Revisit the electron EDM in the NMSSM

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

What is NMSSM?

The Next-to-Minimal Supersymmetric Standard Model extends Minimal SUSY (MSSM) with a gauge singlet superfield, relaxing phenomenological tensions of MSSM with various observations.

Issue	MSSM	NMSSM
EWSB fine tuning	$\Delta_\mu = \frac{\partial \ln v^2}{\partial \ln \mu} > 100$ ☹	$\mu_{\text{eff}} \equiv \lambda \langle v_s \rangle$ 😉
Strong first-order EWPT	$m_{\tilde{t}} \lesssim m_t$ vs. LHC ☹	Singlet scalar 😉
Baryon asymmetry	n_B vs. EDMs ☹	More CP violations ?

Explicit CP violation in the NMSSM

Lagrangian

$$W = \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 + \frac{1}{2}\beta\hat{S}^2 + \alpha\hat{S} + W_{\text{Yukawa}}$$

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \mu'\tilde{H}_d\tilde{H}_u + h.c.\right)$$
$$-\left(A_u\tilde{\bar{u}}\mathbf{y_u}\tilde{Q}H_u - A_d\tilde{\bar{d}}\mathbf{y_d}\tilde{Q}H_d - A_e\tilde{\bar{e}}\mathbf{y_e}\tilde{L}H_d + h.c.\right)$$
$$-\left[(\lambda A_\lambda S + b)H_u^T\epsilon H_d + \frac{\kappa A_\kappa}{3}S^3 + \frac{1}{2}m_7^2S^2 + m_9^3S + h.c.\right]$$

$$z_i = \langle H_i \rangle$$

Can choose a basis of CP-violating phases that remains invariant under the various global U(1) symmetries.

MSSM phases

$$\Phi_1 = \arg\{M_1M_2^*\}, \quad \Phi_2 = \arg\{M_1M_3^*\}, \quad \Phi_3 = \arg\{A_uA_e^*\},$$
$$\Phi_4 = \arg\{A_dA_e^*\}, \quad \Phi_5 = \theta_{CKM}, \quad \phi_0 = \arg\{bz_uz_d\},$$
$$\phi_1 = \arg\{M_1A_e^*\}, \quad \phi_9 = \arg\{M_1\mu' b^*\}$$

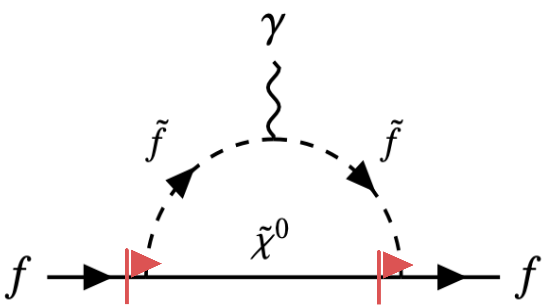
NMSSM phases

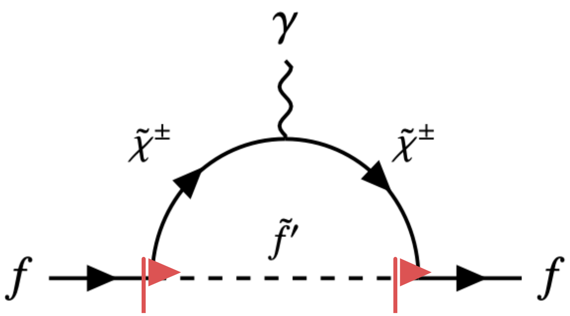
$$\phi_0' = \arg(\kappa A_\kappa z_s^3), \qquad \phi_2 = \arg(M_1\lambda z_s b^*)$$
$$\phi_3 = \arg(\lambda z_u z_d \kappa^* z_s^{*2}), \qquad \phi_4 = \arg(\lambda A_\lambda z_u z_d z_s)$$
$$\phi_5 = \arg(\lambda z_u z_d \beta^* z_s^*), \qquad \phi_6 = \arg(m_7^2 z_s^2)$$
$$\phi_7 = \arg(m_9^3 z_s), \qquad \phi_8 = \arg(\lambda z_u z_d \alpha^*)$$

Compute eEDM in the NMSSM

Relativistic effective EDM operator $\mathcal{L}^{\mathrm{EDM}} = -i \sum_f \frac{d_f}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$

- 1-loop contributions are suppressed by heavy masses of sfermions



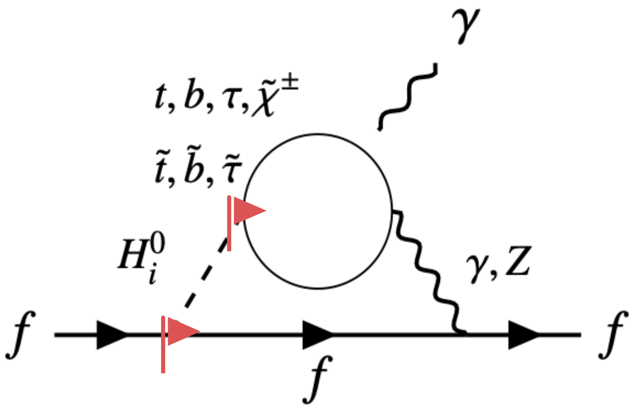


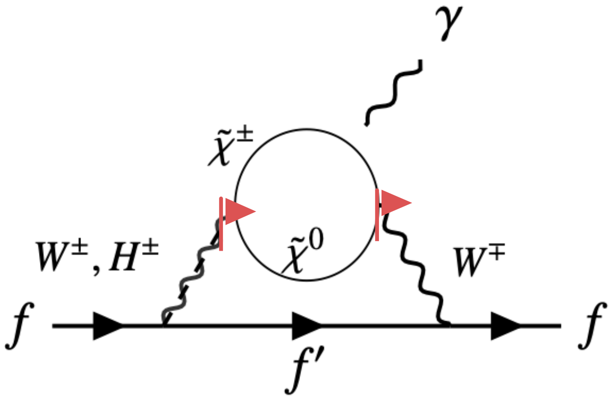
$\tilde{f} \subset (\tilde{e}_L, \tilde{e}_R)$

$\tilde{\chi}^0 \subset (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

$\tilde{\chi}^\pm \subset (\tilde{W}^\pm, \tilde{H}_{u,d}^\pm)$

- 2-loop Barr-Zee diagrams become comparable or even dominant



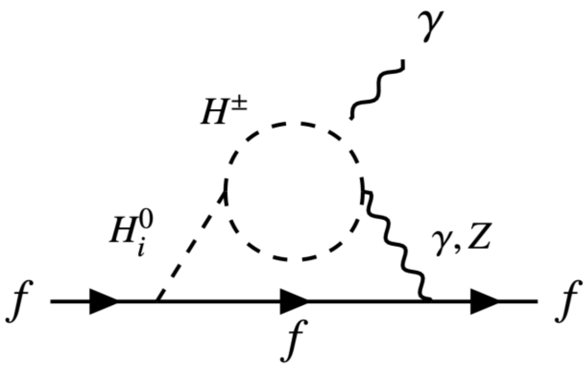


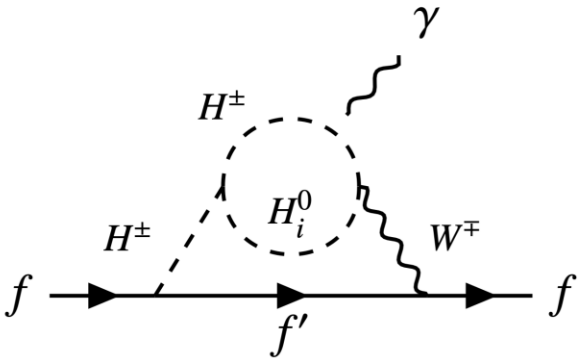
$H_i^0 \subset (H_u^0, H_d^0, S)$

CP violations in the Higgs sector are not fully captured!

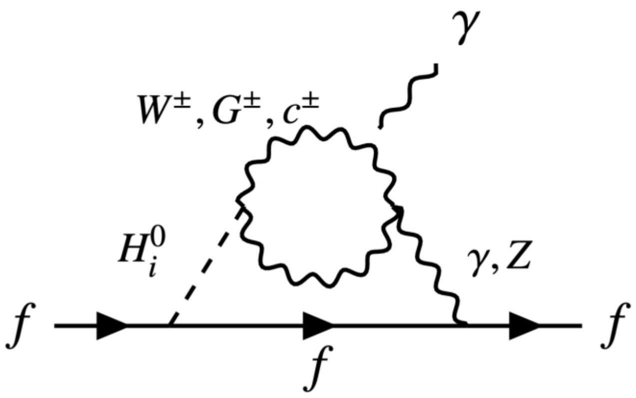
Neglected contributions: gifts from 2HDM

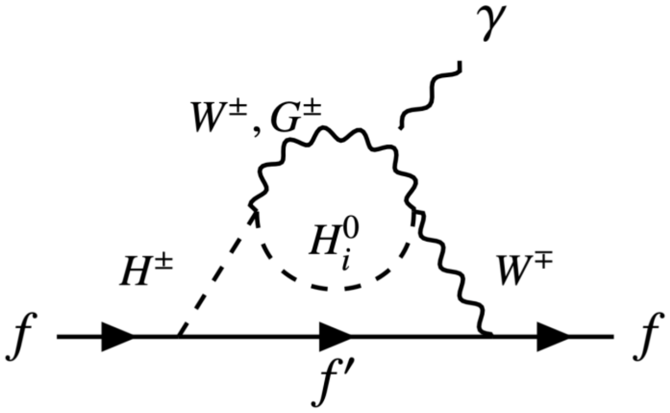
$H^{\pm}$ in the loop





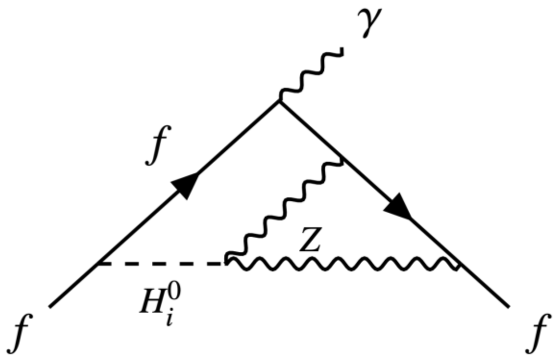
$W^{\pm}$ in the loop

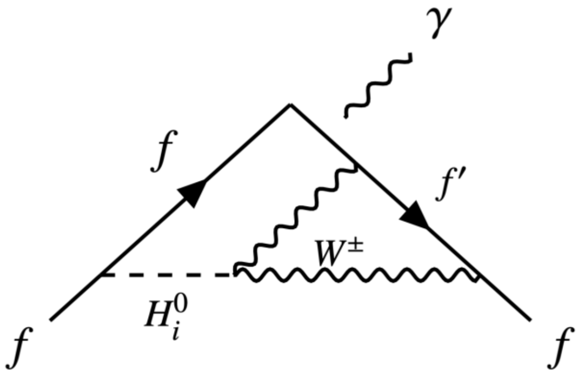




Abe et al. JHEP01(2014)106

Kite





W. Altmannshofer et al. PhysRevD.102.115042

2HDM $\Rightarrow$ NMSSM

How each diagram depends on phases

Source	Diagram	MSSM Phase	NMSSM Phase
MSSM OL	$(d_f^E)^{\tilde{\chi}^0}$	$\Phi_1,\ \phi_{0,1,2,9}$	$\phi_{3,5}$
	$(d_f^E)^{\tilde{\chi}^\pm}$	$\Phi_1,\ \phi_{0,2,9}$	
MSSM TL	$(d_f^E)^{\gamma H}$	$\Phi_{1,3,4},\ \phi_{0,1,2,9}$	$\phi'_0,\ \phi_{3,4,5,6,7,8}$
	$(d_f^E)^{ZH}$	$\Phi_1,\ \phi_{0,2,9}$	$\phi'_0,\ \phi_{3,4,5,6,7,8}$
	$(d_f^E)^{WH}$	$\Phi_1,\ \phi_{0,2,9}$	$\phi_{3,5}$
	$(d_f^E)^{WW}$	$\Phi_1,\ \phi_{0,2,9}$	$\phi_{3,5}$
THDM	$(d_f^E)^{H^\pm}$	ϕ_0	$\phi'_0,\ \phi_{3,4,5,6,7,8}$
	$(d_f^E)^{W^\pm}$	ϕ_0	$\phi'_0,\ \phi_{3,4,5,6,7,8}$
	$(d_f^E)^{\mathrm{Kite}}$	ϕ_0	$\phi'_0,\ \phi_{3,4,5,6,7,8}$

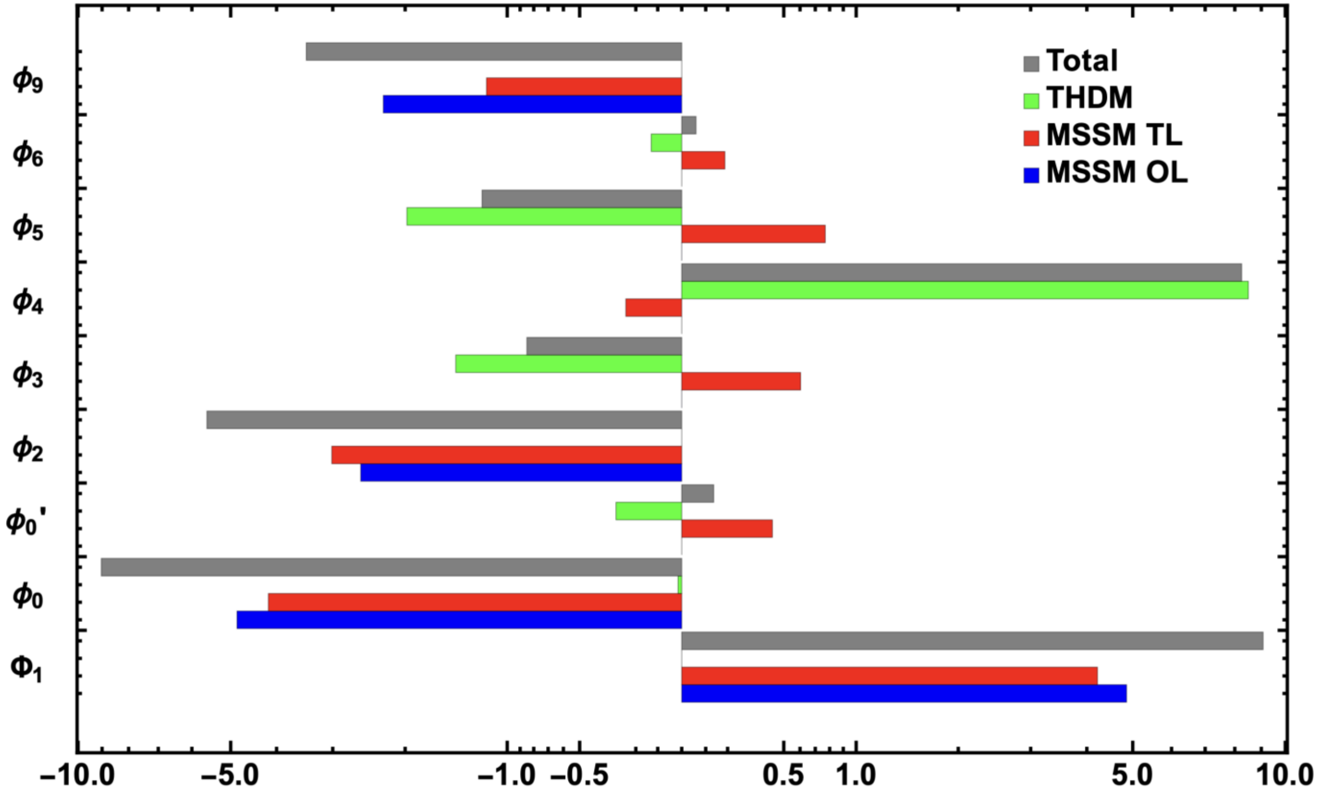
Neutralino & Chargino

Higgs

2HDM impact on phase constraints

- Benchmark

$M_{\tilde{H}^0}, M_{\tilde{H}^\pm}$	200
$M_{\tilde{S}}$	200
$(M_{\tilde{B}}, M_{\tilde{W}})$	(100, 200)
(M_{H_u}, M_{H_d}, M_S)	(204, 615, 217)
$(m_{h^0}, m_{A^0}, m_{H^+})$	(123, 370, 711)
$(m_{\tilde{\chi}^0}, m_{\tilde{\chi}^\pm})$	(95, 189)
$m_{\tilde{e},\tilde{\nu}}$	5000

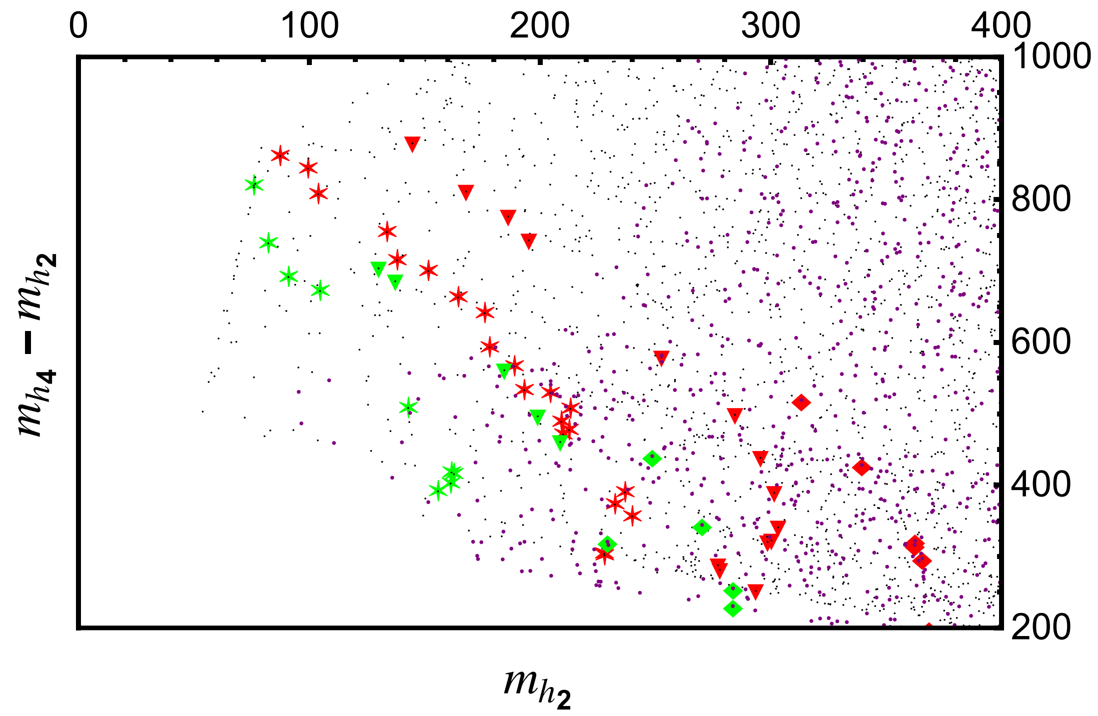


$\sin(\phi) = 0.01$

Length = # of 4.1E-30 e cm

eEDM is highly sensitive to chargino related phases Φ_1 and $\phi_{0,2,9}$
$\phi_{3,4,5}$ are significantly affected by the 2HDM contribution.

2HDM impact on mass reaches



✶ $\mathrm{Sin}[\phi_3] = 10^{-2}$ ▼ $\mathrm{Sin}[\phi_3] = 10^{-1}$ ◆ $\mathrm{Sin}[\phi_3] = 10^{0}$

■ w/o THDM ■ w/ THDM

● Viable region for 10^{-2}, 10^{-1}

● Viable region for $\mathcal{O}(1)$ phase

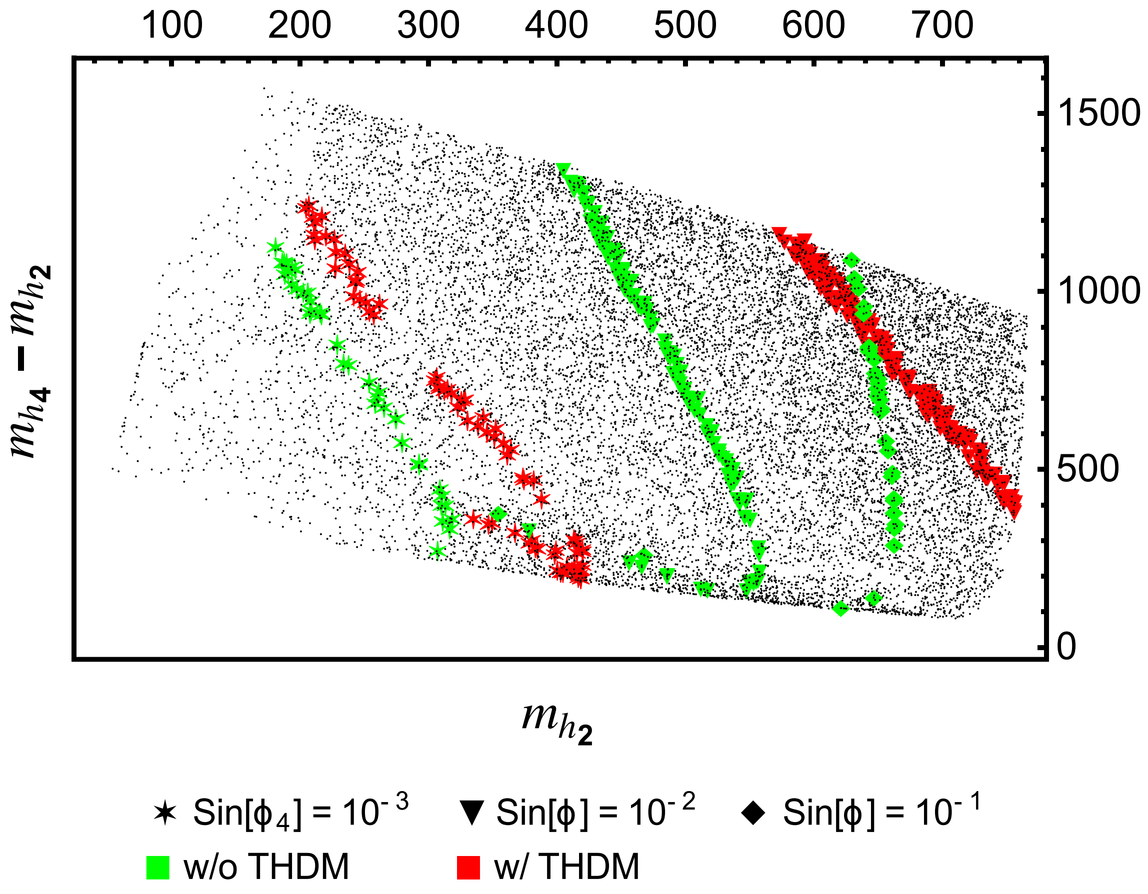
$m_{h_{2,4}}$ are second/fourth lightest neutral Higgs bosons

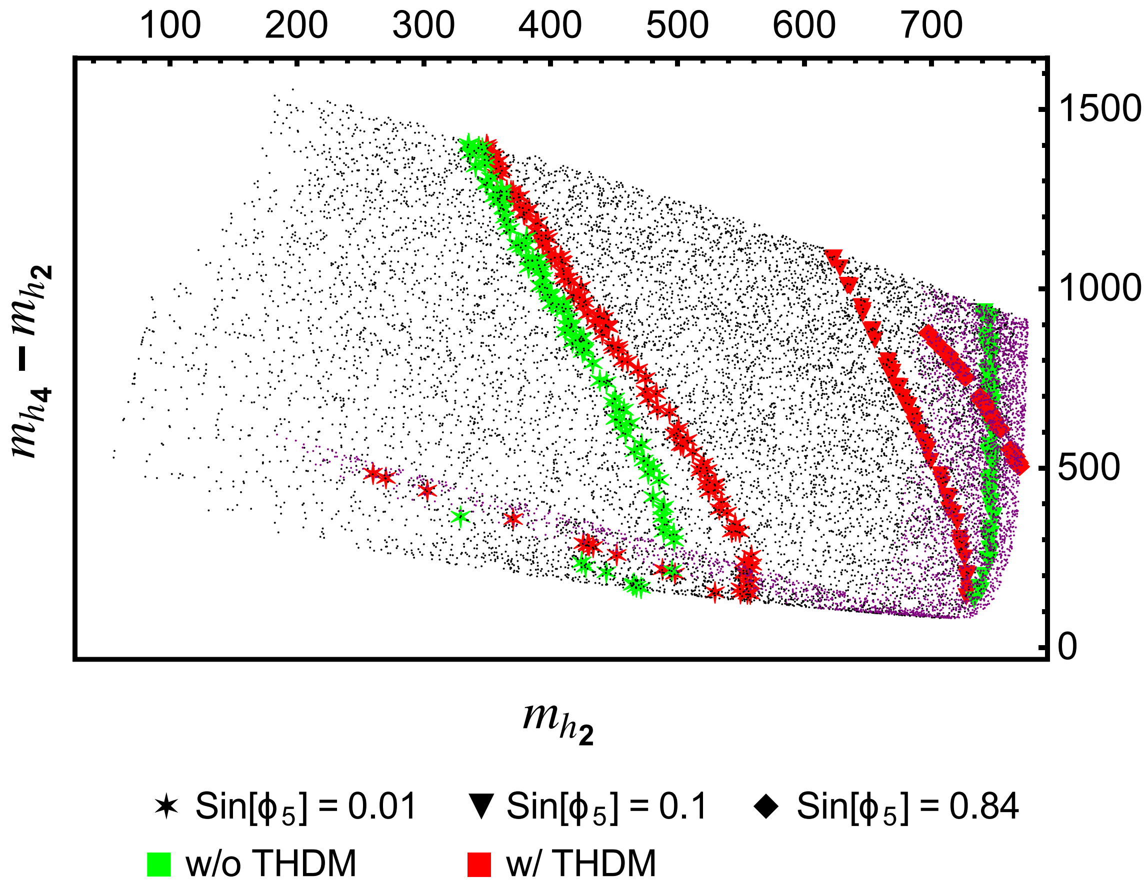
Masses change by varying β and m_9^3

- A larger CP-violating phase raises the mass scale of exclusion.
- Including THDM contributions further tightens the ϕ_3-driven exclusion limits
- An $\mathcal{O}(1)$ phase significantly reshapes the viable mass spectrum.

m_{h_2} is NMSSM-like, m_{h_4} is MSSM-like.
Masses to the left of each band are unlikely to produce $d_e \leq$ 4.1E-30 e cm.

2HDM impact on mass reaches





Viable region for 10^{-2}, 10^{-1}

Viable region for $\mathcal{O}(1)$ phase

NMSSM with complete eEDM

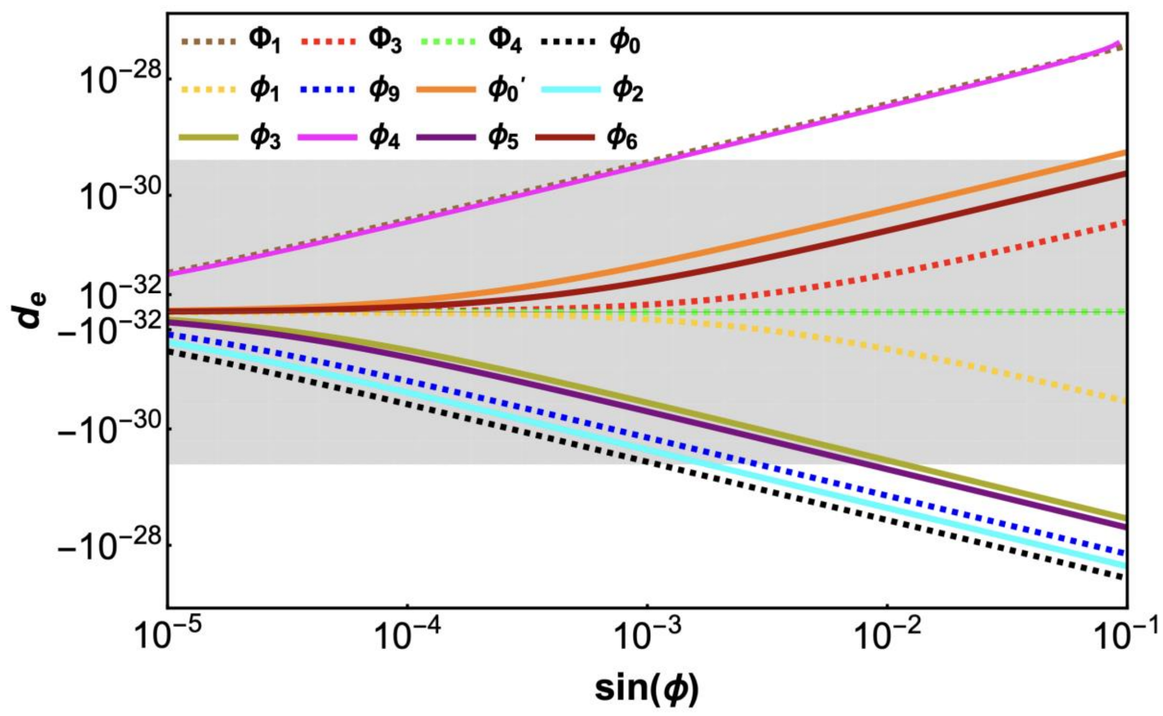
Current eEDM bounds are obtained from measuring frequency displacements of paramagnetic systems (ThO, HIF^+).

$$\left| d_e + \frac{W_S}{\mathcal{E}_{\text{eff}}} C_S^{(0)} \right| < d_e^{\text{exp}}$$

Short-range contribution

$$\mathcal{L}_{eN}^{\text{eff}} = -\frac{G_F}{\sqrt{2}} C_S^{(0)} \bar{e} i \gamma_5 e \bar{N} N + \cdots$$

Long-range semi-leptonic contribution



SM: $C_S^{(0)}$ dominant $\quad d_e \sim$ 1E-35 e cm

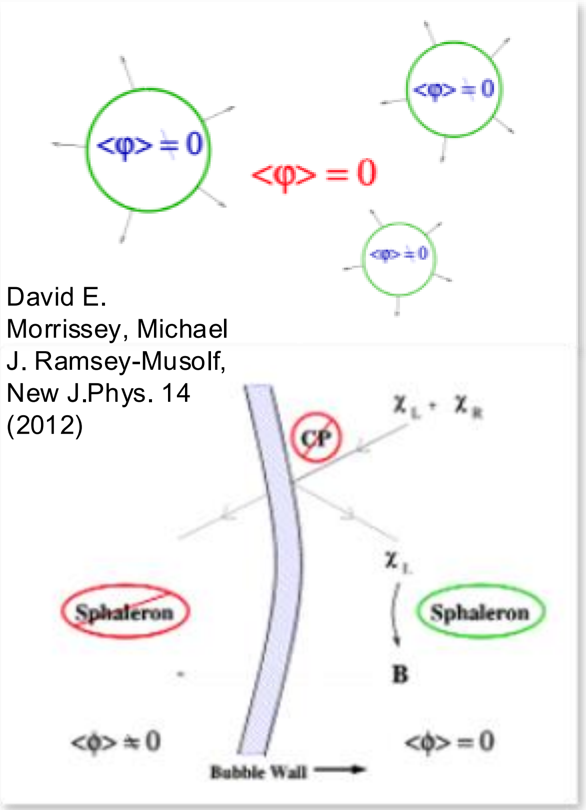
(N)MSSM: d_e dominant $\quad d_e \leq d_e^{\text{exp}}$

Constraints on phases vary substantially.

Complimentary constraint from baryogenesis

Demanding sufficient CP violation for successful baryogenesis sets a lower bound on the CP-violating phases.

Electroweak baryogenesis



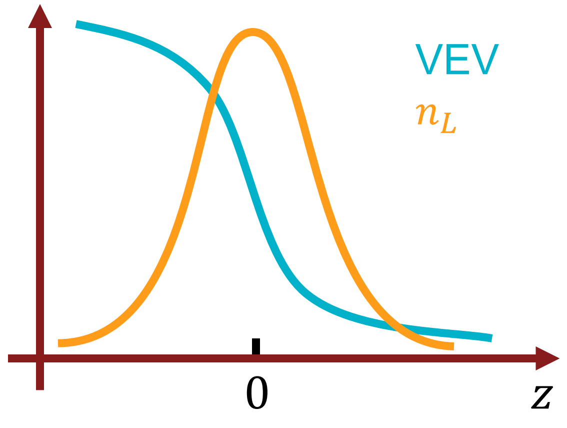
David E. Morrissey, Michael J. Ramsey-Musolf, New J.Phys. 14 (2012)

1) A strongly first-order phase transition is triggered at a temperature around the EW scale T ~ 100GeV.
2) CP violation causes LH and RH particles scatter off the expanding bubble wall at different rates, generating chiral asymmetries.
3) The weak sphaleron in the unbroken phase converts the chiral asymmetries to a net baryon asymmetry, which is preserved as it diffuses into the broken-phase bubbles.

$$Y_B \equiv \frac{n_B}{s} = \begin{cases} (8.64,\ 8.76) \times 10^{-11} & \text{CMB} \\ (8.40,\ 8.75) \times 10^{-11} & \text{BBN} \end{cases}$$

Implementations of EWBG: Boltzmann equation

$$V = A_t m_t(z) \tilde{t}_L^* \tilde{t}_R e^{i\theta(z)} + \text{h.c.}$$



VEV insertion approximation

$$v_w \partial_z n_L - D_L \partial_z^2 n_L = -\Gamma^{\pm}(n_L \pm n_R) + S^{\text{CPV}}$$

$$S^{\text{CPV}} \propto \frac{v_w}{T} A_t^2 m_t^2(z) \theta'(z)$$

Semi-classical / VEV resummation approach

C. Lee, V. Cirigliano, MJRM, arXiv:0412354
V. Cirigliano, MJRM, C. Lee, arXiv:0912.3523
V. Cirigliano, C. Lee, S. Tulin, arXiv:1106.0747

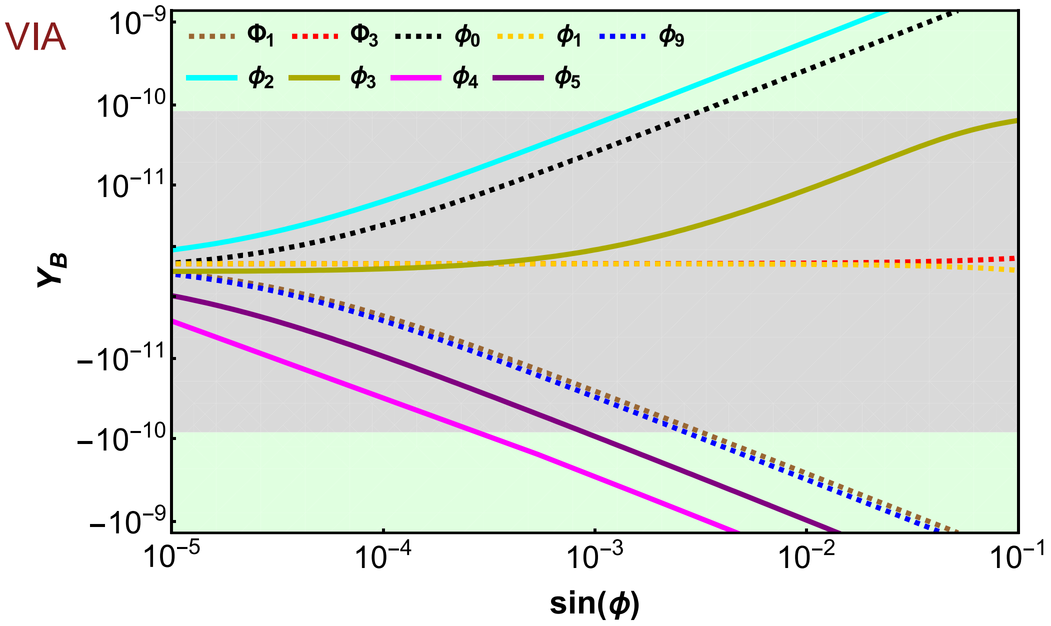
$$(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \mathbf{F} \cdot \nabla_{\mathbf{k}}) f_m(\mathbf{k}, x)$$
$$= -[i\omega_{\mathbf{k}} + \Sigma^0 + \mathbf{v} \cdot \mathbf{\Sigma}, f_m(\mathbf{k}, x)] + \mathcal{C}_m[f_m, \bar{f}_m](\mathbf{k}, x)$$

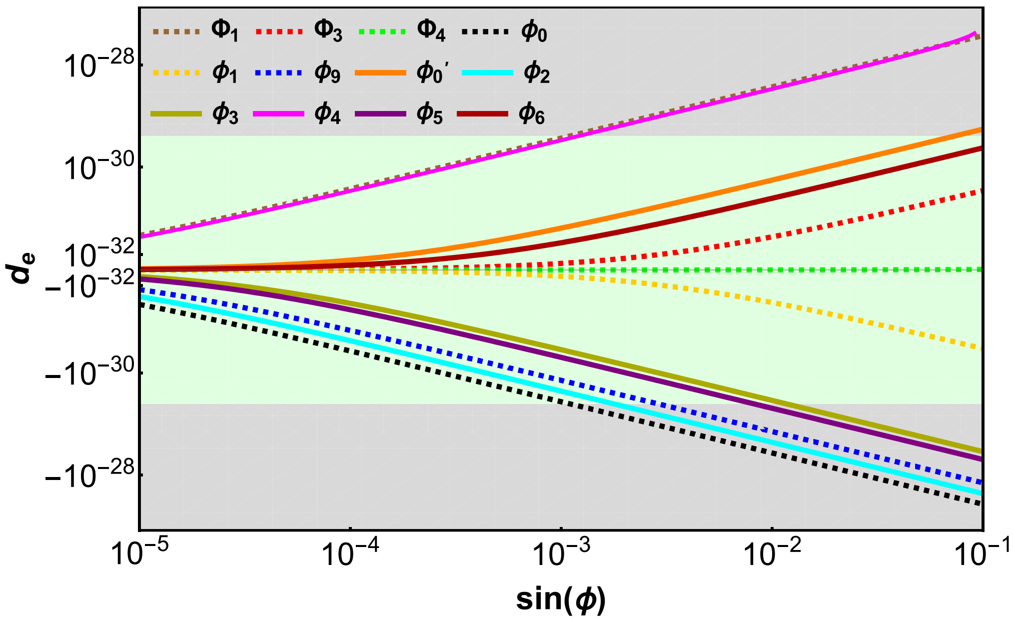
$$\Sigma^\mu(x) \equiv U^\dagger(x) \partial^\mu U(x)$$

$$n_B = -3 \frac{\Gamma_{ws}}{v_w} \int_{-\infty}^{\frac{L_w}{2}} dz\, n_L(z) e^{\frac{15}{4} \frac{\Gamma_{ws}}{v_w} z}$$

Complimentary constraint from baryogenesis

VIA





- $\Phi_{3,4}$ and $\phi_{1,6,0'}$ lie well below the eEDM limit but contribute negligibly to baryogenesis.
- Φ_1 and $\phi_{0,3}$ can generate sufficient baryon asymmetry yet are strongly excluded by eEDM constraints.
- $\phi_{2,9}$ marginally evade these bounds.
- $\phi_{4,5}$ exhibit substantially broader viable parameter regions.

$|\sin\phi_4| \in$ (2.9E-4, 1.2E-3)

$|\sin\phi_5| \in$ (8.8E-4, 7.7E-3)

Future measurements

What precision must future measurements attain to conclusively exclude the NMSSM under the single-phase assumption?

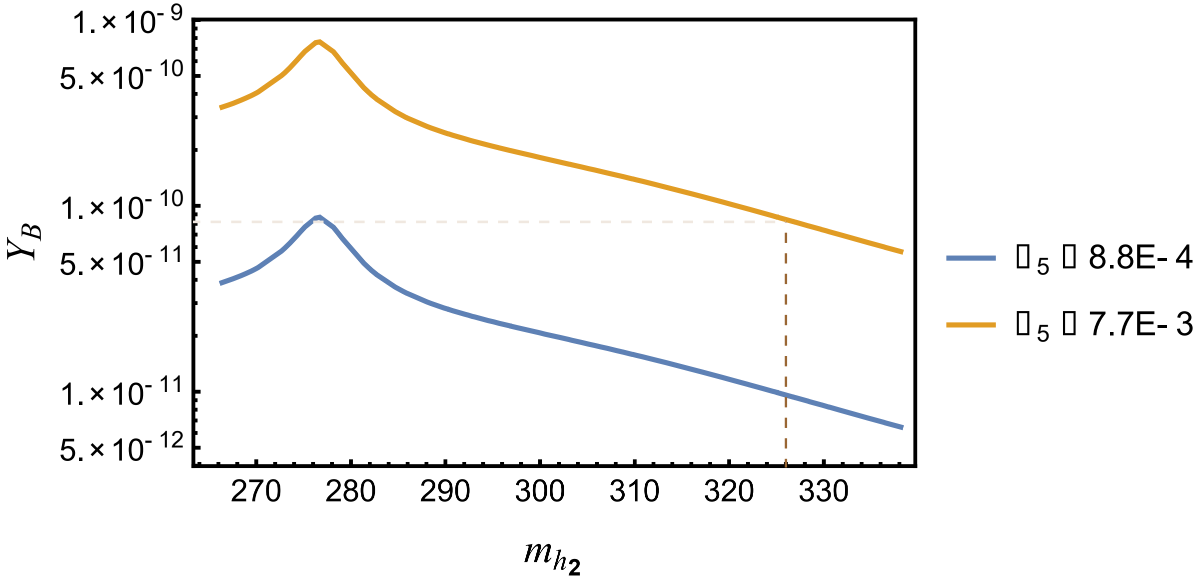
eEDM

$|\sin\phi_4| \in$ (2.9E-4, 1.2E-3) $\quad d_e(\sin\phi_4 = 2.9\text{E}{-4}) = 9.7\text{E-31 e cm}$

$|\sin\phi_5| \in$ (8.8E-4, 7.7E-3) $\quad d_e(\sin\phi_5 = 8.8\text{E}{-4}) = 4.7\text{E-31 e cm}$

ACME III d_e^{proj}~3E-31 e cm

LHC

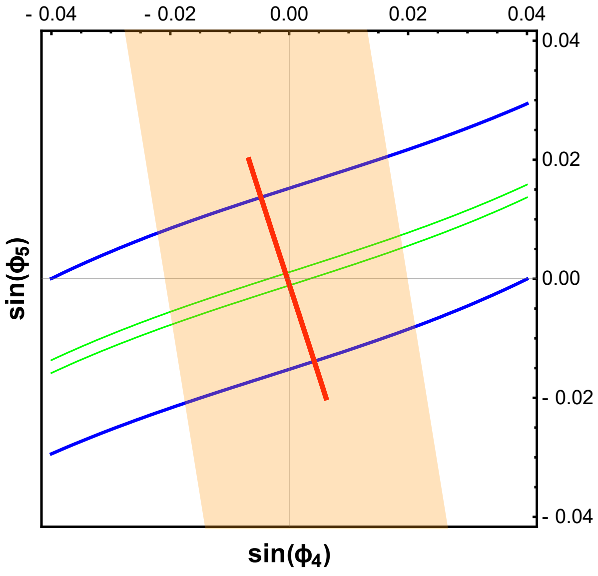


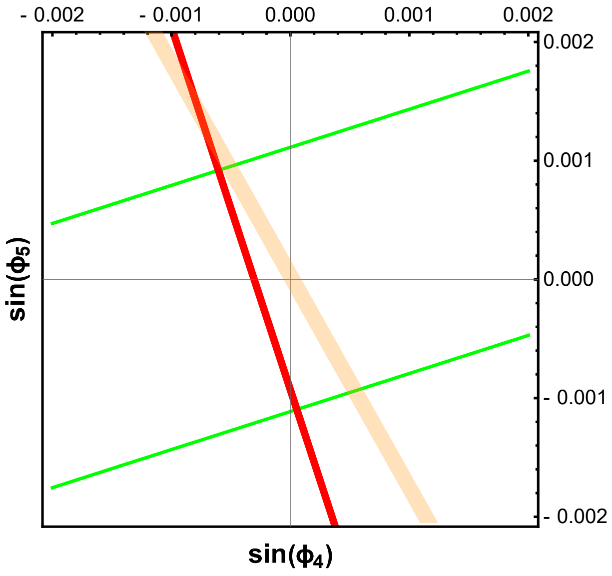
Need to reach an exclusion sensitivity for m_{h_2} up to 326GeV

Current LHC Higgs limits permit m_{h_2} within the range (239, 309)

Future measurements

If multiple CP-violating phases are present, the combined eEDM and EWBG constraints will never suffice to exclude the NMSSM as a CP-violating BSM candidate.





2 constraints ⇔ 2 variables, it is solvable!

More constraints should be incorporated: neutron, Hg, Ra EDMs… Not enough!

They must achieve precision comparable to—or exceeding—that projected for future electron-EDM measurements.

Summary

- We have identified contributions to the electron EDM in the NMSSM that previous studies overlooked, yet which can have a substantial impact.
- $\phi_{4,5}$ emerge as promising candidates, satisfying both eEDM and EWBG requirements.
- Future eEDM measurements could definitively rule out electroweak baryogenesis in the NMSSM under the single-phase assumption.
- To fully test the model, additional high-precision EDM searches (e.g., neutron, mercury, and radium) should achieve sensitivity comparable to or exceeding forthcoming eEDM limits.
- Overall, the NMSSM remains a compelling candidate for physics beyond the Standard Model.

Thank you!

Backup Slides

- BM I

$$\tan\beta = 2.11, \;\; \lambda = 0.65, \;\; \kappa = 0.2,$$
$$v_s = 494\text{GeV}, \;\; \alpha = 6.34 \times 10^4\text{GeV}^2, \;\; \beta = 200\text{GeV}$$

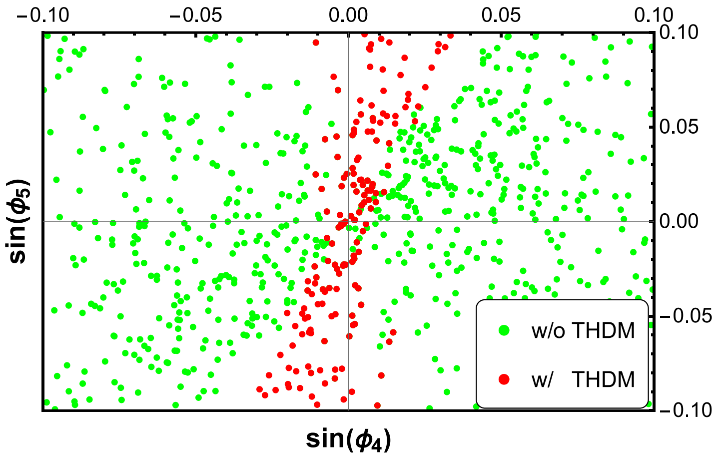
$$M_2 = 2M_1 = 200\text{GeV}, \;\; M_3 = 2.5\text{TeV},$$
$$b = 1.0 \times 10^4\text{GeV}^2, \;\; A_u = A_e = A_d = 200\text{GeV},$$
$$m_7^2 = 5.56 \times 10^4\text{GeV}^2, \;\; m_9^3 = 9.82 \times 10^6\text{GeV}^3,$$
$$A_\lambda = 959\text{GeV}, \; A_\kappa = 900\text{GeV}, \;\; \mu' = 200\text{GeV}.$$

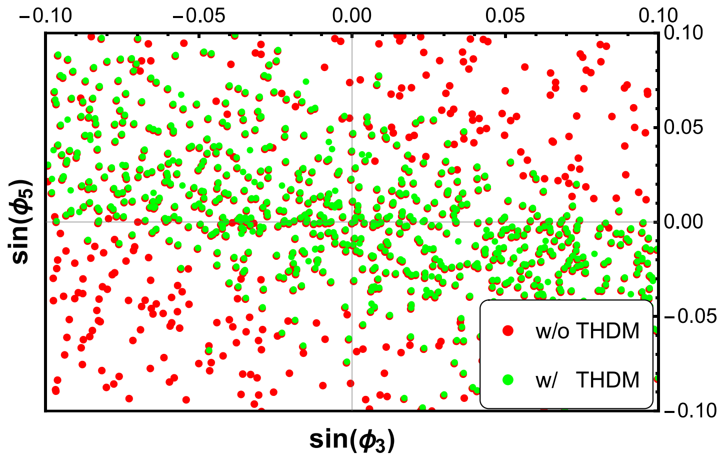
$$\Phi_{1,2,3,4,5} = \phi_{0,1,2,4,6,8,9} = 0, \;\; \phi_0' = \phi_{3,5,7} = \pi.$$

$\vert\sin(\Phi_1, \Phi_3, \Phi_4)\vert >$	(3.10E-3, Ø, Ø)
$\vert\sin(\Phi_1, \Phi_3, \Phi_4)\vert <$	(1.17E-3, 1, 1)
$\vert\sin(\phi_0, \phi_0', \phi_1)\vert >$	(3.10E-3, Ø, Ø)
$\vert\sin(\phi_0, \phi_0', \phi_1)\vert <$	(1.18E-3, 1.23E-1, 1)
$\vert\sin(\phi_2, \phi_3, \phi_4)\vert >$	(1.42E-3, 2.08E-1, 2.88E-4)
$\vert\sin(\phi_2, \phi_3, \phi_4)\vert <$	(1.92E-3, 1.09E-2, 1.22E-3)
$\vert\sin(\phi_5, \phi_6, \phi_9)\vert >$	(8.76E-4, Ø, 2.62E-3)
$\vert\sin(\phi_5, \phi_6, \phi_9)\vert <$	(7.70E-3, 2.90E-1, 3.04E-3)

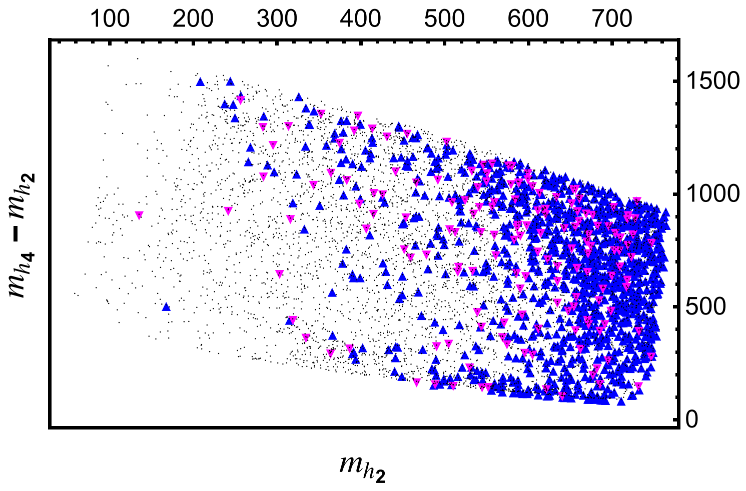
If multiple phases exist

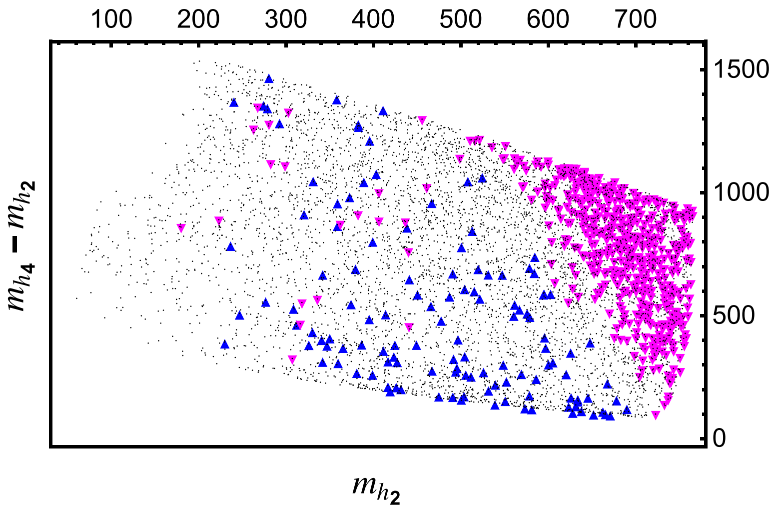
- Including THDM contributions alters the correlation patterns among the CP-violating phases.





- THDM contributions significantly reshape the mass regions favored by electron-EDM constraints.



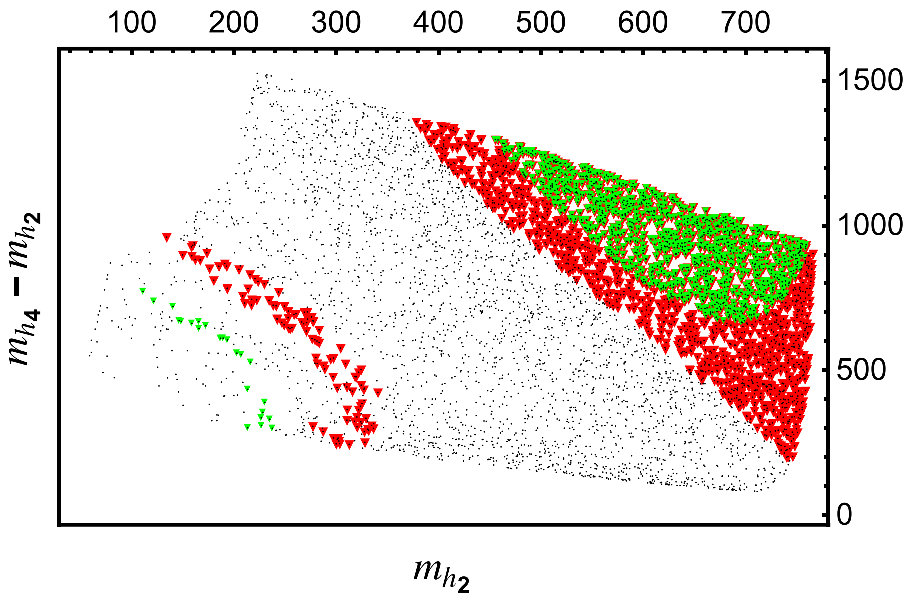


Lost   Gain

$d_e \leq$ 4.1E-30 e cm

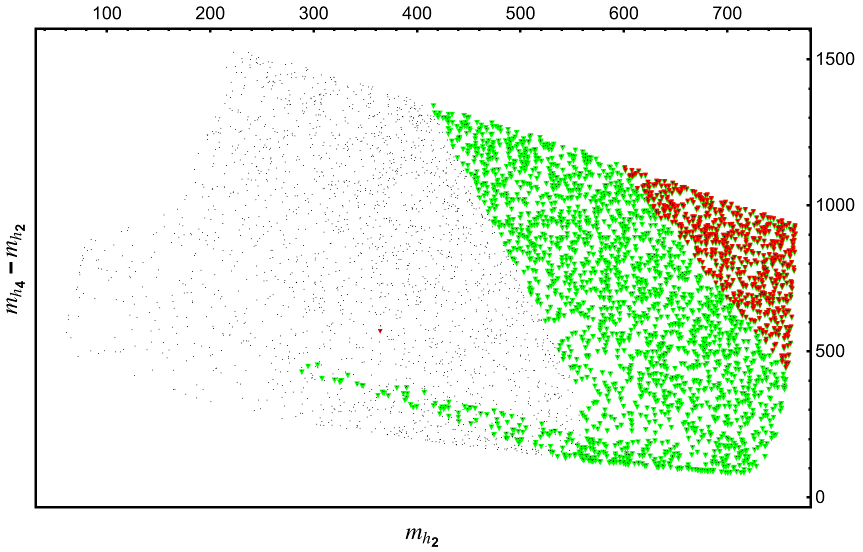
Backup Slides

ϕ_3

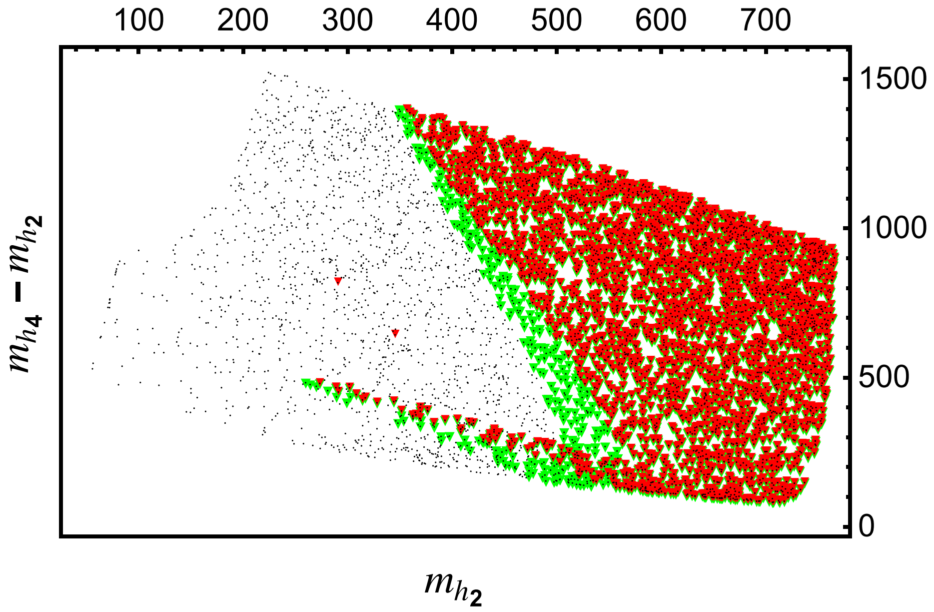


ϕ_3 has strong correlations with m_{h_2} and m_{h_4}

ϕ_4



ϕ_5



Backup Slides

Fields	$U(1)_{PQ}$	$U(1)_R$ boson	$U(1)_R$ fermion	$U(1)_Y$	$U(1)_S$
$Q, U^c, D^c, L\cdot E^c$	-1/2	1/2	-1/2		0
H_u, H_d	1	1	0	$\pm 1/2$	0
S	0	1	0	0	1
V_a	0	0	1		0
μ_0	-2	0		0	0
$Y_{u,d,e}$	0	0		0	0
b_0	-2	-2		0	0
$a_{u,d,e}$	0	-2		0	0
$M_{1,2,3}$	0	-2		0	0
λ	-2	-1		0	-1
κ	0	-1		0	-3
β	0	0		0	-2
α	0	+1		0	-1
λA_λ	-2	-3		0	-1
κA_κ	0	-3		0	-3
m_7^2	0	-2		0	-2
m_9^3	0	-1		0	-1
$\phi_{u,d}$	+1	+1		$\pm 1/2$	0
ϕ_s	0	+1		+1	0

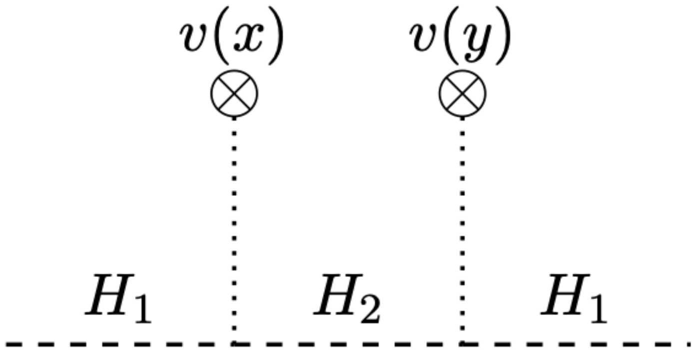
TABLE VI: The PQ, R, S and Y charge assignments on fields, VEVs and spurions. U^c, D^c, E^c denote hermitian conjugates of right-handed (s)fermion fields. V_a is the vector multiplet.

$$O_{\widetilde{W}} = \epsilon^{IJK}\widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$
$$O_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$O_{H\widetilde{B}} = H^\dagger H B^{\mu\nu}\widetilde{B}_{\mu\nu}$$
$$O_{\widetilde{W}} = H^\dagger H W^{I\mu\nu}\widetilde{W}^I_{\mu\nu}$$
H
$$O_{HW\widetilde{B}} = (H^\dagger \sigma^I H) W^{I\mu\nu}\widetilde{B}_{\mu\nu}$$
$$O_{H\widetilde{G}} = H^\dagger H G^{A\mu\nu}\widetilde{G}^A_{\mu\nu}$$

Backup Slides

Vev-insertion approximation



$$\mathcal{L}_{\text{int1}} = \lambda(x) H_1 H_2^* + c.c.$$

$$\partial_\mu j^\mu_{H_1} = -\Gamma^-_{H_1H_2}\left(\mu_{H_1} - \mu_{H_2}\right) + \Gamma^+_{H_1H_2}\left(\mu_{H_1} + \mu_{H_2}\right) + S^{CPV}_{H_1H_2}$$

$$\Gamma^\pm_{H_1H_2} = -\frac{1}{T}\frac{g(x,x)}{4\pi^2}\int \frac{dk k^2}{\omega_1\omega_2}\mathrm{Im}\left\{\frac{h_B(\mathcal{E}_2) \mp h_B(\mathcal{E}_1)^*}{\mathcal{E}_2 - \mathcal{E}_1^*} - \frac{h_B(\mathcal{E}_2) \mp h_B(\mathcal{E}_1)}{\mathcal{E}_2 + \mathcal{E}_1}\right\},$$

$$S^{CPV}_{H_1H_2} = \frac{1}{2\pi^2}\left[\mathrm{Im}\dot{g}(x,x)\right]\int \frac{dk k^2}{\omega_1\omega_2}\mathrm{Im}\left[\frac{n_B(\mathcal{E}_2) + n_B(\mathcal{E}_1)}{(\mathcal{E}_2 + \mathcal{E}_1)^2} - \frac{n_B(\mathcal{E}_2) - n_B(\mathcal{E}_1^*)}{(\mathcal{E}_2 - \mathcal{E}_1^*)^2}\right],$$

where

$$g(x,y) = \lambda(x)^*\lambda(y), \qquad \dot{g}(x,x) = \partial_{y^0} g(x,y)|_{y=x}$$

$$\omega^2_{H_1,H_2} = |\mathbf{k}|^2 + M^2_{H_1,H_2}, \quad \mathcal{E}_{H_1,H_2} = \omega_{H_1,H_2} - i\Gamma_{H_1,H_2}, \quad h_B(x) = -\frac{e^{x/T}}{(e^{x/T} - 1)^2}$$