Two–Component Dark Matter in the SE$_6$SSM

Roman Nevzorov
(Lebedev Physical Inst.)

2nd September 2024

Outline

1. Introduction

2. Exceptional SUSY model (E_6SSM) and its signatures

3. SE$_6$SSM

4. Dark Matter-Nucleon Scattering Cross Section in the SE$_6$SSM

5. Conclusions

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 $SU(5)$: $\overline{5} + 10$.
  - 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

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

  - $\left(16, \frac{1}{\sqrt{24}}\right)$ 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:

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

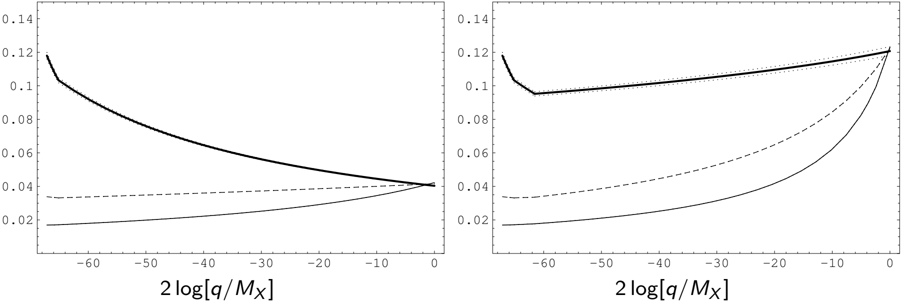
  - Three generations of the SM fermions can be associated with three 27-plets which may also contain the doublet of the Higgs bosons.
  - Some components of the 78-plet may form the multiplets of the SM gauge bosons.
  - Thus all SM bosons and SM fermions may belong to a single 248 representation of E_8.
- 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_6SSM) 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 $\overline{D}_i$) with electric charges $\pm 1/3$ which can be either diquarks or leptoquarks;
  - three pairs of the $SU(2)_W$–doublets (H^d_i and H^u_i) 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 $\overline{D}_i$ and D_i.
- In this case the lightest exotic squark $\tilde{D}_1$ decays either via

$$\tilde{D}_1 \to t + \tau\,, \qquad \tilde{D}_1 \to b + \nu_\tau$$

if exotic quarks are leptoquarks or via

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

if exotic quarks are diquarks.

- In the limit, when all Yukawa couplings of D_i and $\overline{D}_i$ 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 $\mathrm{BR}(\tilde{D}_1 \to t\tau) \approx 1$ 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 $pp \to \tilde{D}_1 \tilde{D}_1^*$ 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 $\overline{D}_i$ 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 $\overline{D}_i$ and D_i it decays either via

$$D_1 \to t + \tau + E_T^{\rm miss} + X\,, \qquad D_1 \to b + \nu_\tau + E_T^{\rm miss} + X$$

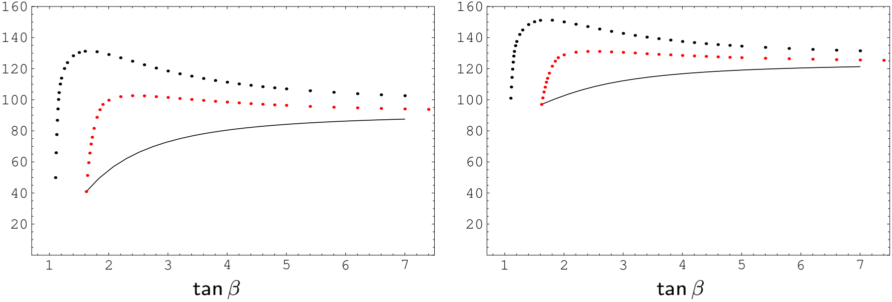
  if exotic quarks are leptoquarks or via

$$D_1 \to \bar{t} + \bar{b} + E_T^{\rm miss} + X$$

  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 $pp \to b\bar{b} + E_T^{\rm miss} + X$ and $pp \to t\bar{t}\tau\bar{\tau} + E_T^{\rm miss} + X$ or $pp \to t\bar{t}b\bar{b} + E_T^{\rm miss} + X$.
- 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 E_6SSM there are theoretical restrictions on the lightest Higgs boson mass m_{h_1}.
- The upper bound on m_{h_1} in the E_6SSM is considerably larger than in the MSSM and NMSSM.
- In the E_6SSM 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 E_6SSM, NMSSM and MSSM



- The presence of extra exotic matter in the E_6SSM 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_6SSM.
- Moreover within the E_6SSM 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.

SE$_6$SSM

- Extra exotic matter may give rise to non-diagonal flavor transitions and rapid proton decay.
- In the modification of the E$_6$SSM (SE$_6$SSM) 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 SE$_6$SSM implies that below the GUT scale M_X three complete 27-plets are accompanied by lepton doublets L_4 and $\overline{L}_4$, a pair of superfields S and $\overline{S}$ as well as four E_6 singlet superfields (ϕ and ϕ_i).
  - The supermultiplets ϕ, S, $\overline{S}$, L_4, $\overline{L}_4$ 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 $\overline{L}_4$ 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 SE$_6$SSM is given by

$$W = \lambda S(H_u H_d) - \sigma \phi S\overline{S} + \frac{\kappa}{3}\phi^3 + \frac{\mu}{2}\phi^2 + \Lambda\phi + \mu_L L_4 \overline{L}_4 + \tilde{\sigma}\phi L_4 \overline{L}_4$$
$$+ W_{IH} + \kappa_{ij} S(D_i \overline{D}_j) + h^E_{i\alpha} e^c_i (H^d_\alpha L_4) + g^D_{ij} (Q_i L_4)\overline{D}_j$$
$$+ g_{ij}\phi_i \overline{L}_4 L_j + W_N + W_{\mathrm{MSSM}}(\mu = 0)\,,$$

where

$$W_{IH} = \tilde{M}_{ij}\phi_i\phi_j + \tilde{\kappa}_{ij}\phi\phi_i\phi_j + \tilde{\lambda}_{ij}\overline{S}\phi_i S_j + \lambda_{\alpha\beta} S(H^d_\alpha H^u_\beta)$$
$$+ \tilde{f}_{i\alpha} S_i (H^d_\alpha H_u) + f_{i\alpha} S_i (H_d H^u_\alpha)\,,$$
$$W_N = \tfrac{1}{2} M_{ij} N^c_i N^c_j + \tilde{h}_{ij} N^c_i (H_u L_j) + h_{i\alpha} N^c_i (H^u_\alpha L_4)\,.$$

Transformation properties of different supermultiplets in the SE$_6$SSM

	$Q_i, u^c_i, d^c_i, L_i, e^c_i, N^c_i$	$\overline{D}_i, D_i, H^d_\alpha, H^u_\alpha, S_i, \phi_i$	$H_d, H_u, S, \overline{S}, \phi$	$L_4, \overline{L}_4$
$\tilde{Z}^H_2$	$-$	$-$	$+$	$+$
Z^M_2	$-$	$+$	$+$	$-$
Z^E_2	$+$	$-$	$+$	$-$

- In the SE$_6$SSM the sector responsible for the breakdown of the gauge symmetry is formed by the scalar components of ϕ, S, $\overline{S}$, H_d and H_u.
    - S and $\overline{S}$ 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 $m_Y \simeq 1\,\mathrm{TeV}$ one can get $\tau_Y \lesssim 1\,\mathrm{sec}$ if gravitino mass $m_{3/2} \lesssim 1\,\mathrm{GeV}$.
- 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.]

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

- Since $\Omega_{3/2}h^2 \leq 0.12$ for $m_{3/2} \simeq 1\,\mathrm{GeV}$ and gluino mass $M_{\tilde{g}} \gtrsim 3\,\mathrm{TeV}$ one finds an upper bound $T_R \lesssim 10^{6-7}\,\mathrm{GeV}$.
- 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 / $\widetilde{N}_1$).
- 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$_6$SSM the interactions of the superfields N_i are described by
$$W_N = \frac{1}{2} M_i N_i N_i + \tilde{h}_{ij} N_i (H_u L_j) + h_{i\alpha} N_i (H^u_\alpha L_4)\,.$$
- After inflation the lightest right-handed neutrino/sneutrino (N_1 /$\widetilde{N}_1$) with mass M_1 may be produced by thermal scattering if $T_R > M_1$.
- To guarantee that leptogenesis takes place we set $M_1 \simeq 10^5$ GeV.
- We also assume that $M_{2,3} \lesssim 10^6$ GeV.
- In order to reproduce the left–handed neutrino mass scale $m_\nu \lesssim 0.1\,\mathrm{eV}$ 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. Nevzorov, Universe **9** (2023) no.3, 137.]
$$N_1 \to L_4 + H^u_\alpha, \quad N_1 \to \widetilde{L}_4 + \widetilde{H}^u_\alpha, \quad \widetilde{N}^*_1 \to L_4 + \widetilde{H}^u_\alpha, \quad \widetilde{N}_1 \to \widetilde{L}_4 + H^u_\alpha\,.$$
- This process is controlled by the set of CP asymmetries
$$\varepsilon^\alpha_{1,\,\ell_4} = \varepsilon^\alpha_{1,\,\widetilde{\ell}_4} = \varepsilon^\alpha_{\widetilde{1},\,\ell_4} = \varepsilon^\alpha_{\widetilde{1},\,\widetilde{\ell}_4} = \frac{\Gamma^\alpha_{N_1\ell_4} - \Gamma^\alpha_{N_1\bar{\ell}_4}}{\sum_\beta \left(\Gamma^\beta_{N_1\ell_4} + \Gamma^\beta_{N_1\bar{\ell}_4}\right)}\,.$$

- H^u_α can be redefined so that only H^u_1 interacts with L_4 and N_1 whereas $h_{12}=0$ and therefore $\varepsilon^2_{1,\ell_4}=\varepsilon^2_{1,\widetilde{\ell}_4}=\varepsilon^2_{\widetilde{1},\ell_4}=\varepsilon^2_{\widetilde{1},\widetilde{\ell}_4}=0$.
- Assuming that the sparticle mass scale M_S is negligibly small as compared with M_1, M_j are real and $h_{j1}=|h_{j1}|e^{i\varphi_{j1}}$ one finds

$$\varepsilon^1_{1,\ell_4}=\varepsilon^1_{1,\widetilde{\ell}_4}=\varepsilon^1_{\widetilde{1},\ell_4}=\varepsilon^1_{\widetilde{1},\widetilde{\ell}_4}=\varepsilon=\frac{1}{8\pi}\left[\sum_{j=2,3}|h_{j1}|^2 f\left(\frac{M_j^2}{M_1^2}\right)\sin 2\Delta\varphi_{j1}\right]$$

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

- 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

$$Y_{\Delta B}\sim 10^{-3}\Big(\varepsilon\cdot\eta\Big)\,,\qquad Y_{\Delta B}=\frac{n_B-n_{\bar{B}}}{s}\bigg|_0=(8.75\pm0.23)\times10^{-11}\,.$$

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

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

- 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^u_α and H^d_α 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^u_α and H^d_α are described by

$$W_{IH} \simeq -\widetilde{\mu}_i S_i S_i + \lambda_{\alpha\alpha} S(H^d_\alpha H^u_\alpha) + \tilde{f}_{i\alpha} S_i (H^d_\alpha H_u) + f_{i\alpha} S_i (H_d H^u_\alpha)\,.$$

- Here we assume that H^d_1 and H^u_1 mostly interact with S_1, H_u and H_d, whereas all other couplings of H^u_1 and H^d_1 are very small.
- The mass of the lightest exotic chargino is determined by $\mu_{11} = \lambda_{11}\langle S\rangle$, i.e. $m_{\chi^\pm_1} = |\mu_{11}|$.
- If $|\widetilde{\mu}_1|$ 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

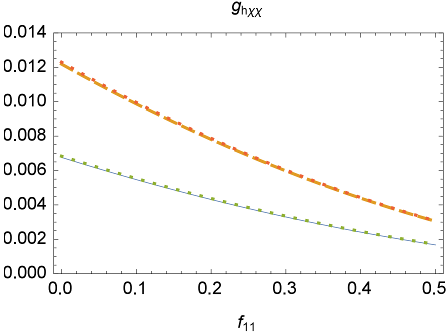
$$m_{\chi_1} \simeq m_{\chi^\pm_1} - \Delta_1, \qquad \Delta_1 \simeq \frac{(\tilde{f}_{11} v_2 + f_{11} v_1)^2}{2(\widetilde{\mu}_1 - m_{\chi^\pm_1})}\,.$$

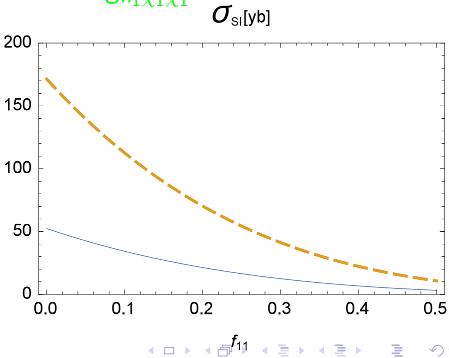
- The contribution of χ_1 to the dark matter density can be estimated as
$$\Omega_{\tilde{H}} h^2 \simeq 0.1 \left(\frac{\mu_{11}}{1\,\text{TeV}}\right)^2 .$$
- Thus in the phenomenologically viable scenarios $\mu_{11} < 1.1\,\text{TeV}$.
- Since the couplings of gravitino to the SM particles are negligibly 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}

$$\sigma_{SI} = \frac{2m_r^2 m_N^2}{\pi v^2 m_{h_1}^4} |g_{h_1\chi_1\chi_1} F^N|^2 , \quad F^N = \sum\nolimits_{q=u,d,s} f_{Tq}^N + \frac{2}{27} \sum\nolimits_{Q=c,b,t} f_{TQ}^N ,$$
$$m_r = \frac{m_{\chi_1} m_N}{m_{\chi_1} + m_N}, \quad m_N f_{Tq}^N = \langle N | m_q \bar{q} q | N \rangle, \quad f_{TQ}^N = 1 - \sum\nolimits_{q=u,d,s} f_{Tq}^N .$$

- 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 $\tilde{f}_{11} = -0.5$, $\tan\beta = \dfrac{v_2}{v_1} = 2$ and $\widetilde{\mu}_1 = 2\,\mathrm{TeV}$.
- The values of σ_{SI} remain smaller than 60 yb for $m_{\chi_1} \simeq 200\,\mathrm{GeV}$ (solid lines) and 300 yb for $m_{\chi_1} \simeq 1\,\mathrm{TeV}$ (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 $\widetilde{\mu}_1$ as well as by the partial cancellation of different contributions to $g_{h_1\chi_1\chi_1}$.





- In the SE$_6$SSM the exotic quarks (D_i and $\overline{D}_i$) are leptoquarks.
- The lightest exotic colored state q_1, which is a superposition of either scalar or fermion components of the supermultiplets $\overline{D}_i$ 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.

$$q_1 \to u_i(d_i) + \ell_j(\nu_j) + E_T^{\mathrm{miss}} + X\,.$$

- 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 $pp \to jj + E_T^{\mathrm{miss}} + X$ and $pp \to jj\ell_k\overline{\ell}_m + E_T^{\mathrm{miss}} + X$.

Conclusions

- The breakdown of E_6 gauge symmetry within SUSY GUTs may result in the $\mathrm{E_6SSM}$ 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 $\mathrm{E_6SSM}$ ($\mathrm{SE_6SSM}$) in which the cold dark matter is composed of the lightest exotic neutralino χ_1 and gravitino.
- In these scenarios the lightest exotic chargino $\chi_1^{\pm}$ 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 $\chi_1^{\pm}$ are too soft so that they escape detection.
- We argued that there are some regions of the $\mathrm{SE_6SSM}$ parameter space, which are safe from all current constraints.
- The discovery of the exotic states and Z' predicted by the $\mathrm{E_6SSM}$ and its extensions will provide a smoking gun signal of these models allowing to distinguish them from other extensions of the SM.