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The CP-Violating pMSSM at the Intensity Frontier*

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Abstract

In this Snowmass whitepaper, we describe the impact of ongoing and proposed intensity frontier experiments on the parameter space of the Minimally Supersymmetric Standard Model (MSSM). We extend a set of phenomenological MSSM (pMSSM) models to include non-zero CP-violating phases and study the sensitivity of various flavor observables in these scenarios Future electric dipole moment and rare meson decay experiments can have a strong impact on the viability of these models that is relatively independent of the detailed superpartner spectrum. In particular, we find that these experiments have the potential to probe models that are expected to escape searches at the high-luminosity LHC.

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The Large Hadron Collider (LHC) has reached a major milestone by discovering a Higgs boson [1]. At present, the properties of this Higgs boson resemble those predicted by the Standard Model, but the naturalness of the electroweak scale remains unexplained. Supersymmetry (SUSY) in general, and its minimal version, the Minimally Supersymmetric Standard Model (MSSM) in particular, explains this scale and is among the best-motivated theory of physics beyond the SM. Many of the LHC searches have focused on its signatures, with null results so far, and the large LHC dataset is pushing the limits on the scale of New Physics (NP) to roughly a TeV. It is thus paramount that signatures of Supersymmetry be studied in all possible manners, including its indirect effects at the intensity frontier.

If no assumptions are made about the SUSY breaking sector then the total number of unknown parameters (the so called soft SUSY breaking parameters) in the R-parity conserving version of the MSSM is large (105), and it becomes difficult to carry out a phenomenological analysis. In order to circumvent this, two complementary approaches are generally taken.

The first common approach is to assume particular patterns for many of the parameters at some high scale. The soft parameters at the electroweak scale are then generated by Renormalization Group (RG) evolution from the high scale. While these minimal models make the phenomenological analysis comparatively straightforward, they do not represent the full set of SUSY signatures and they are now tightly constrained by a host of experimental observables and direct searches. In fact, two of the most commonly studied scenarios, the minimal super gravity (mSUGRA) and minimal gauge mediated SUSY breaking (mGMSB) models [2], are now severely constrained by the LHC data [3].

An alternate approach is to maintain ignorance of the physics at the high scale, and to choose a pattern for the parameters at the weak scale based on current experimental constraints. A study of such models is only feasible because many of these parameters are already tightly constrained by a host of low energy measurements. For example, both the Charge-Parity (CP) conserving and CP-violating observables in K, B and D decays, as well as lepton flavor violating decays and data on electric and magnetic dipole moments, already forbid large values of new CP-violating phases and sfermion mixing angles.

Taking the limit of no new sources of flavor- or CP-violation leads to the general 19/20-parameter pMSSM [4]. The increased dimensionality of the parameter space not only allows for a more unprejudiced study of SUSY, but can also yield valuable information on 'unusual' scenarios, identify weaknesses in the current LHC analyses and provides the means to combine results obtained from many independent SUSY-related searches. To these ends, we have recently embarked on a detailed study of the signatures for the pMSSM at the 7 and 8 TeV LHC, supplemented by input from Dark Matter (DM) experiments as well as from precision measurements of the Higgs properties [5]. The pMSSM is the most general version of the R-parity conserving MSSM when it is subjected to a minimal set of experimentally-motivated guiding principles: (*i*) No new sources of CP-violation, (*ii*) Minimal Flavor Violation at the electroweak scale so that flavor violation is proportional to the CKM mixing matrix elements, (*iii*) degenerate 1st and 2nd generation sfermion masses, and (*iv*) negligible Yukawa couplings and A-terms for the first two generations. In particular, no assumptions are made about physics at high scales, e.g., the nature of SUSY breaking, in order to capture elec-

$m_{\tilde{L}(e)_{1,2,3}}$	$100\,\text{GeV} - 4\,\text{TeV}$
$m_{\tilde{Q}(q)_{1,2}}$	$400\,\text{GeV} - 4\,\text{TeV}$
$m_{\tilde{Q}(q)_3}$	$200\,\text{GeV} - 4\,\text{TeV}$
$\lvert M_1 \rvert$	$50\,\text{GeV} - 4\,\text{TeV}$
$\lvert M_2 \rvert$	$100\,\text{GeV} - 4\,\text{TeV}$
$\lvert \mu \rvert$	$100\,\text{GeV} - 4\,\text{TeV}$
M_3	$400\,\text{GeV} - 4\,\text{TeV}$
$\lvert A_{t,b,\tau} \rvert$	$0\,\text{GeV} - 4\,\text{TeV}$
M_A	$100\,\text{GeV} - 4\,\text{TeV}$
$\tan\beta$	$1 - 60$
$m_{3/2}$	1 eV$-$1 TeV ($\tilde{G}$ LSP)

Table 1: Scan ranges for the 19 (20) parameters of the pMSSM with a neutralino (gravitino) LSP. The gravitino mass is scanned with a log prior. All other parameters are scanned with flat priors, though we expect this choice to have little qualitative impact on our results [4].

troweak scale phenomenology for which a UV-complete theory may not yet exist. Imposing these principles (i)-(iv) decreases the number of free parameters in the MSSM at the TeV scale from 105 to 19 for the case of a neutralino Lightest Supersymmetric Partner (LSP), or to 20 when the gravitino mass is included as an additional parameter when it plays the role of the LSP. We have not assumed that the LSP relic density necessarily saturates the WMAP/Planck value [6] in order to allow for the possibility of multi-component dark matter. For example, the axions introduced to solve the strong CP problem may make up a substantial amount of dark matter. The 19/20 pMSSM parameters and the ranges of values employed in our scans are listed in Table 1. The parameters $M_{1,2}$, μ and $A_{t,b,\tau}$ are all given a randomly chosen sign. Like throwing darts, to study the pMSSM we generate 3.7 million model points in this space (using SOFTSUSY [7] and check for consistency with SuSpect [8]), with each point corresponding to a specific set of values for these parameters. These individual models are then subjected to a global set of collider, flavor, precision measurement, dark matter and theoretical constraints [4, 5]. Roughly $\sim$225k models with either type of LSP survive this initial selection and can then be used for further physics studies. Decay patterns of the SUSY partners and the extended Higgs sector are calculated using privately modified versions of SUSY-HIT [9], CalcHEP [10], and MadGraph [11]. Since our scan ranges include sparticle masses up to 4 TeV, an upper limit chosen by kinematics to enable phenomenological studies at the 14 TeV LHC, the neutralinos and charginos in either of our model sets are typically very close to being in a pure electroweak eigenstate as the off-diagonal elements of the corresponding mass matrices are at most $\sim M_W$.

While MFV arises naturally as a low energy limit of a sizable class of models, such as gauge- or anomaly-mediated SUSY, new physics scenarios are generally expected to have new sources of flavor and CP-violation. In particular, new sources of CP-violation are well-motivated by the large cosmic baryon–anti-baryon asymmetry of our universe. In this work, we aim to go beyond the assumption of vanishing CP-violating phases in the pMSSM.

This opens the door for a complementary approach to discovering SUSY. LHC searches are limited by kinematics, both in SUSY production and decay modes, and dark matter searches are limited by the elastic coupling of dark matter and by astrophysical uncertainties. This provides a window of opportunity that may only be probed at the intensity frontier. In particular, cases in which the superpartners are rather massive or nearly degenerate are well-suited for flavor- and CP-violating searches. By relaxing the first assumption above, we can explore the sensitivity of several current and future intensity frontier experiments to the pMSSM. In addition to studying CP-violating quantities, we study in greater detail several flavor-violating observable that, despite the MFV hypothesis, are sensitive to pMSSM models.

Observable	SM Prediction	Current Exp.	Future Exp. [15]
d_e/e (cm)	$< 10^{-38}$ [16]	$< 1.05 \times 10^{-27}$ [17]	$< 3 \times 10^{-31}$
d_n/e (cm)	$\approx 10^{-32}$ [18]	$< 2.6 \times 10^{-26}$ [19]	$< 10^{-28}$
Δa_μ	0	$(2.61 \pm 0.80) \times 10^{-9}$ [20]	$\pm 0.15 \times 10^{-9}$
$\mathrm{Br}(K_L^0 \to \pi^0 \nu\bar{\nu})$	2.8405×10^{-11} [12]	$< 2.6 \times 10^{-8}$ [21]	$\pm 5\%$
$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	7.8190×10^{-11} [12]	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ [22]	$\pm 2\%$
$\mathrm{Br}(B_u \to \tau\nu)$	1.1×10^{-4}	$(0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$ [23]	$\pm 5\%$
$\mathrm{Br}(B \to X_s\gamma)$	3.15×10^{-4} [24]	$(3.40 \pm 0.21) \times 10^{-4}$ [20]	$\pm 0.13 \times 10^{-4}$

Table 2: The complete set of observables studied in this work. All observables are calculated using `SUSY_FLAVOR v2.02` [12]. The ranges for future experimental results assume that the SM expected values are observed and are based on the most aggressive experimental scenarios in [15].

Our analysis extrapolates 1000 models selected from the neutralino LSP pMSSM sample described above to include CP-violating phases. All of these selected models satisfy current experimental constraints on the flavor observables described in Table 2, where these observables are computed using `SUSY_FLAVOR v2.02` [12]. Of these models, 500 were selected based on the criterion that they are expected to be excluded at 95% CL by null results for a jets + MET search with 300 fb^{-1} of integrated luminosity at the LHC with 14 TeV c.m. energy [13]. The remaining 500 models are *not* expected to be excluded by the same search channel with 3000 fb^{-1} of integrated luminosity at the 14 TeV LHC.

This set of models is extrapolated beyond the pMSSM by including all six CP-violating phases that are allowed in SUSY: $\phi_1 \equiv \arg(M_1)$, $\phi_2 \equiv \arg(M_2)$, $\phi_\mu \equiv \arg(\mu)$, $\phi_t \equiv \arg(A_t)$, $\phi_b \equiv \arg(A_b)$, and $\phi_\tau \equiv \arg(A_\tau)$. One phase in the gaugino-Higgsino sector is unphysical and we choose this to be the phase of M_3, which we set to zero by field redefinition. For each of the 1000 models, we generate random values for each of these phases employing a log uniform distribution between $10^{-6} \times \pi/2$ and $\pi/2$. A random sign for each phase is also selected. 1000 sets of 6 phases are generated for each model, leading to a total sample of 10^6 models. For each of these models, the observables in Table 2 are re-calculated, again using `SUSY_FLAVOR v2.02`. We note that signatures of these 1000 models at energy and cosmic frontier experiments [13, 14] have also been studied for Snowmass, in order to facilitate

comparisons across the frontiers.

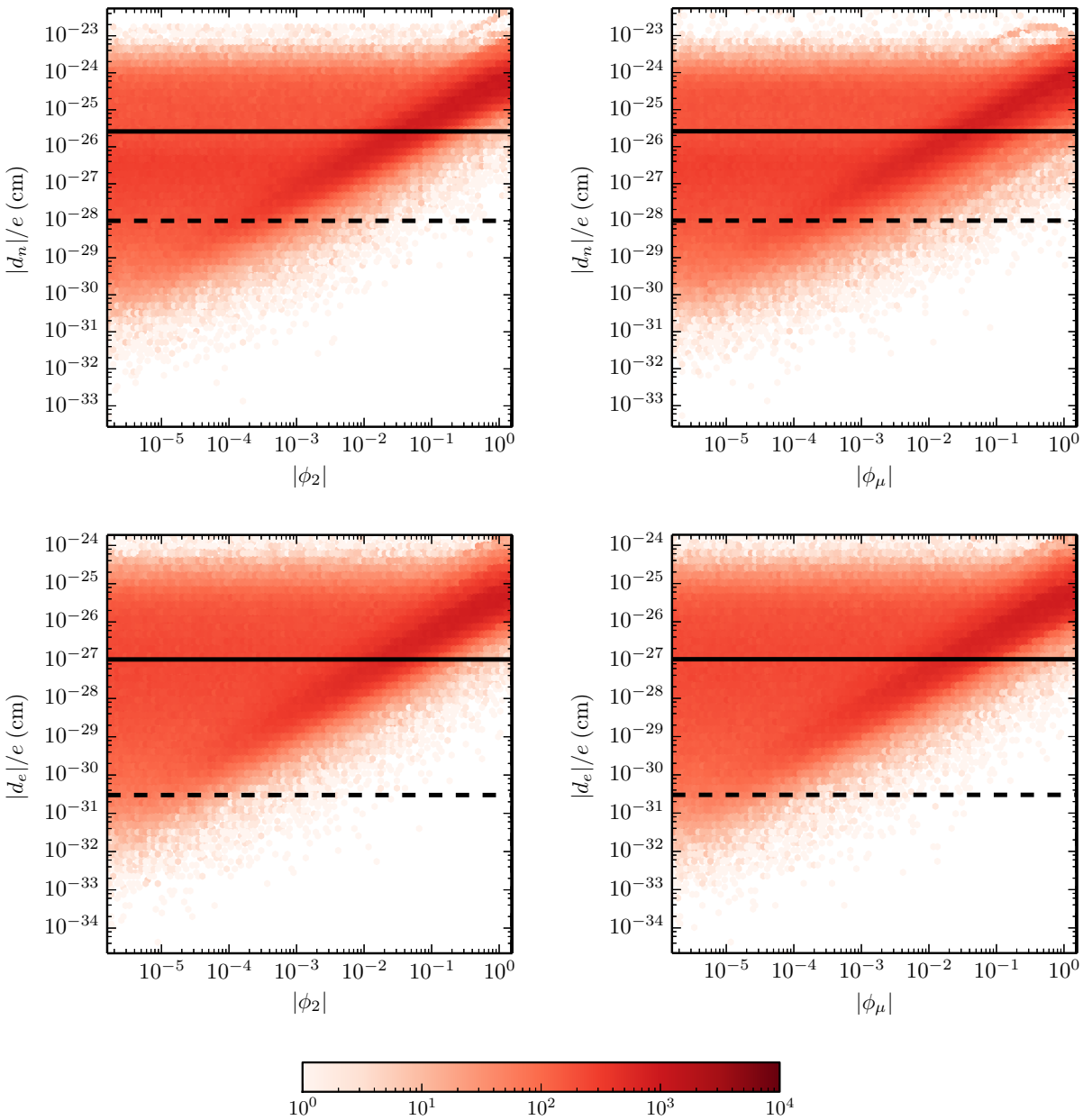

Figure 1: Results for the most sensitive EDM observables over a range of phases. Solid (dashed) lines indicate current (expected future) experimental 2σ bounds.

The results of this scan are summarized in Figures 1 and 2 for various flavor- and CP-violating observables. Current experimental bounds at the 2σ level are represented by solid lines. Projected future sensitivities are indicated by dashed lines, using 2σ limits for the most aggressive experimental scenarios described in [15]. Both sets of limits are summarized in

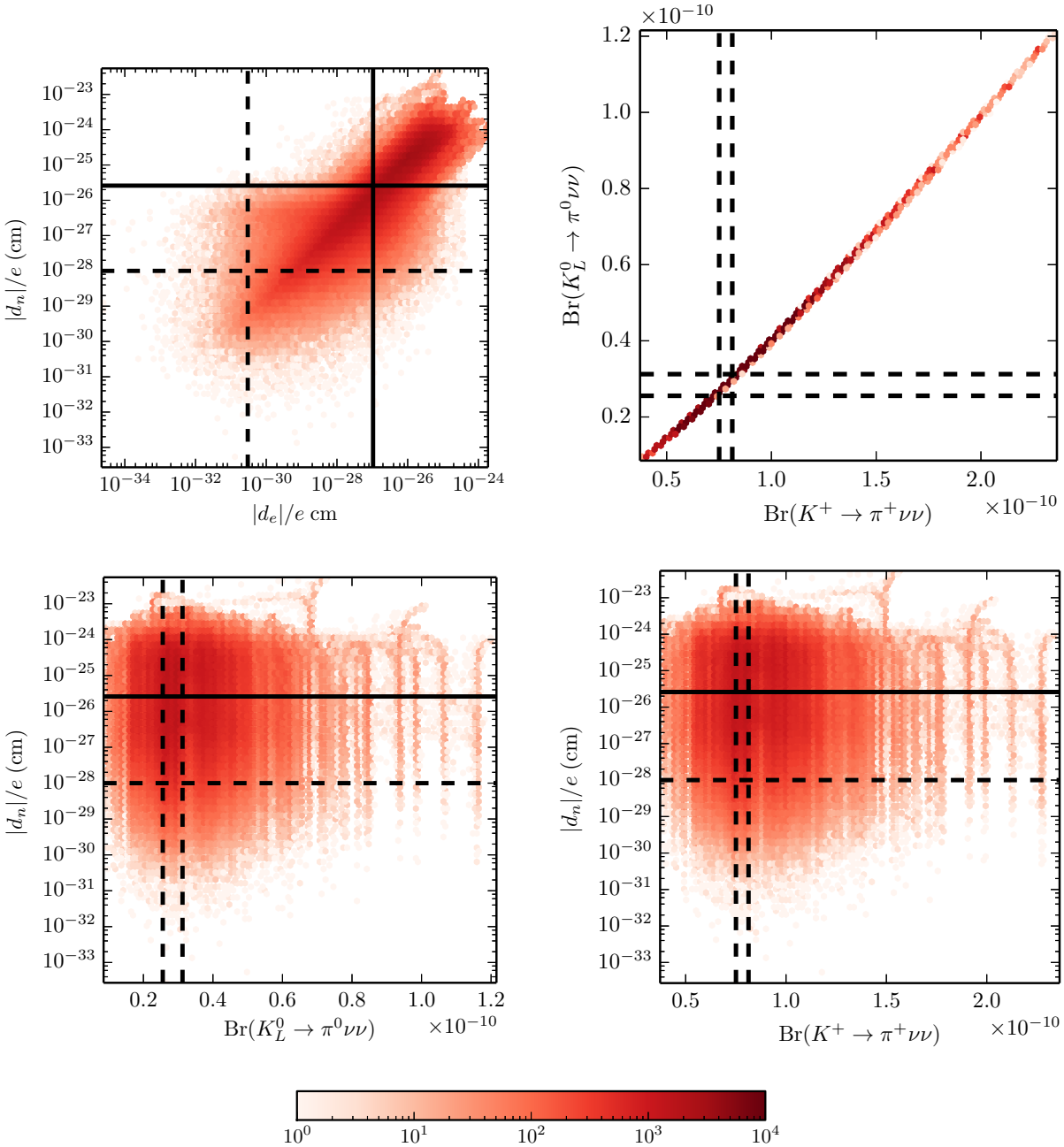

Figure 2: Results for the most sensitive EDM observables over a range of phases. Solid (dashed) lines indicate current (expected future) experimental 2σ bounds.

Table 2. As expected for models with wino or Higgsino LSPs, we find that the CP-violating observables are most sensitive to the phases of M_2 and μ and therefore we only show the dependence on these phases. The EDM searches for the neutron and electron are seen to be complementary: there are many models for which only one of the two most sensitive

observables is large. The branching fractions for the rare Kaon decays demonstrate the well-known MFV linear relationship [25]. Any deviation from this would be a signature of non-minimal flavor violation. In addition, we see that there is no correlation between the EDM values and the rare Kaon decays.

Only the most sensitve observables are shown in these figures. Additional weaker constraints can be obtained from $\mathrm{Br}(B \to X_s\gamma)$ and $\mathrm{Br}(B_u \to \tau\nu)$. The distributions for the two different sets of models, those to which the LHC is expected to have sensitivity and those to which it is not, are comparable and we do not separate the two sets in Figures 1 and 2. In all cases, we find that the expected reach for these observables has sensitivity to models that cannot be probed at the high luminosity LHC, provided that the CP-violating phases do not vanish.

The future for both CP-violating and flavor-violating observables is exciting. Experiments are slated to improve by several orders of magnitude in sensitivity and will have a significant impact on the available parameter space, even for models to which the LHC is unlikely to be sensitive. This work demonstrates the powerful and complementary role that such probes can play in the hunt for new physics.

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