Lightest U-parity Particle (LUP) dark matter

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HL, K. Matchev, T. Wang [0709.0763]; T. Hur, HL, S. Nasri [0710.2653];

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SUSY 2008

Lightest U-parity Particle (LUP) dark matter

in the R-parity violating SUSY model

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SUSY 2008

Outline

- Companion symmetry of SUSY
  - R-parity
  - TeV scale $U(1)'$ gauge symmetry
- R-parity violating, $U(1)'$-extended SUSY model
  - Proton stability
  - Dark matter candidate

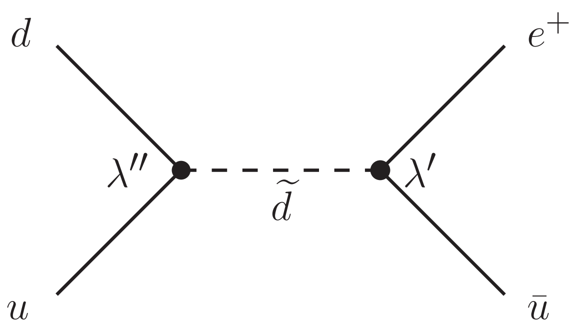
Companion symmetry of SUSY

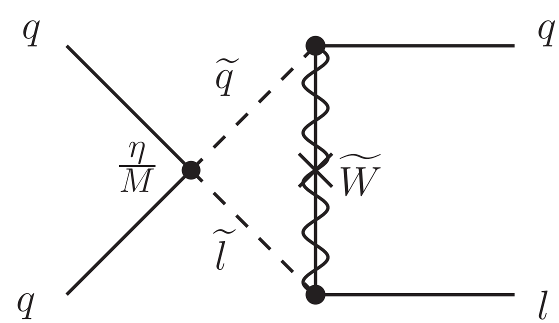
SUSY with R-parity

$$
\begin{aligned}
W_{R_p} &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ (\lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c) \\
&+ \frac{\eta_1}{M} Q Q Q L + \frac{\eta_2}{M} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

1. μ-problem: $\mu \sim \mathcal{O}$(EW) to avoid fine-tuning in the EWSB.
   (Kim, Nilles [1984])
2. over-constraining of the R-parity: All renormalizable $\mathcal{L}$ violating and $\mathcal{B}$ violating terms are (unnecessarily) forbidden.
3. under-constraining of the R-parity: Dimension 5 $\mathcal{L}$&$\mathcal{B}$ violating terms still mediate too fast proton decay. (Weinberg [1982])

Fast proton decay





[Dim 4 $\mathcal{L}$ violation $\&$ Dim 4 $\mathcal{B}$ violation]

R-parity violating terms

[Dim 5 $\mathcal{B}\&\mathcal{L}$ violation]

R-parity conserving terms

Look for an additional or alternative explanation (symmetry).

$\longrightarrow$ We will consider a TeV scale Abelian gauge symmetry, $U(1)'$.

TeV scale $U(1)'$ gauge symmetry

Natural scale of $U(1)'$ in SUSY models is TeV (linked to sfermions scales).

$\longrightarrow$ provides a natural solution to the μ-problem.

Two conditions to "**solve the μ-problem**". ($z[F]$: $U(1)'$ charge of F)

- $\mu H_u H_d : \text{forbidden} \qquad z[H_u] + z[H_d] \neq 0$
- $h S H_u H_d : \text{allowed} \qquad z[S] + z[H_u] + z[H_d] = 0$

S is a Higgs singlet that breaks the $U(1)'$ spontaneously.

$$\mu_{\text{eff}} = h \langle S \rangle \sim \mathcal{O}(\text{EW/TeV})$$

Goal

Construct a stand-alone R_p violating TeV scale SUSY model without

1. μ-problem: $U(1)'$
2. proton decay problem
3. dark matter problem (non-LSP dark matter)

"R-parity violating $U(1)'$ model" as an alternative to the usual "R-parity conserving model".

Use residual discrete symmetry of the $U(1)'$ to address the issues.

Conditions to have $U(1) \to Z_N$

$U(1)$ have a residual discrete symmetry Z_N if their charges satisfy (after normalization to integers):

- $z[S] = N$
- $z[F_i] = q[F_i] + n_i N$

($z[F_i]$: $U(1)$ charge, $q[F_i]$: Z_N charge) for each field F_i.

Discrete symmetry compatible with MSSM sector

Most general Z_N of the MSSM sector (Ibanez, Ross [1992]) is

$$Z_N : \; B_N^b L_N^\ell$$

with family-universal cyclic symmetries ($\Phi_i \longrightarrow e^{2\pi i \frac{q_i}{N}} \Phi_i$)

$$B_N = e^{2\pi i \frac{q_B}{N}}, \quad L_N = e^{2\pi i \frac{q_L}{N}}.$$

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_N	0	-1	1	-1	2	0	1	-1	$-\mathcal{B} + y/3$
L_N	0	0	0	-1	1	1	0	0	$-\mathcal{L}$

General discrete charge of Z_N is

$$\begin{aligned} q &= b q_B + \ell q_L \mod N \\ &= -(b\mathcal{B} + \ell\mathcal{L}) + b(y/3) \mod N. \end{aligned}$$

Residual discrete symmetry of the RPV $U(1)'$ model

: Proton stability without R-parity

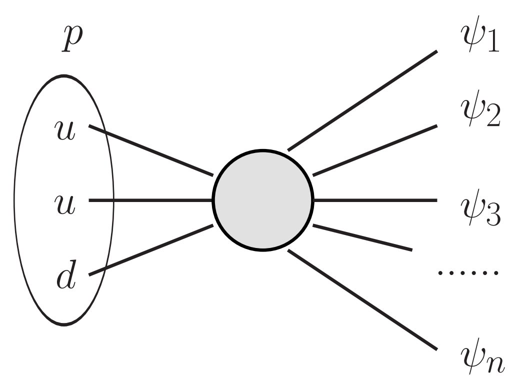
HL, Matchev, Wang [arXiv:0709.0763]

HL, Luhn, Matchev [arXiv:0712.3505]

Discrete symmetries in presence of exotics

- There may be TeV scale exotic fields required to cancel chiral anomaly.
- The MSSM discrete symmetries still hold among the MSSM fields.

For a physics process which has only MSSM fields in its effective operators (such as proton decay), we can still discuss with Z_N^{MSSM}.



$$\text{operator[p-decay]} = \left(\frac{1}{M}\right)^m [\underbrace{F_1 F_2 F_3 F_4 F_5 \cdots}_{\text{MSSM fields only}}]$$

Discrete symmetry in the $\mathcal{L}$ violating case

From the superpotential terms and $[SU(2)_L]^2$-$U(1)'$ anomaly condition, general $U(1)'$ charges for the MSSM sector in the $\mathcal{L}$ violating case :

$$\underbrace{\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix}}_{U(1)'\ \text{charge}} = \alpha' \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta' \begin{pmatrix} 0 \\ 3(1+n)+1 \\ -3n-1 \\ 1 \\ 3(1-a+n) \\ -3n-2 \\ 3n+1 \\ -3(1+n)-1 \\ 3 \end{pmatrix} \longrightarrow \underbrace{\begin{pmatrix} q[Q] \\ q[U^c] \\ q[D^c] \\ q[L] \\ q[N^c] \\ q[E^c] \\ q[H_d] \\ q[H_u] \\ q[S] \end{pmatrix}}_{Z_N\ \text{charge}} = - \begin{pmatrix} 0 \\ -1 \\ 1 \\ -1 \\ 0 \\ -1 \\ -1 \\ 1 \\ 0 \end{pmatrix} \bmod 3.$$

Compare with charge table. $\longrightarrow$ B_3 **(baryon triality) in the MSSM sector**

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_3	0	-1	1	-1	-1	0	1	-1	$-\mathcal{B}+y/3$

Selection rule of B_3 and proton stability

The discrete charge of B_3 for arbitrary operator is $(-\mathcal{B} + y/3) \bmod 3$.

$$\Delta\mathcal{B} = 3 \times \text{integer}$$

for any process. (Castano, Martin [1994])

(Baryon number can be violated by only $3 \times \text{integer}$ under the B_3.)

$\longrightarrow$ Proton decay ($\Delta\mathcal{B} = 1$): Forbidden

Ensuring proton stability in the $\mathcal{L}$ violating model (B_3)

1. Solve the μ-problem with $U(1)'$ gauge symmetry.
2. Require $\mathcal{L}$ violating terms such as $\lambda' LQD^c$.   [B_3 is invoked]
3. **Then proton is absolutely stable!**

Recap of the goal

Construct a stand-alone R_p violating TeV scale SUSY model without

1. μ-problem: $U(1)'$
2. proton decay problem: $U(1)' \rightarrow B_3$
3. dark matter problem (non-LSP dark matter)

A dark matter candidate without introducing an independent symmetry?

Residual discrete symmetry extended to hidden sector

: LUP dark matter from hidden sector

Hur, HL, Nasri [arXiv:0710.2653]

HL [arXiv:0802.0506]

SM-singlet exotics (hidden sector fields)

SM-singlet exotics: often required for anomaly cancellations with $U(1)'$

$$([\text{gravity}]^2 - U(1)',\ [U(1)']^3)$$

We consider Majorana fields for simplicity.

$$W_{\text{hidden}} = \frac{\xi}{2} S X X$$

These hidden sector fields (X) are neutral and massive particles.

$\longrightarrow$ Potentially dark matter candidate if they are stable.

How to stabilize hidden sector field?

Introduce "U-parity"

$$U_p[\text{MSSM}] = \text{even}, \quad U_p[X] = \text{odd}$$

- Lightest U-parity Particle (LUP): $\underbrace{\text{Lightest } X}_{\text{either fermion } (\psi_X) \text{ or scalar } (\phi_X) \text{ component}} \rightarrow$ stable

It can be invoked as a residual discrete symmetry of the $U(1)'$.

$$Z_N^{hid} : \; U_2 \quad (U\text{-parity})$$

$$z[F_i] = q[F_i] + 2n_i$$

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	meaning of q
U_2	0	0	0	0	0	0	0	0	-1	$-\mathcal{U}$ (X number)

(Other exotics: assumed to be heavier than the lightest X.)

Discrete symmetries over the MSSM and the hidden sectors

Now consider $U(1)' \longrightarrow Z_6^{tot}$, which is

$$Z_6^{tot} = B_3 \times U_2$$

with $q = 2q_B + 3q_U \bmod 6$.

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X
$Z_6 = B_3 \times U_2$	0	-2	2	-2	-2	0	2	-2	-3

(Other exotic fields: assumed to be heavier than proton and the LUP
$\longrightarrow$ not stable due to the discrete symmetry.)

More generally, it is $U(1)' \longrightarrow Z_N^{tot}$, which is

$$Z_N^{tot} = Z_{N_1}^{obs} \times Z_{N_2}^{hid}$$

(where $N = N_1 N_2$; N_1 and N_2 are coprime).

A unified picture of the stabilities in the observable and hidden sectors

$$U(1)' \to Z_{N_1}^{obs} \times Z_{N_2}^{hid}$$

MSSM sector		Hidden sector
$Z_{N_1}^{obs}$ (B_3)	—	$Z_{N_2}^{hid}$ (U_2)
: stable proton		: stable dark matter

A single $U(1)'$ gauge symmetry provides stabilities for proton (MSSM sector) and dark matter (hidden sector).

Lightest U-parity Particle (LUP)

- It is a neutral, massive, and stable particle from hidden sector.
- It can be either a fermion or a scalar.
- It is neither the RH neutrino nor RH sneutrino ($H_u L N^c$).
- It naturally arises when an extra $U(1)$ gauge symmetry is present.

To be a viable dark matter candidate, it should satisfy the relic density and direct detection constraints, too.

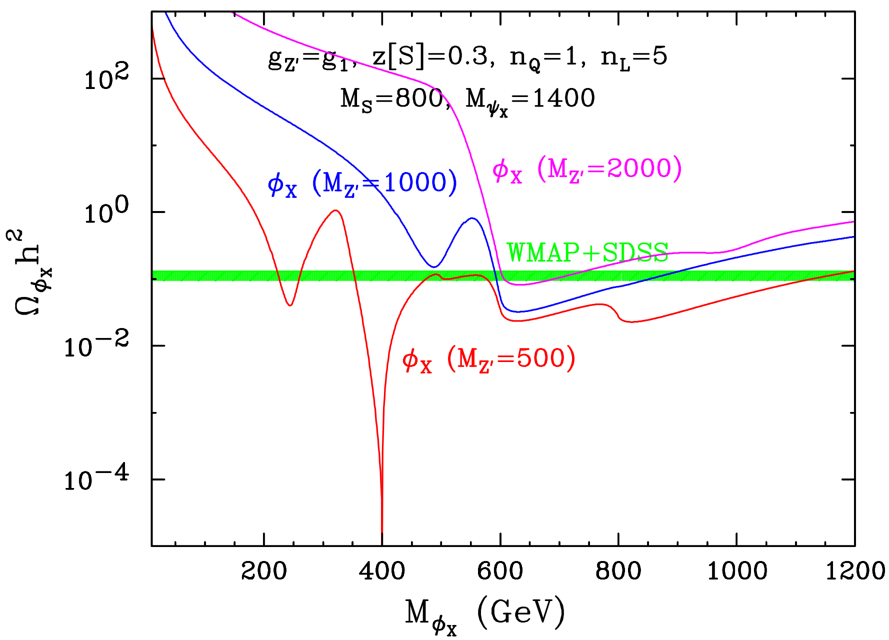
Annihilation channels for the LUP dark matter

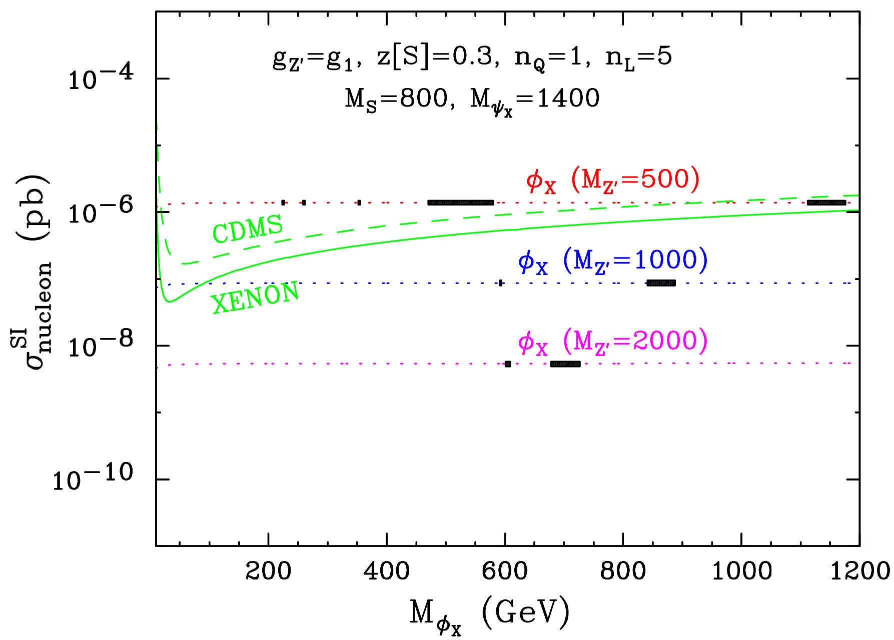
For ψ_X (fermionic) LUP,

1. $\psi_X \psi_X \to f \bar{f}$ (Z' mediated s-channel)
2. $\psi_X \psi_X \to \widetilde{f} \widetilde{f}^*$ (S mediated s-channel, Z' mediated s-channel)
3. $\psi_X \psi_X \to SS$, $Z'Z'$ (S mediated s-channel, ψ_X mediated t-ch)
4. $\psi_X \psi_X \to SZ'$ (Z' mediated s-channel, ψ_X mediated t-channel)
5. $\psi_X \psi_X \to \widetilde{S} \widetilde{S}$ (Z' mediated s-channel, ϕ_X mediated t-channel)
6. $\psi_X \psi_X \to \widetilde{Z}' \widetilde{Z}'$ (ϕ_X mediated t-channel)
7. $\psi_X \psi_X \to \widetilde{S} \widetilde{Z}'$ (S mediated s-channel, ϕ_X mediated t-channel)

and also similarly for ϕ_X (scalar) LUP.

Predictions of relic density and direct detection cross-section (for ϕ_X)





[Simulated with `micrOMEGAs` + newly constructed UMSSM model file]

LUP dark matter can satisfy both the relic density and direct detection constraints.

Summary

R-parity conserving model vs. R-parity violating $U(1)'$ model

	R_p	$U(1)' \longrightarrow B_3 \times U_p$
RPV signals	impossible	**possible**
μ-problem	not addressed	**solvable (**$U(1)'$**)**
proton	unstable w/ dim 5 op. (R_p)	**stable (**B_3**)**
dark matter	stable LSP (R_p)	**stable LUP (**U_p**)**

Summary

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proton	unstable w/ dim 5 op. (R_p)	**stable (B_3)**
dark matter	stable LSP (R_p)	**stable LUP (U_p)**

Conclusion: TeV scale $U(1)'$ is an attractive alternative to R-parity.