

Cold Dark Matter in the SE_6SSM

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Outline

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Based on:

R. Nevzorov, Leptogenesis and Dark Matter-Nucleon Scattering Cross Section in the SE_6 SSM, *Universe* **9** (2023) no.3, 137 [arXiv:2304.04629 [hep-ph]].

R. Nevzorov, On the Suppression of the Dark Matter-Nucleon Scattering Cross Section in the SE_6 SSM, *Symmetry* **14** (2022) no.10, 2090 [arXiv:2209.00505 [hep-ph]].

R. Nevzorov, Phenomenological aspects of supersymmetric extensions of the Standard Model, *Phys. Usp.* **66** (2023) 543.

S. F. King, S. Moretti and R. Nevzorov, A Review of the Exceptional Supersymmetric Standard Model, *Symmetry* **12** (2020) no.4, 557 [arXiv:2002.02788 [hep-ph]].

Introduction

- At very high energies $E \sim M_X \gtrsim 10^{16}$ GeV the SM can be embedded into **Grand Unified Theories (GUTs)** [H. Georgi, S. L. Glashow, Unity Of All Elementary Particle Forces, Phys. Rev. Lett. **32** (1974) 438].
 - In the case of the **minimal GUTs** based on $SU(5)$, each SM family of quarks and leptons fills in a complete representations of $SU(5)$: $\bar{5} + 10$.
 - Within $SO(10)$ GUTs, each family of SM fermions may belong to a single **16-dimensional spinor representation** of $SO(10)$.
 - The SM gauge bosons are assigned to the adjoint representations of $SU(5)$ and $SO(10)$.

- In $N = 1$ SUSY GUTs with the E_6 gauge group the fundamental 27 representation of E_6 decomposes under $SO(10) \times U(1)_\psi$ subgroup as

$$27 \rightarrow \left(16, \frac{1}{\sqrt{24}}\right) \oplus \left(10, -\frac{2}{\sqrt{24}}\right) \oplus \left(1, \frac{4}{\sqrt{24}}\right).$$

- $\left(16, \frac{1}{\sqrt{24}}\right)$ can include one family of quarks and leptons.
- The Higgs doublet may form components of $\left(10, -\frac{2}{\sqrt{24}}\right)$.
- The **SM gauge bosons** are assigned to **78-plet** (adjoint representation of E_6).

- In $N = 2$ SUSY GUTs with the E_8 gauge symmetry 248 representation decomposes under the E_6 subgroup of E_8 as follows:

$$248 \rightarrow 78 \oplus 3 \times 27 \oplus 3 \times \overline{27} \oplus 8 \times 1.$$

- Three generations of the SM fermions can be associated with three 27-plets which may also contain the doublet of the Higgs bosons.
 - Some components of the 78-plet may form the multiplets of the SM gauge bosons.
 - Thus all SM bosons and SM fermions may belong to a single 248 representation of E_8 .
- Currently, the best candidate for the Theory of Everything, i.e. hypothetical single framework that explains and links together all physical aspects of the universe, is ten-dimensional heterotic superstring theory based on $E_8 \times E_8'$.
- Compactification of the extra dimensions gives rise to the breakdown of E_8 to E_6 or its subgroups in the observable sector.
- At very high energies E_6 group can be broken to $SO(10) \times U(1)_\psi$ with sequential breakdown of $SO(10)$ to $SU(5) \times U(1)_\chi$ and $SU(5)$ to the SM gauge group $SU(3)_C \times SU(2)_W \times U(1)_Y$.

Exceptional SUSY model and its signatures

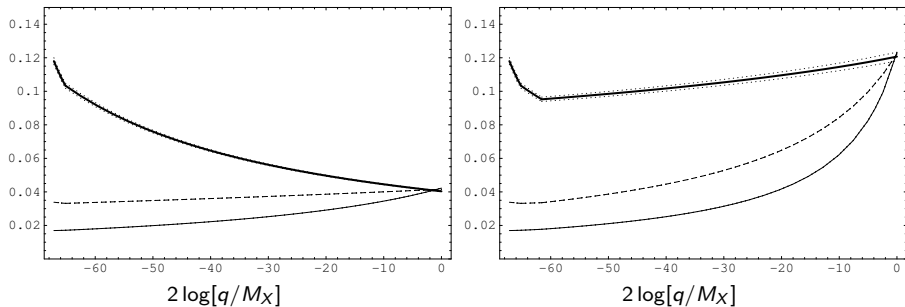
- Around the GUT scale M_X the rank-6 SUSY model with additional $U(1)_\psi \times U(1)_\chi$ can be reduced to rank-5 SUSY models with only one extra $U(1)'$

$$U(1)' = U(1)_\chi \cos \theta_{E_6} + U(1)_\psi \sin \theta_{E_6} .$$

- The $U(1)'$ gauge symmetry forbids μ term in the superpotential of these models if $\theta_{E_6} \neq 0$ or π .
- The μ problem in these models is solved in a similar way to the NMSSM.
- The exceptional supersymmetric standard model (E_6 SSM) is the $U(1)_N$ extension of the MSSM, which corresponds to $\theta_{E_6} = \arctan \sqrt{15}$ [S.F.King, S.Moretti, RN, Phys. Rev. D 73 (2006) 035009; Phys. Lett. B 634 (2006) 278; Symmetry 12 (2020) no.4, 557 [arXiv:2002.02788 [hep-ph]].]
 - It implies that $U(1)_\psi \times U(1)_\chi$ symmetry is broken to $U(1)_N \times Z_2^M$, where $Z_2^M = (-1)^{3(B-L)}$ is a matter parity, B and L are baryon and lepton numbers.
 - Only in this E_6 inspired $U(1)'$ extension of the MSSM right-handed neutrinos N_i do not participate in the gauge interactions so that they can be superheavy.

- To ensure anomaly cancellation the particle content of the E_6 SSM is extended to include three complete 27_i representations of E_6 .
- In addition the spectrum of the E_6 SSM is supplemented by $SU(2)_W$ doublet and anti-doublet from extra $27'$ and $\overline{27}'$ (L_4 and \overline{L}_4) to preserve gauge coupling unification.
- Thus the E_6 SSM predicts the existence of Z' and **extra exotic matter** beyond the MSSM.

Two-loop RG flow of $\alpha_i(\mu)$ in the MSSM and E_6 SSM



- In particular, the E_6 SSM contains:
 - three pairs of the supermultiplets of exotic quarks (D_i and \bar{D}_i) with electric charges $\pm 1/3$ which can be either diquarks or leptoquarks;
 - three pairs of the $SU(2)_W$ -doublets (H_i^d and H_i^u) that have quantum numbers of the MSSM Higgs doublets;
 - three SM singlet superfields S_i that carry non-zero $U(1)_N$ charges.
- It is expected that extra exotic matter supermultiplets couple most strongly with the third family SM fermions and their superpartners.
- The searches for the decays of the $U(1)_N$ gauge boson into e^+e^- and $\mu^+\mu^-$ by the LHC experiments set lower limit on its mass which is about 4.5 TeV.
- In the E_6 SSM the lightest exotic colored state can be a superposition of scalar components of the supermultiplets \bar{D}_i and D_i .
- In this case the lightest exotic squark \tilde{D}_1 decays either via

$$\tilde{D}_1 \rightarrow t + \tau, \quad \tilde{D}_1 \rightarrow b + \nu_\tau$$

if exotic quarks are leptoquarks or via

$$\tilde{D}_1 \rightarrow \bar{t} + \bar{b}$$

if exotic quarks are diquarks.

- In the limit, when all Yukawa couplings of D_i and \bar{D}_i are small, the lightest exotic squarks may only be pair produced at the LHC.
- Assuming Run 2 full luminosity, the sensitivity of LHC searches for scalar leptoquarks predicted by the E_6 SSM was explored [M. Ali, S. Khalil, S. Moretti, S. Munir, R. Nevzorov, A. Nikitenko and H. Waltari, JHEP 03 (2023) 117; arXiv:2302.02071 [hep-ph]].
 - For $BR(\tilde{D}_1 \rightarrow t\tau) \approx 1$ it was found that the fully hadronic channel has a better estimated sensitivity improving the ATLAS lower bound on the mass of \tilde{D}_1 ($m_{\tilde{D}_1}$) by about 150 GeV, i.e. $m_{\tilde{D}_1} \gtrsim 1580$ GeV.

The NLO production cross sections for $pp \rightarrow \tilde{D}_1 \tilde{D}_1^*$ at $\sqrt{s} = 13$ TeV.

$m_{\tilde{D}_1}$ (GeV)	1000	1100	1200	1300	1400	1500	1600
σ_{NLO} (fb)	5.73	2.86	1.50	0.79	0.44	0.25	0.146

- The fermion components of D_i and \bar{D}_i are R -parity odd states.
- Therefore they decay into a final state that contains an odd number of the lightest supersymmetric particles (LSPs) and can only be created in pairs.

- When the lightest exotic colored state D_1 is a superposition of fermion components of the supermultiplets \bar{D}_i and D_i it decays either via

$$D_1 \rightarrow t + \tau + E_T^{\text{miss}} + X, \quad D_1 \rightarrow b + \nu_\tau + E_T^{\text{miss}} + X$$

if exotic quarks are leptoquarks or via

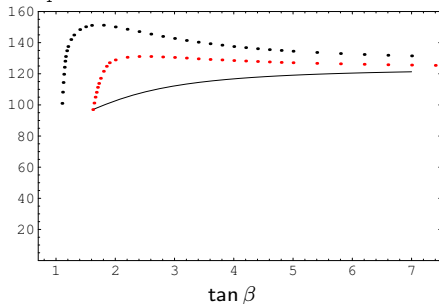
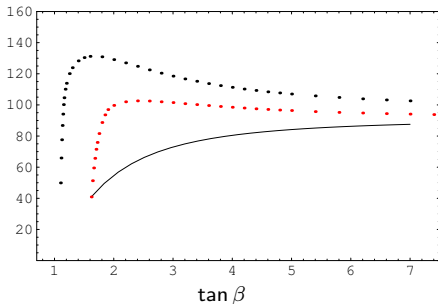
$$D_1 \rightarrow \bar{t} + \bar{b} + E_T^{\text{miss}} + X$$

if exotic quarks are diquarks.

- The pair production of D_1 at the LHC may result in the enhancement of the cross sections of either $pp \rightarrow b\bar{b} + E_T^{\text{miss}} + X$ and $pp \rightarrow t\bar{t}\tau\bar{\tau} + E_T^{\text{miss}} + X$ or $pp \rightarrow t\bar{t}b\bar{b} + E_T^{\text{miss}} + X$.
- At the LHC the components of other exotic matter supermultiplets can be produced via the electroweak interactions.
- As a consequence their production cross section remains relatively small even if the corresponding states have masses around 1 TeV.

- In the **MSSM**, **NMSSM** and **E₆SSM** there are theoretical restrictions on the lightest Higgs boson mass m_{h_1} .
- The upper bound on m_{h_1} in the E₆SSM is considerably larger than in the MSSM and NMSSM.
- In the E₆SSM m_{h_1} can be heavier **120 GeV** even at the tree level.
- New particle with mass around **125 GeV** discovered by the LHC experiments is consistent with these SUSY extensions of the SM.

Tree level and two-loop upper bounds on m_{h_1} in the **E₆SSM**, **NMSSM** and **MSSM**



- The presence of extra exotic matter in the E_6 SSM can result in non-diagonal flavor transitions and rapid proton decay.
- A set of discrete symmetries can be used to suppress the corresponding operators.
- These symmetries do not commute with E_6 .
- The necessity of introducing multiple discrete symmetries to ameliorate phenomenological problems is an undesirable feature of the E_6 SSM.
- Moreover within the E_6 SSM and its simplest modifications the lightest and next-to-lightest SUSY particles (LSP and NLSP) are linear superpositions of the fermion components of the superfields S_i .
- In the simplest scenarios these states are either massless or have masses which are much smaller than 1 eV forming hot dark matter in our Universe.

- Extra exotic matter may give rise to non-diagonal flavor transitions and rapid proton decay.
- In the modification of the E₆SSM (SE₆SSM) a single discrete \tilde{Z}_2^H symmetry forbids flavor-changing transitions as well as the most dangerous baryon and lepton number violating operators.
 - The SE₆SSM implies that below the GUT scale M_X three complete 27-plets are accompanied by lepton doublets L_4 and \bar{L}_4 , a pair of superfields S and \bar{S} as well as four E_6 singlet superfields (ϕ and ϕ_i).
 - The supermultiplets ϕ , S , \bar{S} , L_4 , \bar{L}_4 as well as $SU(2)_W$ doublets $H_d \equiv H_3^d$ and $H_u \equiv H_3^u$ are required to be even under the \tilde{Z}_2^H symmetry whereas all other supermultiplets are odd [R. Nevzorov, Phys. Rev. D 87 (2013) 015029; P. Athron, M. Mühlleitner, R. Nevzorov, A.G. Williams, JHEP 1501 (2015) 153.].
- The presence of L_4 and \bar{L}_4 at low energies allows the lightest exotic colored state to decay before BBN and facilitates the unification of gauge couplings.

- The most general renormalisable superpotential of the **SE₆SSM** is given by

$$\begin{aligned}
 W = & \lambda S(H_u H_d) - \sigma \phi S \bar{S} + \frac{\kappa}{3} \phi^3 + \frac{\mu}{2} \phi^2 + \Lambda \phi + \mu_L L_4 \bar{L}_4 + \tilde{\sigma} \phi L_4 \bar{L}_4 \\
 & + W_{IH} + \kappa_{ij} S(D_i \bar{D}_j) + h_{i\alpha}^E e_i^c (H_\alpha^d L_4) + g_{ij}^D (Q_i L_4) \bar{D}_j \\
 & + g_{ij} \phi_i \bar{L}_4 L_j + W_N + W_{\text{MSSM}}(\mu = 0),
 \end{aligned}$$

where

$$\begin{aligned}
 W_{IH} = & \tilde{M}_{ij} \phi_i \phi_j + \tilde{\kappa}_{ij} \phi \phi_i \phi_j + \tilde{\lambda}_{ij} \bar{S} \phi_i S_j + \lambda_{\alpha\beta} S(H_\alpha^d H_\beta^u) \\
 & + \tilde{f}_{i\alpha} S_i(H_\alpha^d H_u) + f_{i\alpha} S_i(H_d H_\alpha^u), \\
 W_N = & \frac{1}{2} M_{ij} N_i^c N_j^c + \tilde{h}_{ij} N_i^c (H_u L_j) + h_{i\alpha} N_i^c (H_\alpha^u L_4).
 \end{aligned}$$

Transformation properties of different supermultiplets in the SE₆SSM

	$Q_i, u_i^c, d_i^c, L_i, e_i^c, N_i^c$	$\bar{D}_i, D_i, H_\alpha^d, H_\alpha^u, S_i, \phi_i$	$H_d, H_u, S, \bar{S}, \phi$	L_4, \bar{L}_4
\tilde{Z}_2^H	—	—	+	+
Z_2^M	—	+	+	—
Z_2^E	+	—	+	—

- In the SE_6SSM the sector responsible for the breakdown of the gauge symmetry is formed by the scalar components of ϕ , S , \bar{S} , H_d and H_u .
 - S and \bar{S} can develop large vacuum expectation values (VEVs) along the D-flat direction breaking the $U(1)_N$ symmetry and generating masses of all exotic fermions and Z' boson.
- The conservation of Z_2^M and \tilde{Z}_2^H symmetries implies that R -parity and Z_2^E symmetry are also conserved where $\tilde{Z}_2^H = Z_2^M \times Z_2^E$.
- Here we focus on the scenarios in which **gravitino** is the lightest R -parity odd state so that it is stable and contributes to the density of dark matter.
- In this case the lightest exotic state, which is odd under the Z_2^E symmetry, has to be stable as well.
- We assume that the lightest stable exotic state is predominantly formed by the fermion components of H_1^d and H_1^u .
- In order to find a viable scenarios with stable gravitino one needs to ensure that the lightest unstable R -parity odd (or exotic) state Y decays before BBN, i.e. its lifetime $\tau_Y \lesssim 1 \text{ sec}$.

- For $m_{\tilde{\gamma}} \simeq 1 \text{ TeV}$ one can get $\tau_{\tilde{\gamma}} \lesssim 1 \text{ sec}$ if gravitino mass $m_{3/2} \lesssim 1 \text{ GeV}$.
- When gravitinos originate from scattering of particles in the thermal bath their contribution to the dark matter density is proportional to the reheating temperature T_R [M. Bolz, A. Brandenburg, W. Buchmuller, Nucl. Phys. B **606** (2001) 518; H. Eberl, I.D. Gialamas, V.C. Spanos, Phys. Rev. D **103** (2021) 075025.]

$$\Omega_{3/2} h^2 \sim 0.27 \left(\frac{T_R}{10^8 \text{ GeV}} \right) \left(\frac{1 \text{ GeV}}{m_{3/2}} \right) \left(\frac{M_{\tilde{g}}}{1 \text{ TeV}} \right)^2.$$

- Since $\Omega_{3/2} h^2 \leq 0.12$ for $m_{3/2} \simeq 1 \text{ GeV}$ and gluino mass $M_{\tilde{g}} \gtrsim 3 \text{ TeV}$ one finds an upper bound $T_R \lesssim 10^{6-7} \text{ GeV}$.
- Even for so low reheating temperatures the appropriate amount of the lepton asymmetry can be induced within the SE_6 SSM via the decays of the lightest right-handed neutrino/sneutrino (N_1 / \tilde{N}_1).
- Due to **sphaleron interactions** the generated lepton asymmetry is converted into the baryon asymmetry [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, Phys. Lett. B **155** (1985) 36; V.A. Rubakov, M.E. Shaposhnikov, Phys. Usp. **39** (1996) 461].

- In the SE_6SSM the interactions of the superfields N_i are described by

$$W_N = \frac{1}{2} M_i N_i N_i + \tilde{h}_{ij} N_i (H_u L_j) + h_{i\alpha} N_i (H_\alpha^\mu L_4).$$

- After inflation the lightest right-handed neutrino/sneutrino (N_1 / \tilde{N}_1) with mass M_1 may be produced by thermal scattering if $T_R > M_1$.
- To guarantee that leptogenesis takes place we set $M_1 \simeq 10^5 \text{ GeV}$.
- We also assume that $M_{2,3} \lesssim 10^6 \text{ GeV}$.
- In order to reproduce the left-handed neutrino mass scale $m_\nu \lesssim 0.1 \text{ eV}$ the couplings of ordinary leptons L_j to N_i should be rather small, i.e. $|\tilde{h}_{ij}|^2 \ll 10^{-8}$, and can be ignored.
- Then the lepton asymmetry can be generated via the decays [R. Nevezorov, Universe **9** (2023) no.3, 137.]

$$N_1 \rightarrow L_4 + H_\alpha^\mu, \quad N_1 \rightarrow \tilde{L}_4 + \tilde{H}_\alpha^\mu, \quad \tilde{N}_1^* \rightarrow L_4 + \tilde{H}_\alpha^\mu, \quad \tilde{N}_1 \rightarrow \tilde{L}_4 + H_\alpha^\mu.$$

- This process is controlled by the set of CP asymmetries

$$\varepsilon_{1, l_4}^\alpha = \varepsilon_{1, \tilde{l}_4}^\alpha = \varepsilon_{\tilde{1}, l_4}^\alpha = \varepsilon_{\tilde{1}, \tilde{l}_4}^\alpha = \frac{\Gamma_{N_1 l_4}^\alpha - \Gamma_{N_1 \tilde{l}_4}^\alpha}{\sum_\beta \left(\Gamma_{N_1 l_4}^\beta + \Gamma_{N_1 \tilde{l}_4}^\beta \right)}.$$

- H_α^μ can be redefined so that only H_1^μ interacts with L_4 and N_1 whereas $h_{12}=0$ and therefore $\varepsilon_{1,l_4}^2 = \varepsilon_{1,\tilde{l}_4}^2 = \varepsilon_{1,l_4}^2 = \varepsilon_{1,\tilde{l}_4}^2 = 0$.
- Assuming that the sparticle mass scale M_5 is negligibly small as compared with M_1 , M_j are real and $h_{j1} = |h_{j1}|e^{i\varphi_{j1}}$ one finds

$$\varepsilon_{1,l_4}^1 = \varepsilon_{1,\tilde{l}_4}^1 = \varepsilon_{1,l_4}^1 = \varepsilon_{1,\tilde{l}_4}^1 = \varepsilon = \frac{1}{8\pi} \left[\sum_{j=2,3} |h_{j1}|^2 f \left(\frac{M_j^2}{M_1^2} \right) \sin 2\Delta\varphi_{j1} \right]$$

$$\Delta\varphi_{j1} = \varphi_{j1} - \varphi_{11}, \quad f(z) = \frac{2\sqrt{z}}{1-z} - \sqrt{z} \ln \left(\frac{1+z}{z} \right).$$

- For $h_{31} = 0$ and $h_{21} = 0.1$ one can obtain $\varepsilon \simeq 0.01$ if $M_2 \approx M_1$.
- The induced baryon asymmetry can be estimated as follows

$$Y_{\Delta B} \sim 10^{-3} (\varepsilon \cdot \eta), \quad Y_{\Delta B} = \left. \frac{n_B - n_{\bar{B}}}{s} \right|_0 = (8.75 \pm 0.23) \times 10^{-11}.$$

- In the strong washout scenario the efficiency factor η is given by

$$\eta \simeq \frac{H(T = M_1)}{\Gamma_1}, \quad H = 1.66 g_*^{1/2} \frac{T^2}{M_P}, \quad \Gamma_1 = \frac{|h_{11}|^2}{8\pi} M_1.$$

- For $\varepsilon \simeq 0.01$ the observed $Y_{\Delta B}$ can be reproduced if $|h_{11}| \sim 0.001$.

Dark matter-nucleon scattering cross section

- The scalar components of ϕ_i , S_i , H_α^u and H_α^d do not acquire VEVs.
- Their fermion components form the exotic (inert) neutralino and chargino states.
- When the components of ϕ_i are very heavy the interactions of S_i , H_α^u and H_α^d are described by

$$W_{IH} \simeq -\tilde{\mu}_i S_i S_i + \lambda_{\alpha\alpha} S(H_\alpha^d H_\alpha^u) + \tilde{f}_{i\alpha} S_i(H_\alpha^d H_u) + f_{i\alpha} S_i(H_d H_\alpha^u).$$

- Here we assume that H_1^d and H_1^u mostly interact with S_1 , H_u and H_d , whereas all other couplings of H_1^u and H_1^d are very small.
- The mass of the lightest exotic chargino is determined by $\mu_{11} = \lambda_{11}\langle S \rangle$, i.e. $m_{\chi_1^\pm} = |\mu_{11}|$.
- If $|\tilde{\mu}_1|$ is considerably larger than $|\mu_{11}|$, $\langle H_d \rangle = v_1$ and $\langle H_u \rangle = v_2$ the mass of the lightest exotic state χ_1 is given by

$$m_{\chi_1} \simeq m_{\chi_1^\pm} - \Delta_1, \quad \Delta_1 \simeq \frac{(\tilde{f}_{11} v_2 + f_{11} v_1)^2}{2(\tilde{\mu}_1 - m_{\chi_1^\pm})}.$$

- The contribution of χ_1 to the dark matter density can be estimated as

$$\Omega_{\tilde{H}} h^2 \simeq 0.1 \left(\frac{\mu_{11}}{1 \text{ TeV}} \right)^2.$$

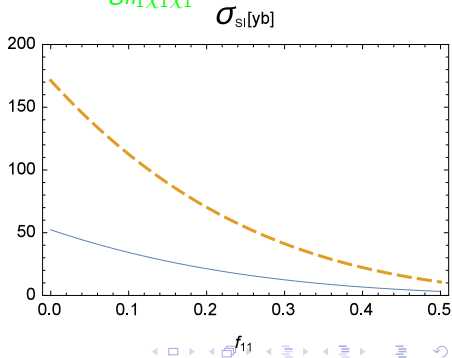
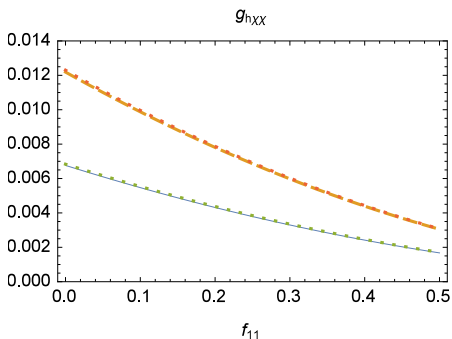
- Thus in the phenomenologically viable scenarios $\mu_{11} < 1.1 \text{ TeV}$.
- Since the couplings of gravitino to the SM particles are negligibly small, the interactions of the dark matter with the baryons are determined by the couplings of χ_1 .
- The dominant contribution to the spin-independent (SI) dark matter-nucleon scattering cross section σ_{SI} comes from the t-channel exchange of the lightest CP-even Higgs boson h_1 with mass m_{h_1}

$$\sigma_{SI} = \frac{2m_r^2 m_N^2}{\pi v^2 m_{h_1}^4} |g_{h_1 \chi_1 \chi_1} F^N|^2, \quad F^N = \sum_{q=u,d,s} f_{Tq}^N + \frac{2}{27} \sum_{Q=c,b,t} f_{TQ}^N,$$

$$m_r = \frac{m_{\chi_1} m_N}{m_{\chi_1} + m_N}, \quad m_N f_{Tq}^N = \langle N | m_q \bar{q} q | N \rangle, \quad f_{TQ}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N.$$

- Here $v = \sqrt{v_1^2 + v_2^2} \simeq 174 \text{ GeV}$, $g_{h_1 \chi_1 \chi_1} \simeq \Delta_1 / (\sqrt{2}v)$ and hadronic matrix elements $f_{Ts}^N \simeq 0.0447$, $f_{Td}^N \simeq 0.0191$ and $f_{Tu}^N \simeq 0.0153$.

- We set $\tilde{f}_{11} = -0.5$, $\tan \beta = \frac{v_2}{v_1} = 2$ and $\tilde{\mu}_1 = 2 \text{ TeV}$.
- The values of σ_{SI} remain smaller than 60 yb for $m_{\chi_1} \simeq 200 \text{ GeV}$ (solid lines) and 300 yb for $m_{\chi_1} \simeq 1 \text{ TeV}$ (dashed lines) which are the values of the experimental bounds on σ_{SI} obtained by the LZ experiment [J. Aalbers, et al. [LUX-ZEPLIN Collaboration], arXiv:2207.03764; E. Aprile et al. [XENON Collaboration], arXiv:2303.14729].
- The suppression of σ_{SI} is caused by large $\tilde{\mu}_1$ as well as by the partial cancellation of different contributions to $g_{h_1\chi_1\chi_1}$.



- In the SE_6SSM the exotic quarks (D_i and \bar{D}_i) are leptoquarks.
- The lightest exotic colored state q_1 , which is a superposition of either scalar or fermion components of the supermultiplets \bar{D}_i and D_i , is odd under \tilde{Z}_2^E symmetry.
- As a consequence its decays always lead to the missing energy E_T^{miss} in the final state, i.e.

$$q_1 \rightarrow u_i(d_i) + \ell_j(\nu_j) + E_T^{\text{miss}} + X.$$

- When q_1 is the lightest exotic quark the missing energy in the final state can be associated with only one lightest exotic neutralino.
- If q_1 is the lightest exotic squark the final state of its decay has to involve at least one lightest exotic neutralino and one gravitino to ensure the conservation of R -parity and Z_2^E symmetry.
- The pair production of q_1 at the LHC may result in some enhancement of the cross sections of $pp \rightarrow jj + E_T^{\text{miss}} + X$ and $pp \rightarrow jj\ell_k\bar{\ell}_m + E_T^{\text{miss}} + X$.

Conclusions

- The breakdown of E_6 gauge symmetry within SUSY GUTs may result in the E_6 SSM and its extensions that involve the 125-GeV Higgs.
- To ensure anomaly cancellation these E_6 inspired extensions of the MSSM with an extra $U(1)_N$ gauge symmetry include exotic matter.
- We considered the variant of the E_6 SSM (SE_6 SSM) in which the cold dark matter is composed of the lightest exotic neutralino χ_1 and gravitino.
- In these scenarios the lightest exotic chargino χ_1^\pm as well as the lightest exotic neutralino states χ_2 and χ_1 are nearly degenerate and have masses below 1.1 TeV.
- Since the mass splitting between these states is very small the decay products of χ_2 and χ_1^\pm are too soft so that they escape detection.
- We argued that there are some regions of the SE_6 SSM parameter space, which are safe from all current constraints.
- The discovery of the exotic states and Z' predicted by the E_6 SSM and its extensions will provide a smoking gun signal of these models allowing to distinguish them from other extensions of the SM.