Identifying the nature of dark matter in GUT framework

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Introduction

Standard Model issues (non exhaustive...) :

- Complex gauge structure : $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$: no gauge coupling unification at high energy scale
- Hierarchy problem and vacuum stability
- Neutrinos masses
- Why 3 families of quark and leptons?

Other important issues :

- Dark matter : Rotation curves, the *Bullet Cluster*, the CMB, N-body simulations, structure formation $\rightarrow$ Cold Dark Matter?
- Dark energy : 70% of the energy budget of the universe

Can we find a more general description of the particle content of the Standard Model and include dark matter?

Toward Grand Unification Theories?

End of the 19th century : First step toward GUTs : James Clerk Maxell in "A Dynamical Theory of the Electromagnetic Field" unify electricity and magnetism

In the 60's : Glashow, Weinberg and Salam describe weak interactions and electromagnetism with a single gauge structure $SU(2) \otimes U(1)$

In the 1974 First attempt to embed the SM gauge group in a single one by Georgi and Glashow with SU(5)

$$\mathbf{24} = \underbrace{(\mathbf{8}, \mathbf{1}, 0)}_{g} \oplus \underbrace{(\mathbf{1}, \mathbf{3}, 0)}_{W^{1,2,3}} \oplus \underbrace{(\mathbf{1}, \mathbf{1}, 0)}_{B} \oplus \underbrace{(\mathbf{3}, \mathbf{2}, -5/6)}_{X} \oplus \underbrace{(\overline{\mathbf{3}}, \mathbf{2}, +5/6)}_{X}$$

Nice features :

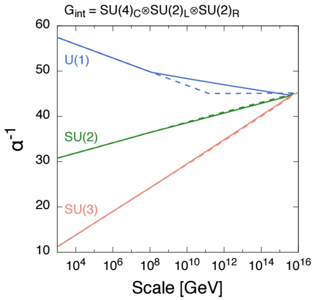
1 generation of SM fermions in $\overline{\mathbf{5}} \oplus \mathbf{10}$
$\sin^2(\theta_w) = 3/8$ predicted at M_{GUT}
$Q(d) = 1/3 Q(e^-)$ natural
Anomaly free theory

But there are some issues :

Proton decay predicted but too fast!
$M_x \approx 10^{12} M_Z$
No gauge coupling unification
No clue about ν_R

GUT with $SO(10)$: Minkowski and Fritzsch

- One generation of SM fermions + ν_R embedded in the **16** representation
- Unification of gauge couplings at $\sim 10^{15}$GeV
- Intermediate scale at $\sim 10^{10}$GeV $\rightarrow$ natural seesaw?
- Anomaly free
- Respecting proton lifetime constraints
- Remnant $\mathbb{Z}_2$ symmetry $\rightarrow$ DM stability? [Mambrini et al. '15]



$$\Psi_L = \begin{bmatrix} u_r \\ u_g \\ u_b \\ \nu \\ d_r \\ d_g \\ d_b \\ e \\ d^c_r \\ d^c_g \\ d^c_b \\ e^c \\ -u^c_r \\ -u^c_g \\ -u^c_b \\ -\nu^c \end{bmatrix}_L$$

Running of SM gauge couplings in SO(10) GUT (1502.06929)

The emergence of a Z'

We consider general GUT inspired scenarios assuming that $SO(10)$ is broken $SO(10) \to G_{int} \to G_{SM} \otimes U'(1)$.

We consider also a larger group E_6 where $E_6 \supset SO(10)$

Grand unification inspired scenarios [Langacker 0801.1345]

- Scenario χ : $SO(10) \to SU(5) \otimes U(1)_\chi$
- Scenario ψ : $E_6 \to SO(10) \otimes U(1)_\psi$
- Scenario η : string inspired $Z'_\eta = \sqrt{3/8} Z'_\chi + \sqrt{5/8} Z'_\psi$
- $B - L$ and LR scenarios :
  $SO(10) \to SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \to SU(2)_L \otimes U(1)_Y \otimes U(1)_{LR}$

Reference model

- *Sequential Standard Model* (SSM) : couplings Z'-SM $=$ Z-SM

Can we include dark matter in those models?

Z' portal : the lagrangian

	χ	ψ	η	LR	B-L	SSM
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}_L^u$	-1	1	-2	-0.109	1/6	$\frac{1}{2}-\frac{2}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_L^d$	-1	1	-2	-0.109	1/6	$-\frac{1}{2}+\frac{1}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_R^u$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_R^d$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2(\theta_W)$
$\hat{\epsilon}_{L,R}^\chi$	?	?	?	?	?	?

Couplings from the different theories considered $\epsilon^i_{L,R} = \hat{\epsilon}^i_{L,R}/D$

- the couplings between SM particles (f) and Z' are fixed by construction
- the mass of the Z' is not fixed
- To parametrize our ignorance, we suppose an interaction between the DM particles (χ) and Z' of the form :

$$\boxed{\mathcal{L} = g' \left(\bar{f}\gamma^\mu(V_f - A_f\gamma^5)fZ'_\mu + \bar{\chi}\gamma^\mu(V_\chi - A_\chi\gamma^5)\chi Z'_\mu\right)} \qquad \alpha = \frac{A_\chi}{V_\chi}$$

1. Introduction

2. From Grand Unification Theories to Z' portal DM
   - Z' from $SO(10)$ GUT
   - Combining Z' and dark matter

3. Distinguish Z' theories and experimental constraints
   - Direct detection
   - Experimental constraints

Direct detection

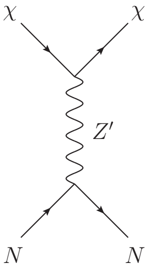
→ Try to measure the energy recoil E_R of a nucleus from an interaction with dark matter : LUX, PICO, XENON100, CDMS... and many more in the next years! (XENON1T, LZ,...)

Event rate ($\mathrm{kg}^{-1}\mathrm{j}^{-1}\mathrm{kev}^{-1}$)

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_0}{M_{nuc}\, m_\chi} \int_{v_{min}}^{v_{esc}} f(v) \frac{d\sigma}{dE_R}(v, E_R) v dv}$$

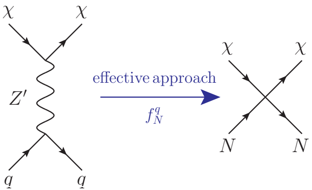
- DM mass m_χ : unknown
- nucleus mass M_{nuc}
- DM density in the solar system ρ_0 and velocity distribution $f(v)$: astrophysical observations
- Differential cross section $d\sigma/dE_R$:

$$\frac{d\sigma}{dE_R} = \frac{M_{nuc}}{2\mu_{nuc}^2 v^2}[\sigma_0^{SI} F_{SI}^2(q) + \sigma_0^{SD} F_{SD}^2(q)]$$



Scattering of a DM particle χ on a nucleus N

Consequences on scattering cross section :



$$\mathcal{L}_{\chi q} = \lambda_{\chi q}\bar{\chi}\chi\bar{q}q \Rightarrow \mathcal{L}_{\chi N} = \lambda_{\chi N}\bar{\chi}\chi\bar{N}N$$

$$\lambda_{\chi N} = \sum_q f_N^q \lambda_{\chi q} \text{ with } N = n, p$$

$$\sigma_{SI}^p = \frac{\mu_{\chi p}^2 g'^4 V_\chi^2}{\pi M_{Z'}^4}\alpha_{SI}$$

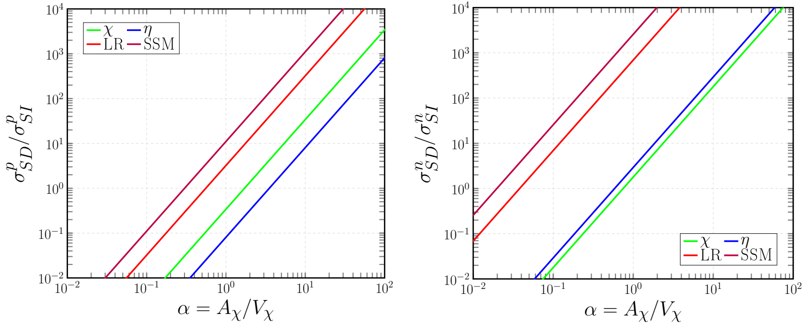
$$\sigma_{SD}^p = \frac{3\mu_{\chi p}^2 g'^4 A_\chi^2}{\pi M_{Z'}^4}\alpha_{SD}$$

$$\alpha_{SI} = \frac{\sum_A \eta_A A^2[V_u(1+Z/A) + V_d(2-Z/A)]^2}{\sum_A \eta_A A^2}$$

$$\alpha_{SD} = \frac{\sum_A \eta_A[A_u(\Delta_u^p S_p^A + \Delta_u^n S_n^A) + A_d(\Delta_d^p S_p^A + \Delta_d^n S_n^A + \Delta_s^p S_p^A + \Delta_s^n S_n^A)]^2}{\sum_A \eta_A[S_p^A + S_n^A]^2}$$

Proton and neutron cross sections

$$\frac{\sigma^p_{SD}}{\sigma^p_{SI}} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}}, \qquad \frac{\sigma^n_{SD}}{\sigma^n_{SI}} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}} \left(\frac{2V_d + V_u}{2V_u + V_d}\right)^2 \left(\frac{A_u\Delta^p_u + A_d(\Delta^p_d + \Delta^p_s)}{A_u\Delta^n_u + A_d(\Delta^n_d + \Delta^n_s)}\right)^2$$

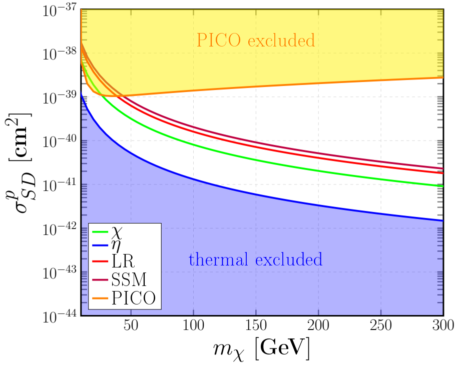


Constraints on σ^p_{SD}

From Boltzmann equation $<\sigma v> \simeq 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} (\simeq 10^{-9}\ \text{GeV}^{-2})$ for a thermal dark matter → velocity expansion of $<\sigma v>$ (N : Numerical factor)

$$<\sigma v> \underset{v\to 0}{\approx} \frac{m_\chi^2 g'^4}{\pi M_{Z'}^4} \left(V_\chi^2 + N A_\chi^2 v^2\right) \sum_f (A_f^2 + V_f^2)$$

We can make a prediction for σ^p_{SD} respecting the strong constraints form the LUX collaboration on σ^p_{SI}, and compare with PICO results (1503.00008).



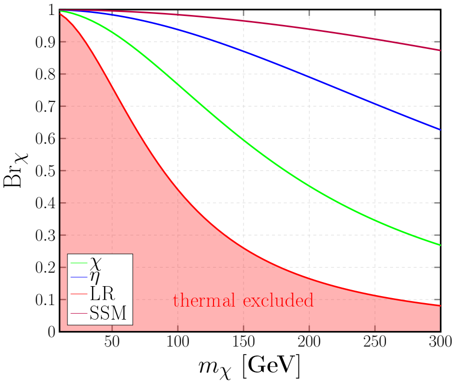
The invisible branching ratio

Strong constraints are set on M'_Z by Tevatron, LEP2 and the LHC (0801.1345), for all theories considered $M'_Z \gtrsim 800$ GeV at least.

Combining those constraints and direct detection we can constraint the invisible branching ratio :

$$Br_\chi = \frac{\Gamma_\chi^{Z'}}{\Gamma_\chi^{Z'} + \sum_f \Gamma_{SM}^{Z'}}$$

$$Br_\chi = \left[1 + \frac{\mu_{\chi p}^2 g'^4 \alpha_{SI}}{\pi M_{Z'}^4} \sum_f \frac{A_f^2 + V_f^2}{\sigma_{SI}^p (1+\alpha^2)}\right]^{-1}$$



Conclusion

Work done :

- SO(10) GUT framework
- Evolution of SD/SI ratio with nature of the DM coupling
- Constraints on σ_{SD}
- Constraints on the branching ratio

Perspectives :

- Combine direct detection and collider experiments constraints
  $\rightarrow$ possible signatures at the LHC?
- Incoporate DM in the theoretical models!
- Paper in preparation : G.Arcadi, Y.Mambrini, M.Pierre