (anomalons) should be introduced for anomaly cancellation, $q \in \mathbb{R}$

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
ν_R^i	1	1	0	1
$L_L' = (\nu_L', e_L')^T$	1	2	-1/2	q
e_R'	1	1	-1	q
χ_R	1	1	0	q
$L_R'' = (\nu_R'', e_R'')^T$	1	2	-1/2	$q + N_g$
e_L''	1	1	-1	$q + N_g$
χ_L	1	1	0	$q + N_g$

- Fermion χ will be Dark Matter

[3] M. Carena, M.Q., Y. Zhang, arXiv:1811.09719 [hep-ph], arXiv:1908.04818 [hep-ph]

- $U(1)_\ell$ is spontaneously broken by a Higgs VEV, $\langle\Phi\rangle = v_\Phi$, with $\ell_\Phi = N_g = 3$, at the (multi)TeV scale
- Anomalons get spontaneous breaking masses by the Yukawa interactions

$$\left(c_L \bar{L}''_R L'_L + c_e \bar{e}''_L e'_R + c_\chi \bar{\chi}_L \chi_R\right)\Phi + \mathrm{h.c.}$$

- Considering $c_L \sim c_e \sim \mathcal{O}(1)$, the charged anomalons L'_L, L''_R, e''_L, s'_R are integrated out at scales (and temperatures) of order v_Φ
- For small g' and c_χ, Z' and χ have masses around the EW scale
- For EWBG we need another scalar S, with $\ell_S = N_g$, coupled to the Higgs portal and the DM

$$\mathcal{L} = -\lambda_{SH}|S|^2|H|^2 + \bar{\chi}_L(m_0 + \lambda_c S)\chi_R + \mathrm{h.c.}$$

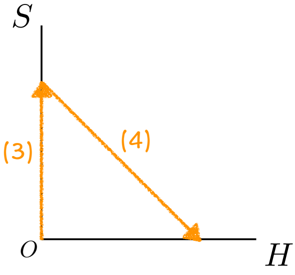
  making the EW phase transition first order
- The mass of χ changes with the S field profile during the electroweak phase transition. If the relative phase between m_0 and $\lambda_c S$ is physical, it will serve as a source of CP violation in our EWBG

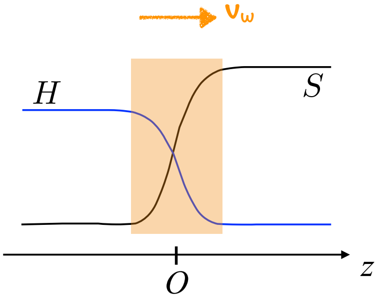
EWBG MEDIATED BY Z'

The global picture for phase transition is as follows

1. At very high temperatures, all symmetries are restored.
2. As the universe cools down to the temperature $T_\Phi \sim v_\Phi$, the Φ field acquires its VEV, $\langle \Phi \rangle = v_\Phi$, and the lepton number symmetry is broken. The nature of this phase transition is not relevant
3. As the universe further cools down to a temperature T_S not far above the electroweak scale T_{EW}, the S field first develops a VEV, $\langle S \rangle \neq 0$, when its mass squared term (including the thermal corrections) becomes negative, while the Higgs VEV remains zero, $\langle H \rangle = 0$. The nature of this transition is not relevant
4. At the critical temperature near the electroweak scale, T_c, a new minimum of the potential with $\langle H \rangle \neq 0, \langle S \rangle \simeq 0$ emerges that turns into the true minimum.This process must involve a first-order phase transition requiring the presence of a barrier between both minima. The universe tunnels from one vacuum to the other via bubbles.

- At high temperatures, there are thermal corrections, $a_H T^2|H|^2$ and $a_S T^2|S|^2$. Thus, at very large T, the potential will be minimized for $\langle H\rangle = \langle S\rangle = 0$ (steps 1 and 2).
- Given that the Higgs field couples to more degrees of freedom than S, it follows that $a_H > a_S$, and it is always possible to find a temperature where the Higgs quadratic term is positive, while the S quadratic term is negative (step 3)
- At lower temperatures, however, the Higgs quadratic term will also turn negative.





- We have considered a potential as

$$V(H,S) = \lambda_H(|H|^2 - v^2)^2 + \lambda_S(|S|^2 - v_S^2)^2 + \lambda_{SH}|S|^2|H|^2 + \mu_S^2 S^2$$

The physical source of CP violation arises from the χ mass term

$$M_\chi = m_0 + \lambda e^{i\theta}|S|, \quad \theta = const$$

- During the first-order electroweak phase transition, in the presence of a bubble wall, the magnitude of $|S|$ is space-time dependent, hence having used the freedom to make m_0 real, the phase of M_χ is not removable
- This phase provides the key source of CP violation for baryogenesis

- The particle chiral asymmetries in the dark sector are

$$\xi_{\chi_{L,R}}(z) = \frac{3}{T_c^3}\left(n_{\chi_{L,R}} - n_{\chi^c_{L,R}}\right), \quad \xi_{\chi_{L,R}} = \mu_{\chi_{L,R}}/T_c$$

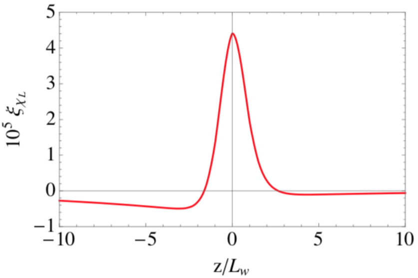
- The chiral asymmetries diffuse with the diffusion equation

$$-D\xi''_{\chi_L}(z) - v_\omega \xi'_{\chi_L}(z) + \Gamma_m[\xi_{\chi_L}(z) - \xi_{\chi_R}(z)] = S_{\rm CPV}$$

- The diffusion constant D is given by $D = \langle v^2\rangle/(3\Gamma_m)$, with $\Gamma_m \sim \lambda^2 T_c/(4\pi)$, v is the particle velocity in the bubble wall rest frame, and $\langle\rangle$ is the thermal average over the Fermi-Dirac distribution function in the rest frame of the bubble wall

- The CP violating source term is [4], $E^2 = p^2 + |M_\chi(z)|^2$

$$S_{\rm CPV} = \frac{v_\omega}{\Gamma_m T_c}\left\langle \frac{v_z}{2E^2}\right\rangle \frac{m_0 v_S \lambda \left[-2+\cosh\left(\frac{2z}{L_\omega}\right)\right]\sin\theta}{L_\omega^3 \cosh^4\left(\frac{z}{L_\omega}\right)}$$



[4] J. Cline et al., hep-ph/0006119

- Unlike in usual EWBG scenarios, here the chiral asymmetry is generated in the dark sector through the χ particle, which is an $SU(2)_L$ singlet and thus does not couple to electroweak sphalerons
- However thanks to the leptonic Z' portal, which couples to both χ and the SM leptons, the CP violating effect in the dark sector can be transferred to the observable sector
- As χ_L and χ_R carry different $U(1)_\ell$ charges ($\mathrm{q}+N_g$ and q respectively), the above chiral asymmetries imply a net $U(1)_\ell$ charge density near the bubble wall as,

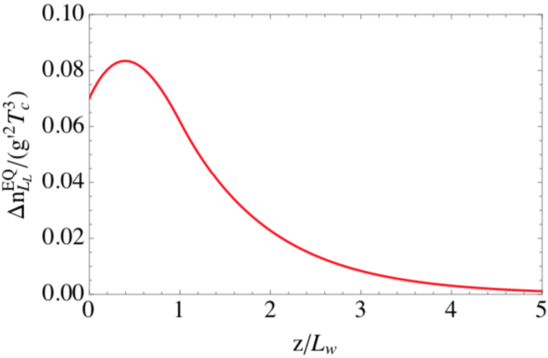
$$\rho_\ell(z) = (\mathrm{q}+N_g)\left[n_{\chi_L} - n_{\chi_L^c}\right] + \mathrm{q}\left[n_{\chi_R} - n_{\chi_R^c}\right] = \frac{1}{3} N_g T_c^3\, \xi_{\chi_L}(z)$$

- The existence of this net $U(1)_\ell$ charge density yields a Coulomb background of the Z' potential, $\langle Z_0' \rangle$

$$\langle Z_0'(z)\rangle = \frac{g'}{2M_{Z'}} \int_{-\infty}^{\infty} dz_1\ \rho_\ell(z_1)\ \exp\left[-M_{Z'}|z-z_1|\right]$$

- As Z_0' couples to the leptonic currents $Z_0'(\bar{L}_L\gamma^0 L_L + e_R\gamma^0 e_R)$ its background acts as a *spontaneous baryogenesis* mechanism and generates chemical potentials, i.e. thermal equilibrium asymmetry, for SM leptons

$$\mu_{L_L}(z) = \mu_{\ell_R}(z) = g'\langle Z_0'(z)\rangle, \quad \Delta n_{L_L}^{\mathrm{EQ}}(z) = \frac{2g' N_g T_c^2}{3}\langle Z_0'(z)\rangle$$



- In the presence of EW sphaleron processes

$$\Delta n_B = \frac{\Gamma_0}{v_\omega}\int_0^\infty dz\, \Delta n_{L_L}^{\rm EQ}(z) e^{-\Gamma_0 z/v_\omega}$$

where $\Gamma_0 \simeq 120\,\alpha_w^5\, T_c \simeq 10^{-6}\, T_c$ is the sphaleron rate in the unbroken phase, an asymmetry is generated

- We have scanned over all free parameters in the range

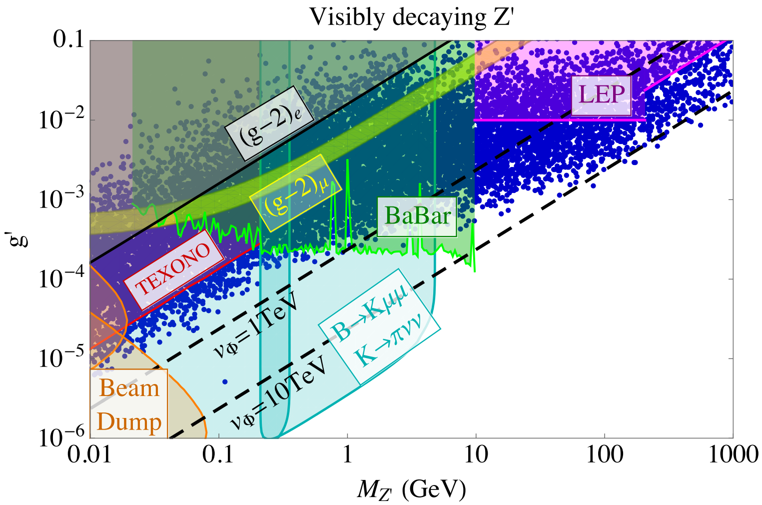
$$(M_{Z'}, m_0) \in (10^{-3}, 10^3)\,\mathrm{GeV}, \quad (v_S,\; T_c) \in (100, 500)\,\mathrm{GeV}$$

$$\lambda \in (10^{-2}, 1), \quad g' \in (10^{-6}, 0.1), \quad \theta \in (-\pi/2, \pi/2),$$

$$L_w \in (1/T_c, 10/T_c), \quad v_\omega \in (0.05, 0.5)$$

$$M_{Z'} < 2m_0$$

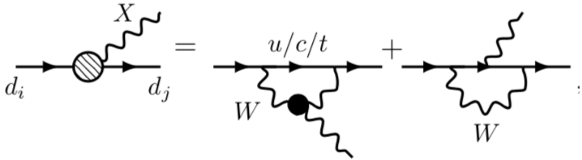
- The case $M_{Z'} > 2m_0$ is practically excluded by the various constraints



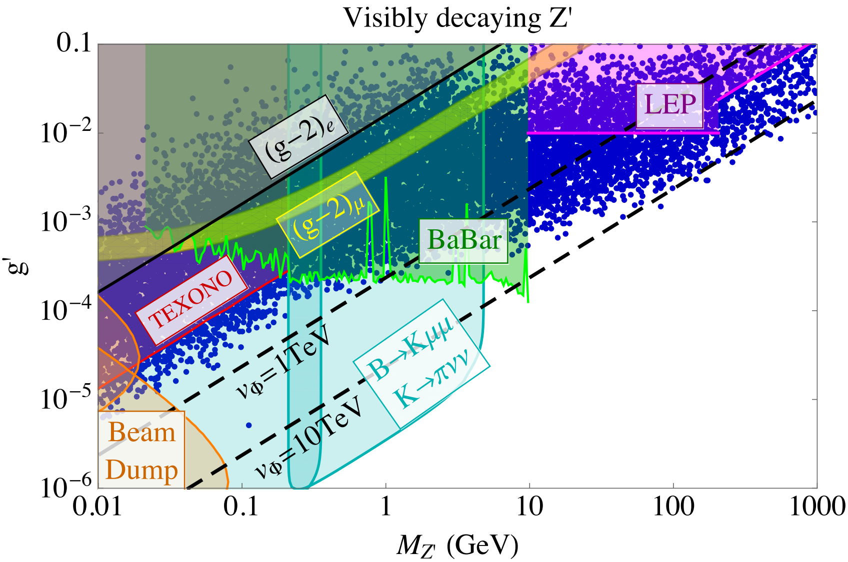
The observed baryon asymmetry of the universe is covered by the blue points, in the g' versus $M_{Z'}$ plane

PHENOMENOLOGY

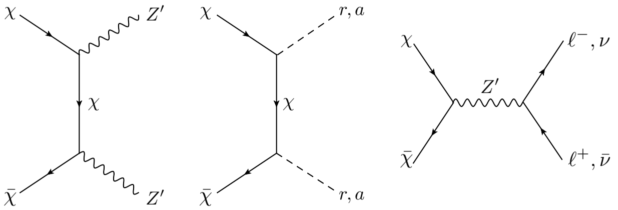
- Z' couples to the SM charged leptons and neutrinos. Directly searched for at e^+e^- colliders, such as LEP, and BaBar, as well as at electron beam dump experiments, and neutrino experiments that are sensitive to neutrino-electron interactions (such as TEXONO)
- At the loop level it can contribute to the anomalous magnetic moments of charged leptons $(g-2)_\mu, (g-2)_e$
- As Z' couples to an anomalous current with respect to $SU(2)_L^2$ in the low energy theory, it makes important contributions to flavor-changing meson decays such as $K \to \pi Z'$ and $B \to KZ'$ [5]



[5] J.A. Dror et al., arXiv:1707.01503


Visibly decaying Z'
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g'
0.01
0.1
1
10
100
1000
$M_{Z'}$ (GeV)
$(g-2)_e$
$(g-2)_\mu$
LEP
BaBar
TEXONO
v_Φ=1TeV
v_Φ=10TeV
$B \to K\mu\mu$
$K \to \pi\nu\nu$
Beam
Dump

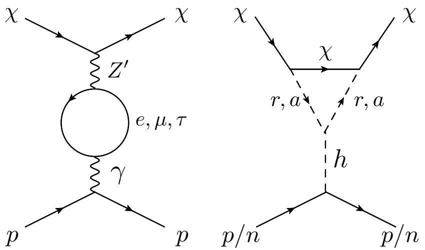
- Particle χ from the dark sector could be a dark matter candidate, since there is a $\mathbb{Z}_2$ symmetry in the Lagrangian ($\chi \to -\chi$) allowing it to be stable.

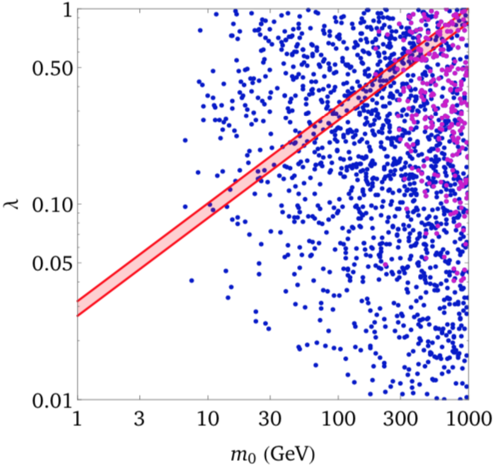


- Obtaining the correct relic density for χ through this channel then requires λ to lie within the window

$$\sqrt{\frac{m_0}{1.4\,\mathrm{TeV}}} < \lambda < \sqrt{\frac{m_0}{1.0\,\mathrm{TeV}}}$$

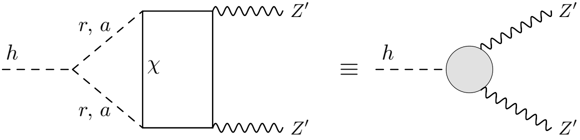
- Direct detection of dark matter in this model could occur through Z' exchange.
- Because the Z' is the gauge boson for lepton number, it does not directly couple to nucleons, implying that the dark matter-nucleon scattering should occur through loop of charged leptons which effectively act as a kinetic mixing $Z'_{\mu\nu}F^{\mu\nu}$
- Diagrams for direct detection are



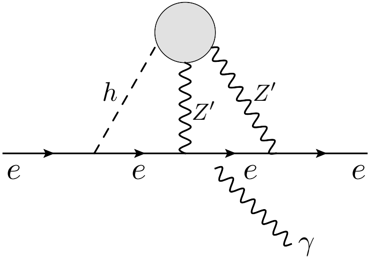


Band is consistent with thermal relic density. Magenta points are consistent with both the observed baryon asymmetry and the dark matter direct detection experiments. Blue points fail to pass direct detection

- A CP violating Higgs-Z' operator, of the form $hZ'_{\mu\nu}\tilde{Z}'^{\mu\nu}$, at two loop level, is shown in



- It generates an EDM for the electron at four loop $d_e \lesssim 10^{-30} e \cdot cm$, below experiment $d_e^{exp} < 1.1 \cdot 10^{-29} e \cdot cm$



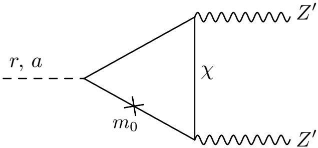
- The scalar $S = r + ia$ decays into $Z'Z'$ via one-loop from the operators $rZ'_{\mu\nu}Z'^{\mu\nu}$, $rZ'_{\mu\nu}\tilde{Z}'^{\mu\nu}$, $aZ'_{\mu\nu}Z'^{\mu\nu}$, $aZ'_{\mu\nu}\tilde{Z}'^{\mu\nu}$ from

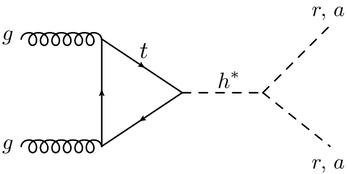
$$\mathcal{L}_{\text{dark Yukawa}} = \lambda e^{i\theta}\bar{\chi}_L\chi_R S + \text{h.c.}$$

$$= \frac{r}{\sqrt{2}}\left(\lambda\cos\theta\bar{\chi}\chi + \lambda\sin\theta\bar{\chi}i\gamma_5\chi\right) + \frac{a}{\sqrt{2}}\left(-\lambda\sin\theta\bar{\chi}\chi + \lambda\cos\theta\bar{\chi}i\gamma_5\chi\right)$$

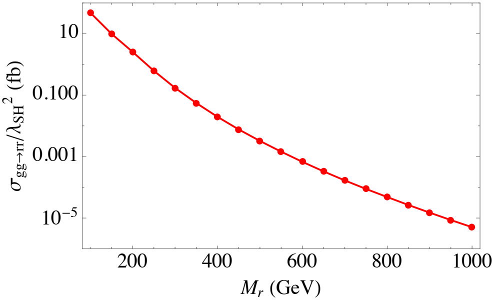
- It is produced in pairs rr and aa via the Higgs portal interaction

$$\mathcal{L}_{HS} = -\lambda_{HS}|S|^2|H|^2$$





- The production cross section at the LHC



- Quantitatively, $\sigma_{gg\to rr,aa} \sim 10\lambda_{SH}^2$ fb ($\sim 0.1\lambda_{SH}^2$ fb) for $M_{r,a} \simeq 150$ GeV (for $M_{r,a} \simeq 300$ GeV)
- After the decays of the r (or a) scalars, the final state could contain as many as 4 pairs of charged leptons, a very striking signal
- We find that the existing LHC data could already cover the region where the dark scalar (r or a) is lighter ~ 200 GeV for $\lambda_{SH} \sim \mathcal{O}(1)$

Conclusion

The role of the dark sector CP violation in our EWBG mechanism for the $U(1)_\ell$ model

1. CP is first violated in the dark sector, containing the $\chi_{L,R}$ fermions. Their mass term has an irreducible phase that becomes time-dependent during the first-order phase transition
2. This time dependent CP violating mass generates particle chiral asymmetries for $\chi_{L,R}$ in the dark sector, which diffuse to the exterior of the bubble wall, where SM sphalerons are active
3. χ_L and χ_R carry different $U(1)_\ell$ charges such that their chiral asymmetries generate a net $U(1)_\ell$ charge density near the wall, that yields a Coulomb background for Z_0'

4 Given that the gauge field Z_0' couples to the SM leptons, it generates a chemical potential for the SM leptons

5 In the presence of sphaleron processes, active outside the bubble, the SM lepton number asymmetry is generated

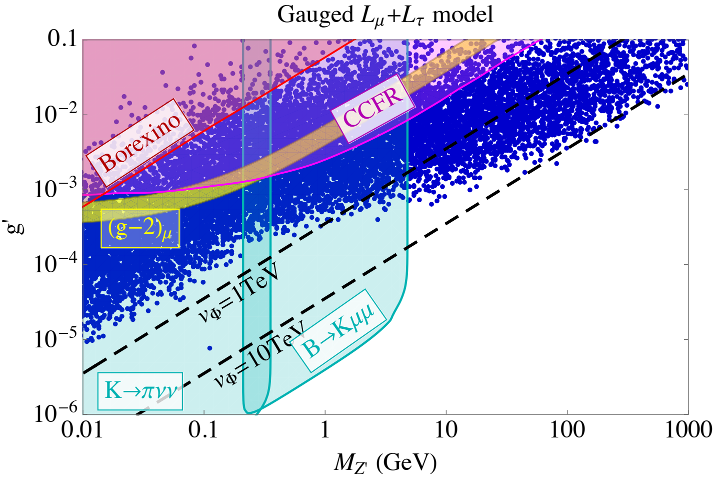
7 As sphalerons preserve $B-L$, they can change the generated SM lepton number into baryon number. Hence, a baryon number asymmetry will be equally generated

8 Inside the bubbles the sphaleron processes are suppressed, and the baryon asymmetry generated at the phase transition is not washed out.

Phenomenological features

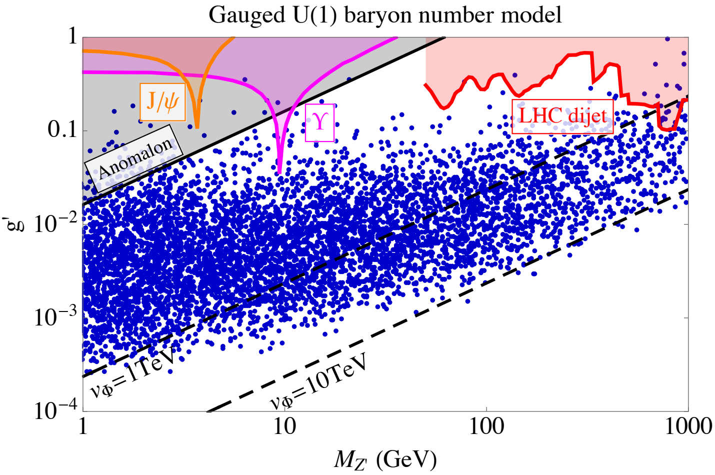
- The model has a candidate for Dark Matter in the dark sector, satisfying all direct detection bounds
- As CP is violated in the dark sector, it contributes to the electron EDM at four loop, below present experimental limits and possibly with no signal in the next generation experiments
- The lighter the Z' the more weakly coupled it should be. Near future and prospective experiments: BELLE II, NA64 (μ mode), SHiP, Higgs factories,...
- New extra scalar can be produced at the LHC with 8 charged leptons as the final state
- The model belongs to a wider class of models as gauging $L_\mu + L_\tau$ ($N_g = 2$) or baryon number B with similar (but not quite the same) phenomenology

The case $U(1)_{L_\mu+L_\tau}$



CCFR (neutrino trident production), Borexino (solar neutrino-electron scattering)

The case $U(1)_B$



LHC hadronic widths of Υ, J/Ψ