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11 Electric Dipole Moment and Dark Matter in a CP Violating Minimal Supersymmetric SM

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Abstract. We consider a dark matter scenario in the minimal supersymmetric standard model with CP violation where the Bino-like neutralino is a dark matter and its annihilation cross section is enhanced enough to reproduce the observed relic abundance of the dark matter through heavy Higgs bosons exchange. In this benchmark scenario, we examine the electric dipole moments of the electron, the mercury, and the neutron. We also consider the spin-independent cross section for the dark matter scattering with nuclei. We show that the electric dipole moments will be very powerful tool to explore the parameter space in this model, even when most of the new particles are very heavy.

Povzetek. Avtor obravnava model za temno snov v okviru minimalnega supersimetričnega standardnega modela s kršitvijo CP, v katerem temno snov tvori vrsta nevtralina z dovolj velikim sipalnim presekom za anihilacijo z izmenjavo težkih Higsovih bozonov, da da njegova gostota ustreže izmerjeni pogostosti temne snovi. V tem modelu oceni električne dipolne momente elektrona, jedra živega srebra in nevtrona. Obravnava od spina neodvisne sipalne preseke za sipanje te temne snovi na jedrih. Ugotovi, da je električni dipolni moment elektrona koristno orodje za raziskavo prostora parametrov tega modela tudi v primeru, če je večina delcev v tem supersimetričnem modelu zelo masivnih.

Keywords: dark matter, neutralino, EDM, MSSSM

11.1 Introduction

Though there is no evidence of supersymmetry (SUSY) at the LHC experiments, SUSY is still an attractive candidate of physics beyond the Standard Model (SM). There are several motivations to consider the minimal SUSY Standard Model (MSSM) than it in the SM. For example, (i) the gauge coupling unification is improved in the MSSM, (ii) quadratic divergence in the scalar sector is cancelled, (iii) spin-0 scalar fields are naturally introduced, (iv) MSSM provides a well-defined ultraviolet picture of type-II two Higgs doublet model, (v) If R-parity is unbroken, the lightest SUSY particle (LSP) can be a dark matter (DM) candidate, and so on.

Among such attractive motivations, we focus on the point (v). In the SM, there are several unsolved problems and one of the most serious problems is absence of

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the DM candidate. In the MSSM, all the SM particles are R-parity even and all the SUSY partner particles are R-parity odd, so that the lightest R-parity odd particle cannot decay. Therefore, unbroken R-parity guarantees the stability of the LSP which can be a DM.

Several different candidates can be considered in the MSSM such as the neutralino, the gravitino, the axino, the saxion and the sneutrino. In this talk, we briefly review the analysis studied in Ref. [1] where a neutralino DM scenario is considered.

In the neutralino DM scenario, the relic abundance of the LSP tends to be much more than the observed value. In order to realise the observed relic abundance of the DM, a mechanism to enhance the annihilation cross section of LSP is necessary. For example, following scenarios are sometimes considered: (i) neutralinos annihilate significantly through $SU(2)$ gauge interaction, or (ii) annihilation cross section of Bino-like neutralino is enhanced with a particular mass spectrum of other associated particles. In the former class, one possible case is the Higgsino-like neutralino DM scenario with the mass of about 1 TeV. In this scenario, phenomenology such as the direct detection of DM, contribution to the EDMs, and collider signals have been studied in Ref. [2]. There is another possibility that a neutralino DM whose main component is Bino annihilates through heavy Higgs boson resonance [3–7].

We, here, focus on the second case. In this scenario, masses of the heavy Higgs boson are about twice of the mass of the neutralino DM. This Bino-like neutralino also contains small Higgsino component so that the neutralino can directly be searched through Higgs bosons exchange by the spin-independent scattering off nucleus [8].

We consider the MSSM with CP violating phases. In this case, the CP violating phases can significantly affect the electric dipole moments (EDM). Therefore the EDMs are powerful tools to explore the CP violating phases in the model. In this talk, we examine the electron EDM, the nucleon EDM, and the mercury EDM. CP phases can also contribute to the DM-nucleon spin-independent scattering cross section. Since the pseudo scalar exchange process is strongly suppressed in the non-relativistic limit, the spin-independent cross section is suppressed with a significant size of CP phase.

11.2 The benchmark of our analysis

The superpotential and the soft SUSY breaking terms in the MSSM are given by[9]

$$\begin{aligned} W = \epsilon_{ab} \big[& (y_e)_{ij} H_1^a L_i^b \bar{E}_j \\ & + (y_d)_{ij} H_1^a Q_i^b \bar{D}_j \\ & + (y_u)_{ij} H_2^a Q_i^b \bar{U}_j \\ & - \mu H_1^a H_2^b \big] \,, \end{aligned} \tag{11.1}$$

and

$$\begin{aligned}\mathcal{L}_{\text{soft}} = &-\frac{M_1}{2}\tilde{B}\tilde{B} - \frac{M_2}{2}\tilde{W}^{\alpha}\tilde{W}^{\alpha} - \frac{M_3}{2}\tilde{G}^{A}\tilde{G}^{A}\\ &- m_{H_1}^2 H_{1a}^{*}H_1^a + m_{H_2}^2 H_{2a}^{*}H_2^a - \tilde{q}_{iLa}^{*}(M_{\tilde{q}}^2)_{ij}\tilde{q}_{jL}^a - \tilde{\ell}_{iLa}^{*}(M_{\tilde{\ell}}^2)_{ij}\tilde{\ell}_{jL}^a\\ &- \tilde{u}_{iR}(M_{\tilde{u}}^2)_{ij}\tilde{u}_{jR}^{*} - \tilde{d}_{iR}(M_{\tilde{d}}^2)_{ij}\tilde{d}_{jR}^{*} - \tilde{e}_{iR}(M_{\tilde{e}}^2)_{ij}\tilde{e}_{jR}^{*}\\ &- \epsilon_{ab}\left[(T_e)_{ij}H_1^a\tilde{\ell}_{iL}^b\tilde{e}_{jR} + (T_d)_{ij}H_1^a\tilde{q}_{iL}^b\tilde{d}_{jR}\right.\\ &\left.\quad + (T_u)_{ij}H_2^a\tilde{q}_{iL}^b\tilde{u}_{jR} + m_3^2 H_1^a H_2^b + \text{h.c.}\right] , \end{aligned} \tag{11.2}$$

respectively. In the following, we ignore the Yukawa couplings except for the third generation quarks and leptons. Then y_t, y_b, and y_τ denote the Yukawa couplings of top, bottom, and tau, respectively. We also neglecting the flavor mixing in the soft SUSY breaking terms, we take flavor diagonal soft scalar masses as $M_{\tilde{q}_i}^2 = (M_{\tilde{q}}^2)_{ii}$, $M_{\tilde{\ell}_i}^2 = (M_{\tilde{\ell}}^2)_{ii}$, $M_{\tilde{u}_i}^2 = (M_{\tilde{u}}^2)_{ii}$, $M_{\tilde{d}_i}^2 = (M_{\tilde{d}}^2)_{ii}$, and $M_{\tilde{e}_i}^2 = (M_{\tilde{e}}^2)_{ii}$. For the trilinear couplings, A parameters defined by $(T_u)_{33} = A_\tau y_t$, $(T_d)_{33} = A_\tau y_b$, and $(T_e)_{33} = A_\tau y_\tau$ are used. Since we consider the CP violating case, the each parameter in the above superpotential and the soft SUSY breaking Lagrangian can be a complex number.

The mass of the SM-like Higgs boson in the MSSM is calculated by the input parameters in the superpotential and the SUSY breaking Lagrangian. In order to reproduce the observed mass value $m_h = 125$ GeV, we take $\tan\beta := \langle H_2\rangle/\langle H_1\rangle = 30$ and we fix the stop mass parameters as $M_{\tilde{q}_3} = 7$ TeV, $M_{\tilde{t}} := M_{\tilde{u}_3} = 7$ TeV and $A_t = 10$ TeV. The other SUSY particles are irrelevant to the mass of the SM-like Higgs boson as well as the DM relic density. Therefore we can take their masses much heavier than stop. In such a case, they are decoupled from low energy observables. Here we take masses of the other sfermions as 100 TeV and $M_2 = M_3 = 10$ TeV. In our analysis, we focus on the Bino-like DM with the Higgs funnel scenario so that the heavy Higgs boson mass is close to twice the mass of the DM. In the scenario, the Bino-like neutralino rapidly annihilate through the heavy Higgs bosons resonance and the appropriate cosmic abundance for DM is reproduced. In addition, the masses of heavier neutral Higgs bosons, m_H and m_A, are close to the charged Higgs boson mass $m_{H^\pm}$ in the MSSM. Thus we fix $m_{H^\pm}$ to be twice of Bino mass parameter M_1. Note that the $\tilde{\chi}$-$\tilde{\chi}$-Higgs boson coupling depends on non-vanishing Higgsino component in the neutralino. We choose $|\mu|$ to reproduce the correct amount of DM relic density as $\Omega_{\text{DM}}h^2 = 0.1198 \pm 0.0015$ [10]. As a consequence of these fact, both the Bino mass $|M_1|$ and the Higgsino mass $|\mu|$ should be of the order of TeV. We consider M_1 as a free parameter and solve $|\mu|$ from the measured dark matter energy density.

In the following, we summarise our benchmark parameter set:

$$|M_2| = |M_3| = 10 \text{ TeV}, \tag{11.3}$$

$$M_{\tilde{q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2,3}} = M_{\tilde{\ell}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = 100 \text{ TeV}, \tag{11.4}$$

$$M_{\tilde{q}_3} = M_{\tilde{t}} = 7 \text{ TeV}, \tag{11.5}$$

$$A_t = 10 \text{ TeV}, \tag{11.6}$$

$$m_{H^\pm} = 2M_1, \tag{11.7}$$

$$\tan\beta = 30. \tag{11.8}$$

The other A-terms are zero.

With this parameter set, CP phases in the five parameters, $(\mu, M_1, M_2, M_3, A_t)$, may be relevant to our analysis of EDMs and the spin-independent cross section. The CP phases of these parameters are described as $(\phi_\mu,\ \phi_{M_1},\ \phi_{M_2},\ \phi_{M_3},\ \phi_{A_t})$, respectively, where each phases of a quantity X are defined by $X = |X|e^{i\phi_X}$.

Note that some of those CP phases are unphysical. It is known that there is a rephasing degree of freedom in the MSSM. Actually, all the physical quantities are described by the following combinations of the parameters,

$$\begin{aligned}&\arg(M_i M_j^*)\ ,\\&\arg(M_i A_t^*)\ ,\\&\arg(\mu M_i)\ ,\\&\arg(\mu A_t)\ ,\\&(i, j = 1, 2, 3)\ .\end{aligned} \tag{11.9}$$

By using the rephasing degree of freedom, without loss of generality, we can take the basis of CP phases as $\phi_{M_3} = 0$. We also take $\phi_{A_t} = 0$ for simplicity. In general, the CP phase ϕ_{A_t} also significantly contributes to the predictions of the EDMs. However, in our benchmark parameter set given in Eqs. (11.3) – (11.8), the contribution from ϕ_{A_t} is strongly suppressed because the mass splitting between two stops is small. Therefore we scan the following four parameters,

$$(|M_1|,\ \phi_\mu,\ \phi_{M_1},\ \phi_{M_2}). \tag{11.10}$$

11.3 Numerical analysis

In calculations of dark matter thermal relic density and the Higgs mass, we use `micrOMEGAs 4.3.5` [11] with `CPsuperH2.3` [12]. The Higgs mass is almost fixed to be 125 GeV in our benchmark point. When we scattered the parameters, we pick up the parameter sets which reproduce the correct DM relic abundance and the correct Higgs mass. Then we calculate the electron EDM, the neutron EDM, and the mercury EDM. We also discuss the scattering cross section for the direct detection experiments.

Since the sfermions are too heavy to contribute to the EDMs via one-loop diagrams, the two-loop Barr-Zee diagrams provide dominant contributions unless Wino, stop, and sbottom masses are heavy enough to be decoupled.

In Fig. 11.1, we show our numerical results. We can see the M_1 dependence by comparing the left panels and the right panels where $M_1 = 1$ TeV and 2 TeV, respectively. It is easily seen that larger M_1 weaken the constraint from EDM experiments. The Bino mass M_1 is approximately identified to be the mass of the dark matter neutralino. Then for larger M_1, heavy Higgs bosons and Higgsinos become heavier, and the contributions to the EDMs become smaller. We also discuss the ϕ_μ and ϕ_{M_2} dependence of the EDMs. The left panels in Fig. 11.1 shows the electron EDM, the mercury EDM, and the neutron EDM with $\phi_{M_1} = 0$. The shaded regions are already excluded by the current upper bound on the EDMs. We find the combination of the electron EDM and the mercury EDM exclude the large region of the parameter space. Both ϕ_μ and ϕ_{M_2} cannot be large. We also find that the electron EDM strongly depends on ϕ_{M_2}. On the other hand, ϕ_{M_2} dependence of the mercury EDM and the neutron EDM are milder.

Fig. 11.2 displays the ϕ_{M_1} dependence. Taking into account the constraint from the mercury EDM, we find that the mercury EDM and the neutron EDM are almost independent of ϕ_{M_1}. On the other hand, the dependence of the electron EDM on ϕ_{M_1} is mild but visible.

From these figures, one can see that the neutron and the mercury EDMs are sensitive to ϕ_μ, and also weakly depend on ϕ_{M_2}. On the other hand, the electron EDM is sensitive to $\phi_{M_2} + \phi_\mu$, and weakly depend on ϕ_{M_1}. Most of the parameter space in Figs. 11.1 and 11.2 are within the future prospects of the electron EDM and the neutron EDM. In Summer of 2018, the constraint on the electron EDM is updated to be $|d_e/e| < 1.1 \times 10^{-29} e{\cdot}\text{cm}$ by ACME collaboration[13]. With this new constraint, the allowed regions in Figs. 11.1 and 11.2 become very thin stripes. Thus the correlation among the EDMs in future experiments provide a strong hint to explore the CP phases in the SUSY breaking sector.

Let us discuss DM-nucleon scattering cross section. Since we consider the Higgs funnel scenario, the DM neutralino couples to neutral scalar bosons. Through these couplings, the DM neutralino and nucleon interact with each other.

Though the couplings are rather small in the scenario, the couplings lead to a significant size of the spin-independent cross section and it will be within future prospects of the DM direct detection experiments.

In Figure 11.3, the ϕ_{M_2} and ϕ_μ dependence of σ_{SI} is shown. In this figure, the parameter choice is the same as in Fig. 11.1. Figure 11.4 displays the ϕ_{M_1} and ϕ_μ dependence of σ_{SI} with the same parameter choice as in Fig. 11.2.

The spin-independent cross section is found to be smaller than the current upper bound [14–16] in all the region of the parameter space. However is is within the future prospects of the DARWIN [17], the DarkSide-20k [18], and the LZ [19].

Note that the scattering cross section depends on $\phi_{M_1} + \phi_\mu$, and the ϕ_{M_2} dependence is not significant.

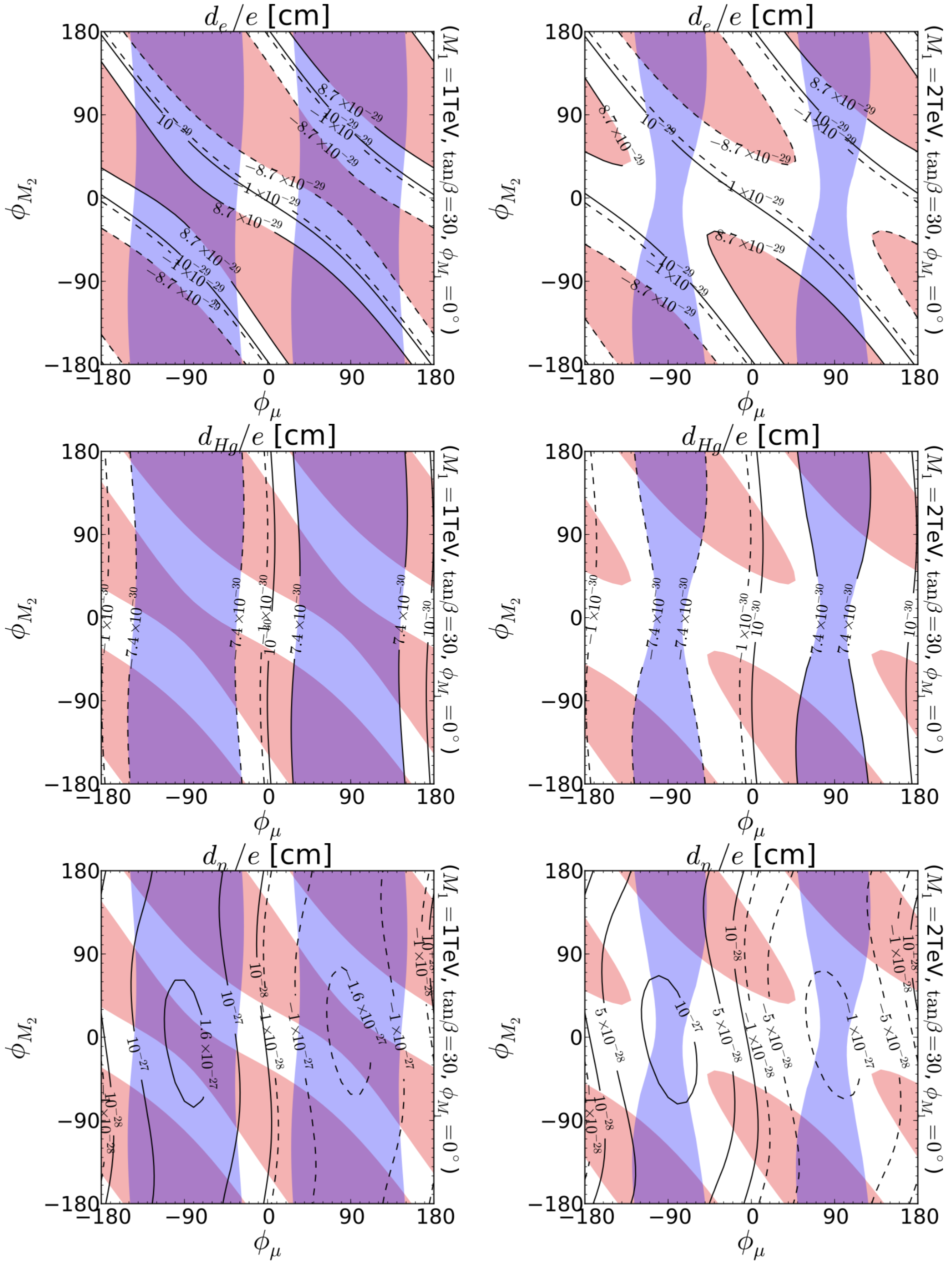

Fig. 11.1. The EDMs for $\tan\beta = 30$ and $\phi_{M_1} = 0^\circ$. The left (right) panels are for $M_1 = 1$ TeV ($M_1 = 2$ TeV). The contours in the top, the center, and the bottom panels are those of the electron EDM, the mercury EDM, and the neutron EDM, respectively. The dashed lines show the negative values. The red and blue shaded regions are excluded by the electron EDM and the mercury EDM, respectively. The figures are taken from Ref. [1].

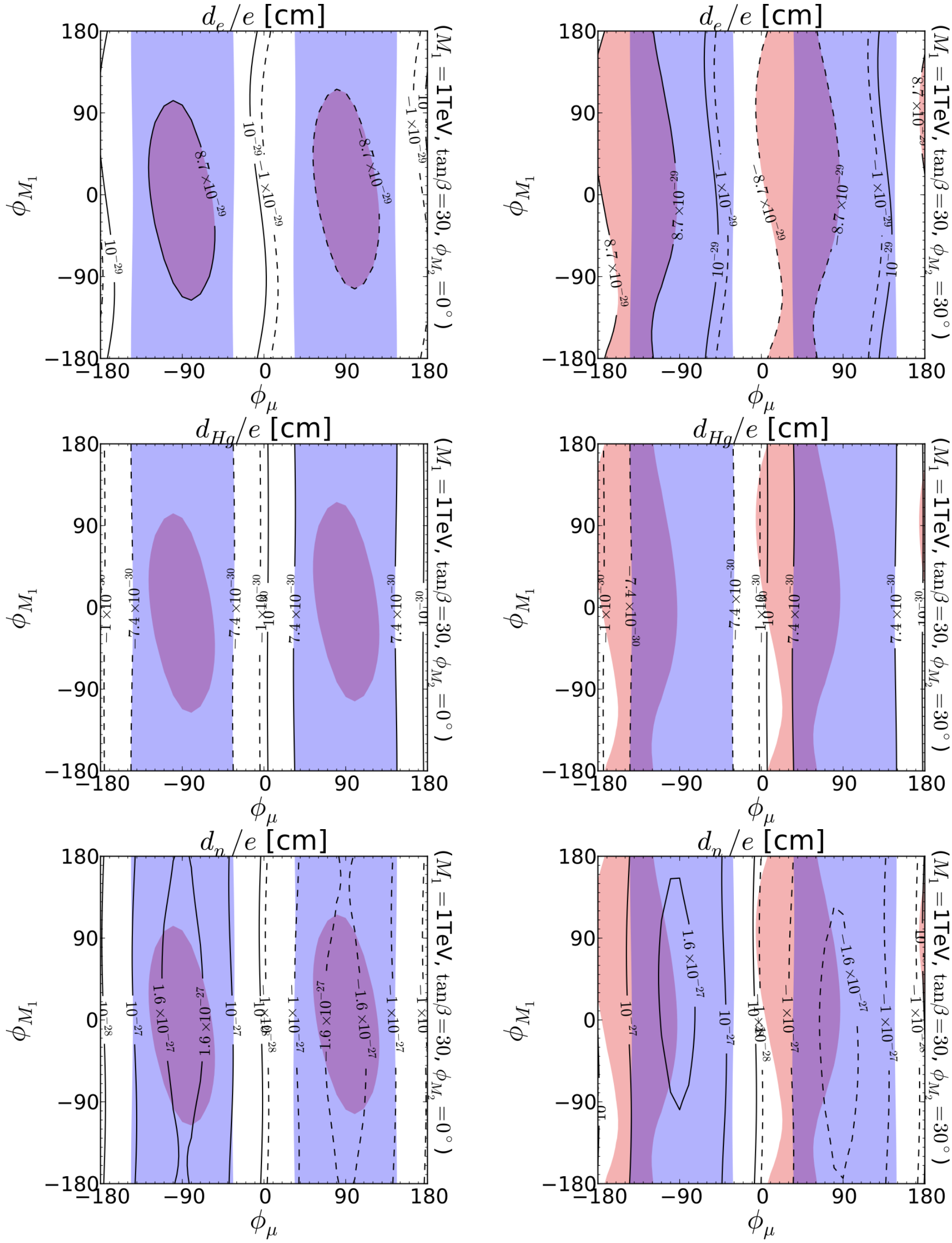

Fig. 11.2. The EDMs for $M_1 = 1$ TeV and $\tan\beta = 30$. In the left (right) panels, $\phi_{M_2} = 0^\circ$ (30°). The shadings and contours are the same as in Fig. 11.1. The figures are taken from Ref. [1].

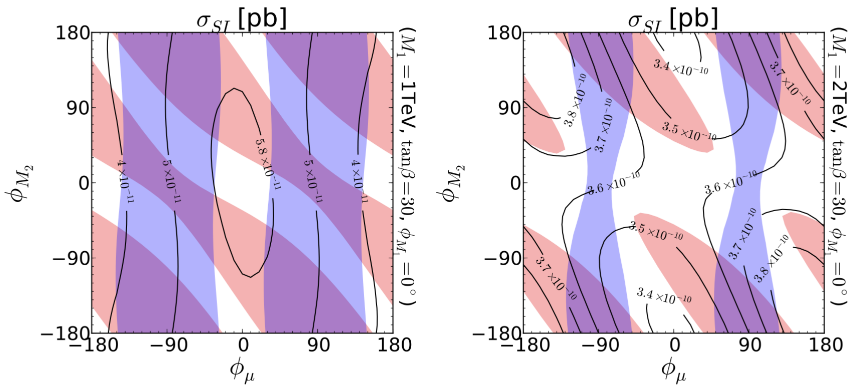

Fig. 11.3. The DM-nucleon scattering cross sections for $\tan\beta = 30$ and $\phi_{M_1} = 0^\circ$. The left (right) panel is for $|M_1| = 1$ TeV (2 TeV). The shadings are the same as in Fig. 11.1. The figures are taken from Ref. [1].

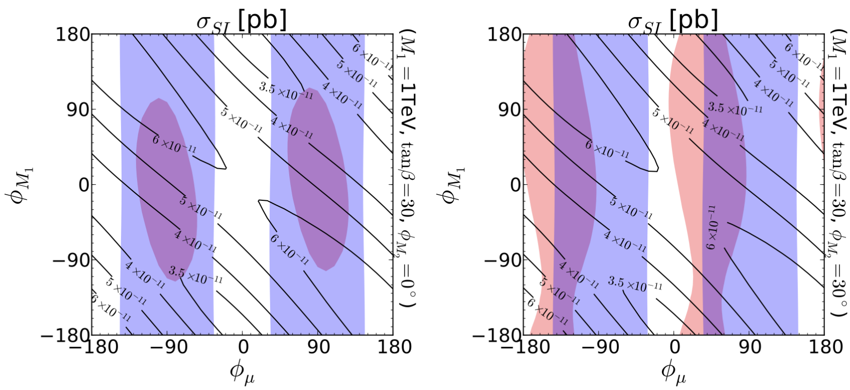

Fig. 11.4. The DM-nucleon scattering cross sections for $M_1 = 1$ TeV and $\tan\beta = 30$. The left (right) panel is for $|\phi_{M_2}| = 0^\circ$ (30°). The shadings are the same as in Fig. 11.1. The figures are taken from Ref. [1].

11.4 Summary

In this talk, we have considered the MSSM with CP phases, and we have focused on a DM scenario where the Bino-like neutralino is a DM whose annihilation cross section is enhanced enough through heavy Higgs bosons exchange so that the observed relic abundance of the DM can be explained. In this benchmark scenario, we have examined several EDMs and the spin-independent cross section for DM scattering with nuclei. We have shown that the EDMs are very powerful tool to explore the parameter space in the MSSM with CP phases even when most of the SUSY particles are very heavy.

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