Dark Matter in the *Exo*-Higgs scenario

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Based mainly on: H. Davoudiasl, P.P.G., C. Zhang arXiv:1605.00037

and H. Davoudiasl, P.P.G., C. Zhang arXiv:1612.05639

The Exo-Higgs scenario

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- The Exo-Higgs is an extension of the SM that allows an EW-like baryogenesis.
- The EW baryogenesis is an attractive and testable way to generate a baryon-antibaryon asymmetry.
- The SM has all the ingredients for a successful baryogenesis, but not in the right quantities.
- To get around this, one can assume that a new gauge group breaks down at some scale $\sim$ TeV and triggers the Baryogenesis.

$SU(2)_e$ symmetry

- As a simple implementation of this idea, we assume the existence of $SU(2)_e$ gauge symmetry.
- The *exo*-symmetry is completely broken by the vev of a Higgs field η at some temperature

$$T > T(EWPT)$$

- SM fields are neutral under $SU(2)_e$, however there are (3 generations of) new fermions charged under this symmetry and the SM gauge group.

Ω's and Λ's

An interesting choice of quantum numbers for the new fermions is

$$\mho_L = (2, 3, 1, -\frac{1}{3}) \quad ; \quad 2 \times \mho_R = (1, 3, 1, -\frac{1}{3})$$
$$2 \times \Lambda_L = (1, 1, 1, -1) \quad ; \quad \Lambda_R = (2, 1, 1, -1)$$

under the $SU(2)_e \times SU(3) \times SU(2)_L \times U(1)_Y$ gauge group.

The fermions get their masses through Yukawa coupling to η.

The Exo Higgs Langrangian

The Lagrangian is the sum of three contributions:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_e + \mathcal{L}_m$$

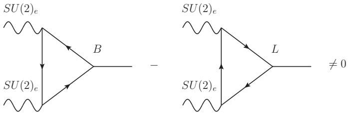
We focus on the third piece:

$$\mathcal{L}_m = 2k_{\eta H}\eta^\dagger \eta H^\dagger H - Y_{\Upsilon q}\eta \bar{\Upsilon}_L d_R - Y_{q\Upsilon} H \bar{q}_L \Upsilon_R - \mathcal{M}_\Lambda \bar{\Lambda}_L e_R.$$

We impose that $k_{\eta H} v_\eta^2 = \mu_H^2$. This ties the EW symmetry breaking to the Exo symmetry breaking.

At tree level the Lagrangian preserves B and L. However at one-loop level the $B - L$ current is anomalous under $SU(2)_e$.

$\Delta(B-L)$



The $B-L$ anomaly can lead to the generation of $\Delta(B-L) \neq 0$ if the $SU(2)_e$ breaking involves a strong first order phase transition.

Condition for a first order transition

$$\eta(T_c)/T_c \sim \frac{3\, g_e^3}{16\pi\, \lambda_\eta} \gtrsim 1$$

The strong phase transition at a temperature of order 1 TeV implies gravitational wave signals that may be detectable by future space-based missions, such as LISA.

Dark Matter

We introduce a new complex scalar χ that carries a good global charge $Q_\chi = +1$. We also demand that $\Lambda_{L,R}$ both have $Q_\chi = +1$. This forbids the $\mathcal{M}_\Lambda \bar{\Lambda}_L e_R$ mixing, and allows us to write

$$\lambda_\ell \, \chi \bar{\Lambda}_L \ell_R .$$

We will assume that χ is the lightest $Q_\chi \neq 0$ state, and so it will be a stable particle and a potential DM candidate.
We add the new quartic interactions

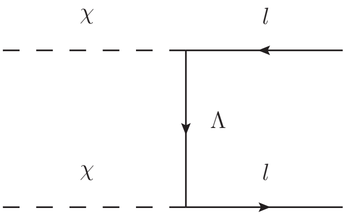
$$\lambda_\chi (\chi^\dagger \chi)^2 + 2k_{\chi H} \chi^\dagger \chi H^\dagger H + 2k_{\chi\eta} \chi^\dagger \chi \eta^\dagger \eta \, .$$

The mixed terms can in principle supply the required mass term for χ, after exo-spin and electroweak symmetry breaking.

Relation between Q_χ and ΔB

Exo-baryogenesis generates $\Delta(B-L)$ in the *exo*-sector;
Fast decay of *exo*-fermions injects $\Delta(B-L)$ into the SM and and net Q_χ charge into χ;
$\Delta(B-L)$ is processed into B and L by the EW sphaleron, χ particles stay stable since Q_χ is conserved.

Since $\chi\chi^*$ pairs annihilate efficiently through *t*-channel into leptons, and the number density of χ and baryons are tied, χ is required to have a particular mass m_χ.



Dark Matter Mass

We have the following relations for the chemical potentials:

$$
\begin{aligned}
&\mu_{dR} = \mu_{♀}, \qquad \mu_{uL} = \mu_{♀} + \mu_0, \\
&\mu_{iR} = \mu_\Lambda - \mu_\chi, \qquad 3\mu_{♀} - \mu_\Lambda = 0, \\
&\sum_i (\mu_{iR} + \mu_{iL}) + 3(\mu_{dR} + \mu_{dL}) - 6(\mu_{uR} + \mu_{uL}) \\
&+12(\mu_\Lambda + \mu_{♀}) - 2\mu_0 = 0,
\end{aligned}
$$

As a result

$$
\Delta_{B-L} = \frac{789}{19}\mu_{♀}, \qquad \Delta Q_\chi = \frac{1008}{19}\mu_{♀}.
$$

After Δ_{B-L} is processed into ΔB we find

$$
\frac{\Delta Q_\chi}{\Delta B} = \frac{1036}{263} \Rightarrow m_\chi \approx 1.3\ \mathrm{GeV}.
$$

Benchmark scenario.

First we set a benchmark scenario

m_η	$=$	$1.5\,\mathrm{TeV}$	Mass of the η field
v_η	$=$	$2.5\,\mathrm{TeV}$	Vev of the η field
$m_{♀}^{h}$	$=$	$1.5\,\mathrm{TeV}$	Mass of the heaviest ♀
$m_{♀}^{l}$	$\sim$	$1\,\mathrm{TeV}$	Mass of the lightest ♀'s
m_Λ	$=$	$1\,\mathrm{TeV}$	Mass of Λ's
g_e	$=$	2	$SU(2)_e$ gauge coupling,

$$\mathcal{L}_m \;=\; 2k_{\eta H}\eta^\dagger\eta H^\dagger H - Y_{♀q}\eta\,\bar{♀}_L d_R - Y_{q♀}H\bar{q}_L ♀_R$$

- induces changes in the Higgs couplings and FCNC operators.
- $k_{\eta H}v_\eta^2 = \mu_H^2 \to \tan(2\theta_{\eta H}) = \frac{4k_{\eta H}\,v_H\,v_\eta}{m_\eta^2 - m_H^2} \sim 7\times 10^{-4}$.
- $♀ \leftrightarrow q\eta$ and $♀ \leftrightarrow qH$ in equilibrium at $T_c^e \Rightarrow Y_{♀q}, Y_{q♀} \gtrsim 10^{-4}$

Exo-fermion phenomenology

- The ♀'s decay through three channels, ♀ $\to tW^-$, ♀ $\to bZ$, and ♀ $\to bH$, with BR $\sim 50\%$, $\sim 25\%$, and $\sim 25\%$, respectively.
- The bounds come from the searches for -1/3 vector-like quark.
- Λ are mostly produced in pairs through Drell-Yan and can decay only through the process $\Lambda \to \chi\ell$.
- For $\Lambda \sim 1\,\mathrm{TeV}$, the signal would be a pair of opposite-sign-same-flavor leptons, with $p_T \gtrsim$ a few hundred GeV, and a large missing E_T.
- Main background: $t\bar{t}$, W pair, and tW production. After cuts we can expect $\mathcal{O}(10)$ events at the $13\,\mathrm{TeV}$ LHC with 100 fb^{-1}.

Boson phenomenology

- η is produced through gluon-fusion with $\sim$ 10 fb at 13 TeV
- with a $\sim$ 98% BR into gluons. The second largest $\mathrm{BR} \sim$ 0.4% is into photons $\Rightarrow$ possible search at HL-LHC.
- Cross section of a pair of ω's is completely irrelevant at LHC energies, while a 100 TeV collider could produce it with a $\approx$ 5 fb cross section.

Conclusion

- The Exo-Higgs scenario is a possible extension of the SM that offers a frameworks for a EW-like baryogenesis.
- The model also allows a scalar asymmetric dark matter, whose mass is defined by structure of the model.
- Many possible signals at LHC.
- The strong phase transition could result in GW detectable at LISA.