The darkness within: Unification & revival of the right

by

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Unsolved Questions

- Neutrino Mass
- Baryon Asymmetry

- Parity Violation (!)
- Dangling generator (!)
- Fractional Charges (!)
- Coupling Unification (!)

- Naturalness
- Hierarchy

- Dark Matter (?)

Unsolved Questions

- Neutrino Mass — See saw
- Baryon Asymmetry — Sphalerons(???)

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Left-Right Symmetry

$$SU(3)_C \times U(1)_Y \times SU(2)_L \longrightarrow SU(3)_C \times U(1)_{EM}$$

$$SU(2)\left\{ \overbrace{\begin{bmatrix} u_L \\ d_L \end{bmatrix} + u_R + d_R}^{\text{Quarks}} \quad \overbrace{\begin{bmatrix} \nu_L \\ e_L \end{bmatrix} + e_R}^{\text{Leptons}} \right.$$

Pati, Salam [1973]
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Mohapatra, Pati [1975]
Senjanović, Mohapatra [1975]

Left-Right Symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

$$W_R^{\pm}, Z_R \Big\downarrow M_R$$

$$SU(3)_C \times U(1)_Y \times SU(2)_L \xrightarrow[W^{\pm}, Z]{} SU(3)_C \times U(1)_{EM}$$

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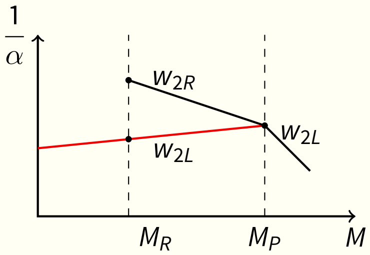
Parity Breaking

- Discrete $L \leftrightarrow R$ symmetry
- Under $L \leftrightarrow R$:
  - $F_L \leftrightarrow F_R$
  - $\Phi \leftrightarrow \Phi^\dagger$
  - $\Delta_L \leftrightarrow \Delta_R$
  - $\eta \leftrightarrow -\eta$
- $\mathcal{L} \rightarrow \mathcal{L}' = \mathcal{L}$



- η gets *vev* $\rightarrow v_\eta$
  - $L \leftrightarrow R$ broken
  - $SU(2)_L$ scalars heavy at v_η
  - Asymmetric contributions to loops
  - $g_L \neq g_R$

Chang,Mohapatra,Parida [1984]

SO(10)

- All the fermions (15+1) of a generation reside in the same representation of $SO(10) \to$ 16 dim.

  Georgi [1975]; Fritzsch, Minkowski [1975]

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  - Adjoint (45 dim.) and other representations have scalars odd under this operator

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...Falsifiability?

Unified Left-Right model with Dark Matter

The natural Z2

- **U(1)** broken by scalar of charge **'n'** $\longrightarrow$ remnant $\mathbf{Z_n}$
- $U(1)_{B-L}$ of LRS broken by the B-L=2 Δ_R, $\longrightarrow$ remnant Z_2
  - $P \equiv (-1)^{3(B-L)}$, “matter parity" if you will!
  - A bit more subtle than what is being said here

    M. Kadastik, Kannike, Raidal, 2009

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Screams “Dark Sector"

The natural Z_2

- SM Fermions:
  - Leptons: $3(B-L) = -3$, i.e. ‘odd’
  - Quarks: $3(B-L) = -1$, i.e. ‘odd’
- Scalars: $3(B-L) = 0$, i.e. ‘Even’

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- Scalars: $3(B-L)=0$, i.e. 'Even'

- Fermions with $B-L=$ even, belong in the dark sector
- The other way round for scalars

Mambrini, Nagata, Olive, Quevillon, Zheng, 2013

Heeck, Patra 2015

Model Mechanics

- ‘Real’ (Self-conjugate) $SU(2)$ multiplets

  $X_L \oplus X_R \equiv (1_C, (2m+1)_L, 1_R, 0) \oplus (1_C, 1_L, (2m+1)_R, 0)$

  $m \in \mathbb{N}$
- Each multiplet contains :
  - Majorana fermion
  - m pairs of Dirac fermions
  - electric charges 1 to m

Fermion Mass

$$\mathcal{L}_{X_M} = \frac{\mathcal{M}_i}{2}\left(\overline{X_L^{i\,c}} X_L^i + R \leftrightarrow L\right) + \frac{h_i}{2}(v_\eta + \eta)\left(\overline{X_L^{i\,c}} X_L^i - R \leftrightarrow L\right) + h.c.$$

All couplings set equal by $L \leftrightarrow R$ symmmetry

After parity breaks

$$M_i^L = \mathcal{M}_i + h_i v_\eta;\ M_i^R = \mathcal{M}_i - h_i v_\eta$$

$M_L \longrightarrow$ High scale
$M_R \longrightarrow$ Low scale

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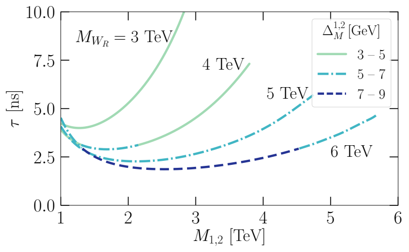
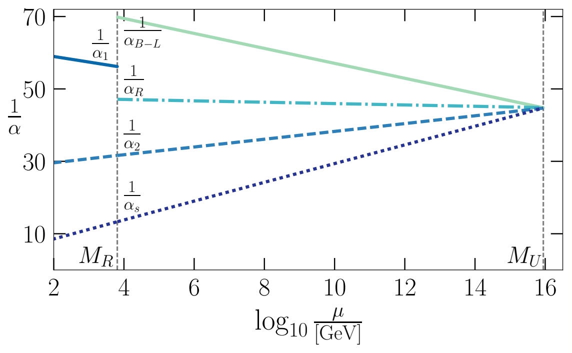


Gauge Coupling Unification



$g_R = 0.52$
$g_U = 0.53$
$4 < M_R < 9$ TeV
$M_U \sim 10^{16}$ GeV

Triplets (m=1)

- 1 'generation' $\longrightarrow M_R \sim \mathcal{O}(\text{PeV})$
- 2 'generations' $\longrightarrow M_R \sim \mathcal{O}(\text{TeV})$

SO(10)

Embedding

$$45 \supset (1,3,1) + (1,1,3) \quad + \quad (15,1,1) + (6,2,2)$$

$$\mathcal{L}_{\text{Mass}} = -\frac{\mathcal{M}_{1,2}}{2} \overline{45_F^{1,2}}^C 45_F^{1,2} + h.c. \quad ,$$

For triplets

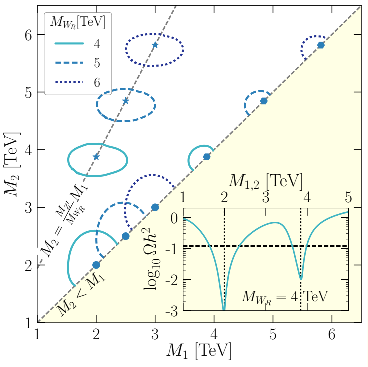
$$M_i^L = \mathcal{M}_i + h_i v_\eta ; \; M_i^R = \mathcal{M}_i - h_i v_\eta$$

(15,1,1),(6,2,2)

Do not couple to $\eta \longrightarrow$ No splitting

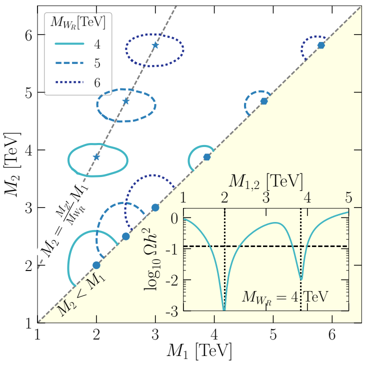
Only consistent way of keeping the mass of a submultiplet low

Relic Density



- Resonance mediated
- Around:
  - $(W_R, W_R), (Z', Z'), (W_R, Z')$
- $\chi^{\pm}\chi^0 \to SM\ SM$
- $\chi^+\chi^- \to SM\ SM$
- $\chi^0\chi^0 \to W_R W_R$

Relic Density



- Resonance mediated
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  - $(W_R, W_R), (Z', Z'), (W_R, Z')$
- $\chi^{\pm}\chi^0 \rightarrow SM\ SM$
- $\chi^{+}\chi^{-} \rightarrow SM\ SM$
- $\chi^0\chi^0 \rightarrow W_R W_R$

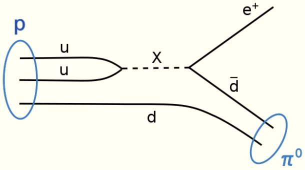
- g_R, M_R, M_χ determined $\Longrightarrow$ Highly predictive
- Very small leeway for parameters to vary
- Falsifiable $\longrightarrow$ How???

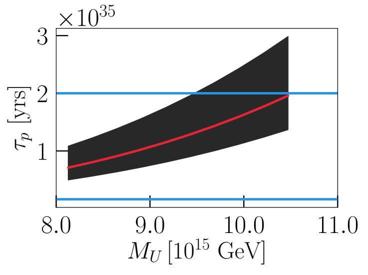
Experimental Verification

Proton Decay

Protons decay in unified theories

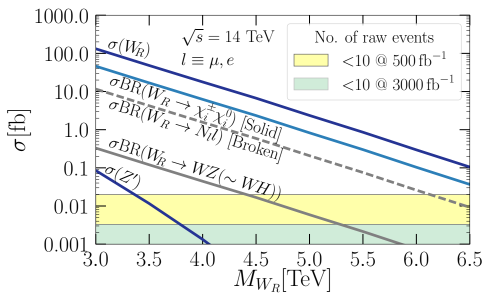
- Leptoquark gauge bosons
- Dominant Channels
  - $p \to \pi^0 e^+ / K^+ \overline{\nu}$





- Super-K exclusion
  - $\tau_p > 1.6 \times 10^{34}$ yrs.
- Hyper-K projected [2045]
  - $\tau_p \gtrsim 2 \times 10^{35}$ yrs.

Collider Searches (W_R)

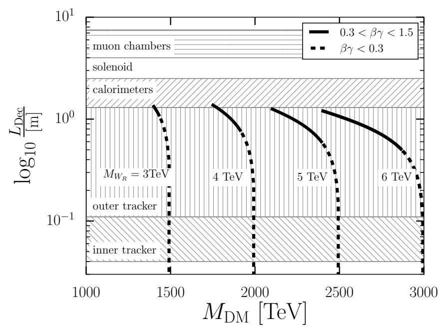


- $M_{Z'} \sim 1.9 \times M_{W_R}$
- $M_{\chi_1} = M_{\chi_2} = M_N$

- χ lighter than W_R
- Wildly different branching fractions
- Slim parameter space
- Easy to distinguish from standard LRS

Collider Searches (χ)

$$pp \to W_R^+ \to \chi^0 \chi^+ \to \chi^0 \chi^0 jj$$



- $\tau \sim$ ns
- $L = \beta c \gamma \tau$
- $L \to 0.1 - 1$m

- $\beta\gamma \longrightarrow$ Bethe Bloch

$\longrightarrow$ Highly ionizing

- Easy to distinguish from SM
- CMS, ATLAS, MoEDAL $\to$ Longlived heavy charged particle searches

Conclusions

- Unified models $\rightarrow$ answers to questions raised by SM
- Notoriously difficult to have ‘clean’ unification with $\mathcal{O}$(TeV) Physics
- We propose a left-right symmetric SO(10) ‘formalism’:
  - Mechanism to keep parts of larger fermionic multiplets light
  - Suitable dark matter candidates
  - Highly restricted parameter space
  - Falsifiability at all thresholds

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... Spectre of fermion hierarchy

Acknowledgements

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"Left-right model with TeV fermionic dark matter and unification," trip and A.Raychaudhuri
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Thank You

Questions/Input/Critique?