Dark Matter from Weak Polyplets

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Based on 1205.xxxx, André de Gouvêa, Wei-Chih Huang, JK

Motivation

- Standard Model works really well, yet leaves many questions: hierarchy problem, fermion masses, cosmological constant.....
- Suggests possible strategy: try to address one or more issues by making small additions to the SM.

Idea: Add larger fermion multiplets charged under SM gauge group.

- SM gauge group is $SU(3) \times SU(2) \times U(1)$.
- SM fermions transform as singlet or fundamental under $SU(2)$, $SU(3)$.
- Could we put in larger multiplets?
- Could a larger $SU(2)$ multiplet contain a DM candidate?

The Model

- Strategy: retain the SM gauge group, but add new fermions in higher multiplets of $SU(3) \times SU(2) \times U(1)$.
- Interested in finding DM candidate: take all multiplets to be colorless, want lightest new particle neutral.
- Theoretical issues:
  - Must make all new fermions massive.
  - Must avoid triangle anomalies.
- Multiplets denoted by left-handed chiral spinors, χ_{n_i,Y_i} ($n_i = 2I_i + 1 =$ number of components, $Y_i =$ hypercharge).
- Will introduce 4 multiplets; call set of multiplets a *polyplet*.

The Model

Fermion masses:

- Must give all new particles masses.
- Want predictive model w/masses tied to EW scale; require all masses be from $d = 4$ Yukawa couplings to SM Higgs, no 3D mass terms.
- Mass terms in Lagrangian:

$$\chi_{n_i,Y_i} \times \chi_{n_j,-Y_i-\frac{1}{2}} \times H_{2,\frac{1}{2}}$$
$$\chi_{n_i,Y_i} \times \chi_{n_j,-Y_i+\frac{1}{2}} \times H^*_{2-\frac{1}{2}}$$

  where $\times$ is multiplication to make $SU(2)$ singlet.

- For large multiplets, mixing with SM fermions can only happen via higher-dimensional operators. Also prevents DM decay.
- Requiring all fields massive constrains multiplet quantum numbers:

$$\begin{array}{cc} \chi_{n,Y} & \chi_{n+1,\frac{1}{2}-Y} \\ \chi_{n,Y-1} & \chi_{n-1,\frac{1}{2}-Y+A} \end{array}$$

  where $A = 0, 1$ or -1 (to be determined via anomaly cancellation).

The Model

Relation to SM?

- Let's ignore anomaly cancellation for the moment, consider $n = 1$ polyplet:

$$\begin{array}{cc} \chi_{1,Y} & \chi_{2,\frac{1}{2}-Y} \\ \chi_{1,Y-1} & -- \end{array}$$

- This relation of quantum numbers is satisfied by d_R^c, u_R^c, Q_L in SM.
- l_R^c, L in SM form incomplete polyplet–thus ν is massless.
- In SM, anomalies cancelled by having leptons, 3 colors of quarks.

The Model

Anomaly cancellation:

- Have introduced new fermions charged under $SU(2)$, $U(1)$; do not wish to ruin anomaly cancellation of SM.
- Must fulfill $U(1)$-gravity-gravity, $U(1)^3$, and $U(1) \times SU(2)^2$ cancellation relations:

$$\sum_{\text{multiplets } i} n_i Y_i = 0$$

$$\sum_{\text{multiplets } i} n_i Y_i^3 = 0$$

$$\sum_{\text{multiplets } i} C(i) Y_i = 0,$$

with $C(i) = I_i(I_i + 1)(2I_i + 1)$.

- Anomaly cancellation plus requiring fields to have integer charges gives $Y = 1/2$, $A = 0$.

The Model

- After giving masses to all new particles and imposing anomaly cancellation, we obtain

$$\begin{array}{cc} \chi_{n,+\frac{1}{2}} & \chi_{n+1,0} \\ \chi_{n,-\frac{1}{2}} & \chi_{n-1,0} \end{array}$$

- This set of quantum numbers allows for dimension-3 mass terms: $m_1(\chi_{n-1,0} \times \chi_{n-1,0})$, $m_2(\chi_{n+1,0} \times \chi_{n+1,0})$, and $m_3(\chi_{n,+\frac{1}{2}} \times \chi_{n,-\frac{1}{2}})$.
- Would like to disallow these terms, to have predictive model.
- Can add more multiplets to polyplet, loosen anomaly cancellation eqs.
- Instead, for simplicity, assign conserved "pseudo-lepton number" to multiplets.
- No restriction on n: take simplest polyplet w/integer charge, $n = 2$.
- Assign $\chi_{2,+\frac{1}{2}}$ and $\chi_{2,-\frac{1}{2}}$ PLN $= 1$, $\chi_{3,0}$ and $\chi_{1,0}$ PLN $= -1$.
  All SM fields: PLN $= 0$.
- PLN also prevents mixing with SM leptons.

The Model

Particle content:

- 8 chiral states

$$\chi_{2,+\frac{1}{2}} = \begin{pmatrix} \chi^{+}_{2,+\frac{1}{2}} \\ \chi^{0}_{2,+\frac{1}{2}} \end{pmatrix}, \qquad \chi_{3,0} = \begin{pmatrix} \chi^{+}_{3,0} \\ \chi^{0}_{3,0} \\ \chi^{-}_{3,0} \end{pmatrix},$$

$$\chi_{2,-\frac{1}{2}} = \begin{pmatrix} \chi^{0}_{2,-\frac{1}{2}} \\ \chi^{-}_{2,-\frac{1}{2}} \end{pmatrix}, \qquad \chi_{1,0}$$

- Form 4 massive Dirac fermions (neutral N_1, N_2, charged χ_1, χ_2).
- $\chi^0_{3,0}$ and $\chi_{1,0}$ both have $I_3 = Y = 0$, do not couple to Z.
- $\chi^0_{2,+\frac{1}{2}}$ and $\chi^0_{2,-\frac{1}{2}}$ have opposite I_3, Y, thus couplings to Z are equal with opposite sign. N_1, N_2 will have tunable Z couplings.
- N_1, N_2 also have off-mass-diagonal coupling to Z, W has both left/right couplings.

The Model

Yukawa couplings:

$$\begin{aligned}\mathcal{L} \supset \quad & -y_{+1}\left(\chi_{2,+\frac{1}{2}}\ \epsilon\ \tilde{H}\ \chi_{1,0}\right) - y_{-1}\left(\chi_{2,-\frac{1}{2}}\ \epsilon\ H\ \chi_{1,0}\right) \\ & -y_{+3}(\chi_{2,+\frac{1}{2}} \times \tilde{H} \times \chi_{3,0}) - y_{-3}(\chi_{2,-\frac{1}{2}} \times H \times \chi_{3,0}),\end{aligned}$$

give charged states χ_1, χ_2 masses of $\frac{|y_{+3}|v}{\sqrt{2}}$ and $\frac{|y_{-3}|v}{\sqrt{2}}$, respectively, Masses of neutral states N_1, N_2 are determined by the mass matrix

$$M = \frac{v}{\sqrt{2}}\begin{pmatrix} -y_{+1} & \frac{-y_{+3}}{\sqrt{2}} \\ y_{-1} & \frac{-y_{-3}}{\sqrt{2}} \end{pmatrix}$$

Can ensure that lightest particle is neutral by perturbing around

$$M = \frac{v}{\sqrt{2}}\begin{pmatrix} -y_{+1} & \frac{-y_{+3}}{\sqrt{2}} \\ y_{-1} & \frac{-y_{-3}}{\sqrt{2}} \end{pmatrix} = \frac{v}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix}$$

which gives χ_1, χ_2 mass v, neutral masses $m_1 = 0$, $m_2 = \sqrt{2}v$.

Constraints

- Invisible width of Z measured at LEP requires new particles with couplings same as SM ν's to have mass of at least 45.0 GeV.
- L3 considered new charged lepton $L^{\pm}$ decaying to new neutral L^0, $L^{\pm} \to L^0 W^{\pm}$; assumed $m_{L^0} > 40$ GeV, $5 < m_{L^{\pm}} - m_{L^0} < 60$ GeV. Lower bound on $L^{\pm}$ mass ~ 100 GeV.
- Studies of Tevatron monojets (Bai et al, arxiv:1005.3797), Delphi monophotons (Fox et al, arxiv:1103.0240) apply to $N_1 \bar{N}_1$ produced via Z. Constraints generally weaker than from direct detection; can be relevant for low DM masses.
- Could produce heavier invisible state N_2 at colliders, $Z \to N_2 N_1$ or $Z \to N_2 N_2$, followed by $N_2 \to N_1 Z$. LEP SUSY searches likely would rule out N_2 masses below ≈ 100 GeV (Carpenter arXiv:1010.5502).
- Higgs searches often used to constrain 4th-family scenarios, but not relevant here (no gg fusion contribution).
- Oblique parameters (in progress–stay tuned).

N_1 as a DM candidate

Two main constraints which we want the model to satisfy:

- Relic density: Want N_1 relic density to agree with observed $\Omega_d h^2 = 0.112 \pm 0.006$, requires thermally-averaged ann. x-sect

  $$< \sigma |v|/c > \sim 10^{-36} \text{ cm}^2$$

    - WIMP miracle: This cross-section is reasonable for interactions close to the electroweak scale.
    - $N_1 \bar{N}_1 \to$ SM via s-channel Z or H.
- Direct detection
    - Current limits on spin-indpt DM-nucleon x-sect from Xenon100: $\sim 10^{-44} \text{ cm}^2 \sim \frac{2\times 10^{-17}}{\text{GeV}^2}$.
    - Typical direct detection x-sect if governed by NP scale Λ: $\sim \frac{\mu^2}{\Lambda^4}$ ($\mu =$ reduced mass, ~ 1 GeV).
    - Weak-scale x-sect ruled out by several orders of magnitude.

Need significant enhancement in annihilation relative to nucleon scattering.

N_1 as a DM candidate

Considered:

- Tuning Z coupling to 0, annihilation via $N_1\bar{N}_1 \rightarrow H \rightarrow b\bar{b}, c\bar{c}, \tau\bar{\tau}$. (Relic density too large, direct detection too strong.)
- Z coupling full-strength, resonant annihilation via H. (Relic density tiny, but still ruled out by direct detection.)

Solution:

- Tune $N_1\bar{N}_1 Z$ coupling to 0, N_1 interacts with SM only via Higgs.
- Take N_1 sufficiently heavy to allow annihilation via $N_1\bar{N}_1 \rightarrow W^+W^-, ZZ$; no small Yukawa suppression.
- Direct detection x-sect suppressed by light quark Yukawa couplings.
- Get observed relic density and evade direct detection constraints if $m_1 \sim 150$ GeV and have somewhat heavy Higgs, ~ 600 GeV. (Solutions also possible for heavier m_1, m_H.)
- Note: Heavy SM Higgs ruled out by CMS (but not Atlas) up to 600 GeV, but constraints could be slightly loosened by new decays $H \rightarrow N_i\bar{N}_i$, $H \rightarrow \chi_i\bar{\chi}_i$.

Conclusions

- Larger fermionic $SU(2)$ multiplets very simple SM extension.
- If multiplets large, gives simple mechanism for stability of DM.
- Can tie masses to electroweak scale, produce predictive model.
- Gives new particles charged under SM gauge group, so have to worry about triangle anomalies and precision electroweak constraints.
- Large regions of mass and mixing parameters not well constrained.
- Can produce a viable DM candidate.