CP violation in the Minimal Linear σ Model

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[arXiv:2012.03990]

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1. A useful theoretical laboratory

The MLσM is a BSM with a rich pheno.:

- ✓ The Higgs, h, is a pseudo-NGB
- ✓ A radial scalar mode, s,
  - mixes with h
  - its VEV breaks the extended symmetry
- ✓ Operators additional to SMEFT after integrating-out its heavy fermions

GOALS

1. Generalizing MLσM with complex phases, see limitations of EFT approach using electron EDM (eEDM) bounds
2. Discuss EW Phase Transition (EWPhT)

Successful EW baryogenesis (EWBG)??

2. The Minimal Linear σ Model (MLσM) [1]

INGREDIENTS

1. Global symmetry

$$SO(5)\times U(1)_X \xrightarrow{f} SO(4)\times U(1)_X$$

2. Spectrum:
   - SM Gauge bosons & 3rd family quarks
   - Exotics
     - Real scalar SO(5) quintuplet

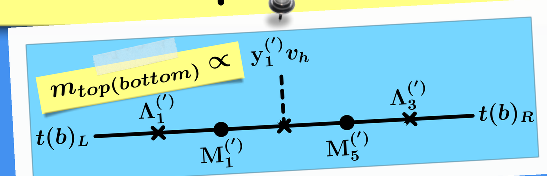
SM Higgs doublet comp. — EW singlet

$$\phi = (\pi_1,\, \pi_2,\, \pi_3,\, \text{h},\, \text{s})^T \xrightarrow{u.g.} \phi = (0,\,0,\,0,\,\text{h},\,\text{s})^T$$

   - Vector-like quarks (VLQs)
     - Two SO(5) quintuplets: $\psi^{(2/3)}, \psi^{(-1/3)}$
     - Two SO(5) singlets: $\chi^{(2/3)}, \chi^{(-1/3)}$

$U(1)_X$ charges

3. Fermion Partial Compositeness

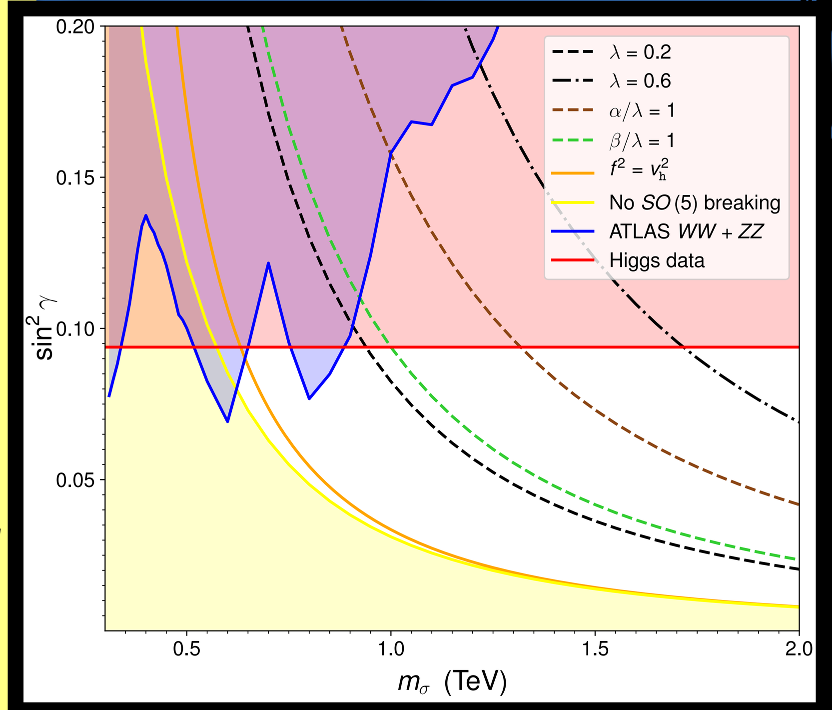


[1] Feruglio, Gavela, Kanshin, Machado, Rigolin, and Saa, [arXiv:1603.05668]

✓ $\langle h\rangle = v_h = 246$GeV, $\langle s\rangle = v_s$
✓ GB Higgs: $|v_h| < |v_s|$

Scalar mixing

$h = \text{h}\cos\gamma - \text{s}\sin\gamma$
$\sigma = \text{h}\sin\gamma + \text{s}\cos\gamma$



LHC Constraints

$\mathcal{L}_{ferm.}$

1. Kinetic terms (SM and exotics)
2. Mass terms (exotics): $\text{M}^{(\prime)}_{1,5}$
3. Yukawa interactions (exotics): $\text{y}^{(\prime)}_{1,2}$
4. Portal terms (SM-exotics): $\Lambda^{(\prime)}_{1,2,3}$

$\exists$ two physical CPV phases: $\text{y}_{1,2} = |\text{y}_{1,2}|\, e^{i\alpha_{1,2}}$

3. Effective operators

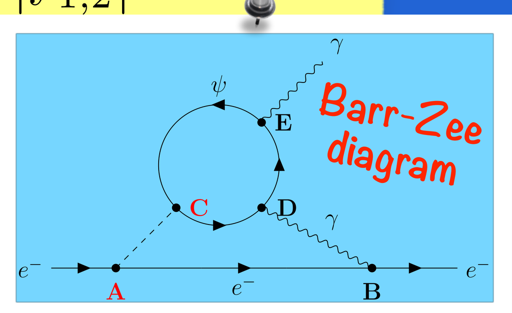
d	Operator	c_i	Leading Order in f/M
4	$\bar q_L\, \widetilde H\, t_R$	$-y_t$	$-\lvert \text{y}_1\rvert \frac{\Lambda_1\Lambda_3}{M_1M_5}\mathcal{Z}_{q_L}^{-1/2}\mathcal{Z}_{t_R}^{-1/2}$
5	$\text{s}\,(\bar q_L \widetilde H t_R)$	$c^t_{\text{s}1}$	$\frac{y_t}{M_5}\left[\text{y}_2^*\frac{\Lambda_2}{\Lambda_3} - \left(\text{y}_1\frac{\Lambda_2\Lambda_3}{M_1M_5} + \text{y}_2^*\frac{\Lambda_2\Lambda_3}{M_1^2}\right)\mathcal{Z}_{t_R}^{-1}\right]$
6	$\text{s}^2\,(\bar q_L \widetilde H t_R)$	$c^t_{\text{s}2}$	$-\frac{y_t}{M_1M_5}\left\{\text{y}_1\text{y}_2^* - \left[\text{y}_1\text{y}_2^*\left(2\frac{\Lambda_2^2}{M_5^2}+\frac{\Lambda_3^2}{M_1^2}\right) + \frac{(\lvert\text{y}_2\rvert^2+2\text{y}_2^{*2})\Lambda_2^2+\lvert\text{y}_1\rvert^2\Lambda_3^2}{2M_1M_5}\right]\mathcal{Z}_{t_R}^{-1} + 2\frac{\Lambda_2^2\Lambda_3^2}{M_1M_5}\left(\frac{\text{y}_1\text{Re}[\text{y}_1]}{M_5^2} + \frac{\text{y}_1\text{Re}[\text{y}_2]+\text{y}_2^*\text{Re}[\text{y}_1]}{M_5M_1} + \frac{\text{y}_2^*\text{Re}[\text{y}_2]}{M_1^2}\right)\mathcal{Z}_{t_R}^{-2}\right\}$
	SMEFT $\lvert H\rvert^2\,(\bar q_L \widetilde H t_R)$	c^t_{H2}	$-\frac{y_t}{M_1M_5}\left[2\text{y}_1\text{y}_2^* - \left(2\text{y}_1\text{y}_2^*\frac{\Lambda_3^2}{M_1^2} + \lvert\text{y}_1\rvert^2\frac{\Lambda_3^2}{M_1M_5}\right)\mathcal{Z}_{t_R}^{-1} - \left(\text{y}_1\text{y}_2^*\frac{\Lambda_1^2}{M_5^2} + \frac{\lvert\text{y}_1\rvert^2}{2}\frac{\Lambda_1^2}{M_1M_5}\right)\mathcal{Z}_{q_L}^{-1}\right]$

d=5 and d=6 have independent suppression scale

$\mathcal{Z}_{q_L} = 1 + \Lambda_1^2/M_5^2 + \Lambda_1'^2/M_5'^2$
$\mathcal{Z}_{t_R} = 1 + \Lambda_2^2/M_5^2 + \Lambda_3^2/M_1^2$

Leading order eff. operators contributing to eEDM after integrating out VLQs ($M_i^{(\prime)} \gg m_\sigma \gg v_h$) and $f/M \ll 1$

1. Bounds on $\text{Im}\,[c_i^t]$ if each one saturates the eEDM bound?
2. Bounds on $\text{Im}\,[c_i^t]$ when they are correlated by the model?
3. Role of the scalar σ?



4. eEDM bounds

The imaginary parts of tth and $tt\sigma$ couplings contribute to the eEDM through the Barr-Zee diagram

Effective Higgs-top $\mathscr{L}$

$$\mathscr{L}_{\text{eff}} = -\frac{y_t}{\sqrt{2}}\left(\kappa_t^h\,\bar t\, t + i\,\tilde\kappa_t^h\,\bar t\,\gamma_5\, t\right)h + (h\to\sigma)$$

eEDM Barr-Zee contribution [2]

$f_1(m_t^2/m_h^2) \simeq 2.87$

$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha_{\text{em}}}{(4\pi)^3}\sqrt{2}\,G_F\, m_e\left[\kappa_e^h\,\tilde\kappa_t^h\, f_1(m_t^2/m_h^2) + \kappa_e^\sigma\,\tilde\kappa_t^\sigma\, f_1(m_t^2/m_\sigma^2)\right]$$

ACME II Bound

$|d_e| < 1.1\times 10^{-29}$ e cm, at 90% C.L.

Benchmark Values: $m_\sigma = 1.5$ TeV, $\sin^2\gamma = 0.08$ — $f_1(m_t^2/m_\sigma^2) \simeq 0.3$, $v_s = 768$ GeV

I. General EFT Analysis

$\kappa_e^h = \cos\gamma$
$\kappa_e^\sigma = \sin\gamma$

$$\tilde\kappa_t^h = -(v_s\cos\gamma - v_h\sin\gamma)\,\text{Im}[c^t_{s1}]/y_t - v_s(v_s\cos\gamma - 2\,v_h\sin\gamma)\,\text{Im}[c^t_{s2}]/y_t + -\frac{3}{2}v_h^2\cos\gamma\,\text{Im}[c^t_{H2}]/y_t$$

$$\tilde\kappa_t^\sigma = -(v_s\sin\gamma + v_h\cos\gamma)\,\text{Im}[c^t_{s1}]/y_t - v_s(v_s\sin\gamma + 2\,v_h\cos\gamma)\,\text{Im}[c^t_{s2}]/y_t + -\frac{3}{2}v_h^2\sin\gamma\,\text{Im}[c^t_{H2}]/y_t$$

Effective parameters

a) BZ contributions: h VS σ

$$\tilde\kappa_t^{eff} = \kappa_e^h\,\tilde\kappa_t^h\, f_1(x_{t/h}) + \kappa_e^\sigma\,\tilde\kappa_t^\sigma\, f_1(x_{t/\sigma})$$

$x_{t/s} \equiv m_t^2/m_s^2$

c^t_i	h	σ
c^t_{s1}	98	2
c^t_{s2}	97	3
c^t_{H2}	99	1

Suppressing effects: κ_e^σ, f_1

% to $\tilde\kappa_t^{eff}$ with $m_\sigma = 1.5$ TeV and $\sin^2\gamma = 0.08$ if only c^t_i enters in the eEDM

b) Effects of $v_s > v_h$, mixing and m_σ on $\tilde\kappa_t^h$

	c^t_{s1}	c^t_{s2}	c^t_{H2}
Λ (TeV)	5.5×10^2	20	9

Limits on the WC eff. scale if only c^t_i enters in the eEDM. with $m_\sigma = 1.5$ TeV and $\sin^2\gamma = 0.08$

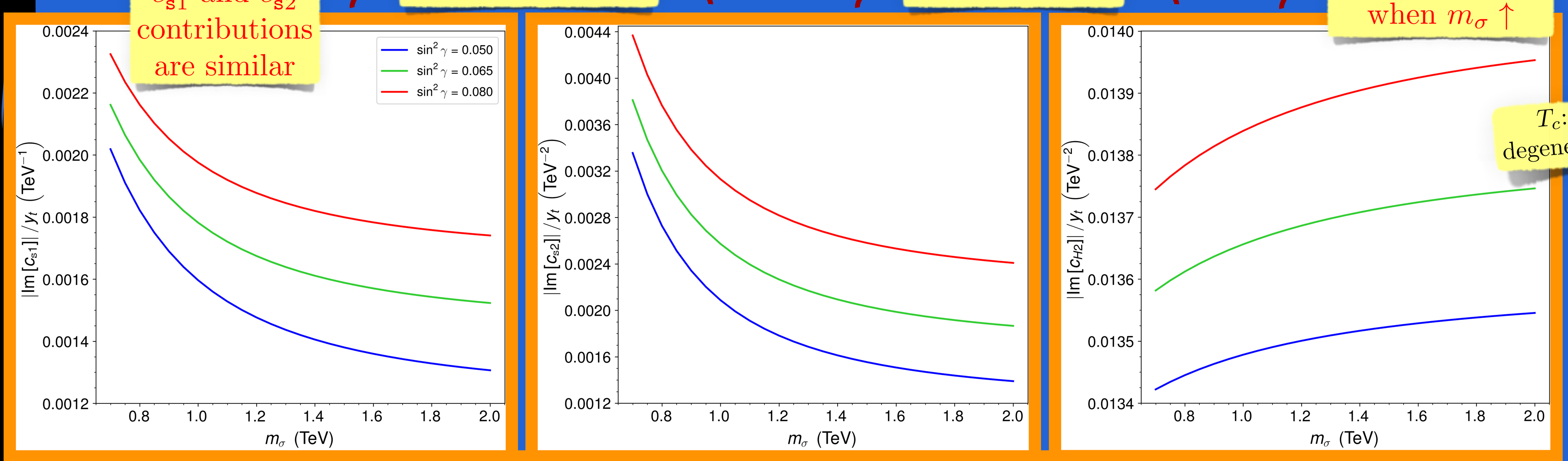
Softer for the SMEFT one

c^t_{s1} and c^t_{s2} contributions are similar

Stronger limits as $v_s\uparrow$ when $m_\sigma\uparrow$

Stronger on c^t_{s2} due to $v_s > v_h$

Softer limits as $f_1(m_t^2/m_\sigma^2)\downarrow$ when $m_\sigma\uparrow$



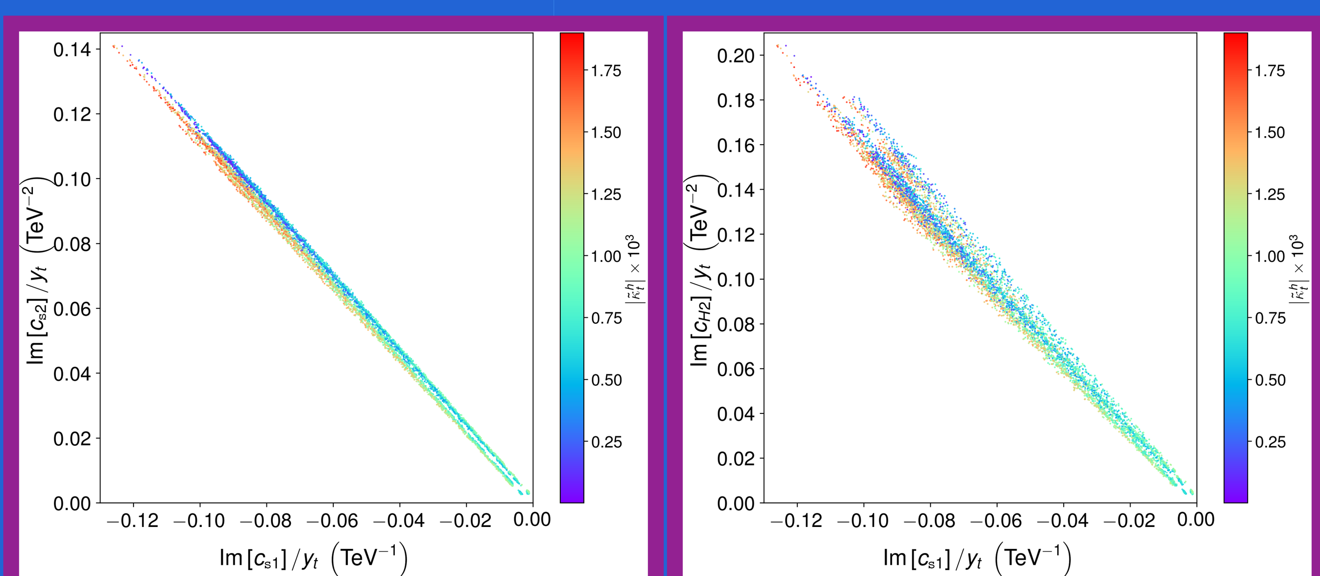
Bounds on the Im $[c_i^t]$ assuming only one operator at a time in eEDM

II. MLσM calculations

Results after a MLσM parameter scan compatible with limits discussed in [3], requiring $|d_e/e| = (0.5-1.1)\times 10^{-29}$ cm

c^t_i are correlated by the model!

a) Bounds on c^t_i

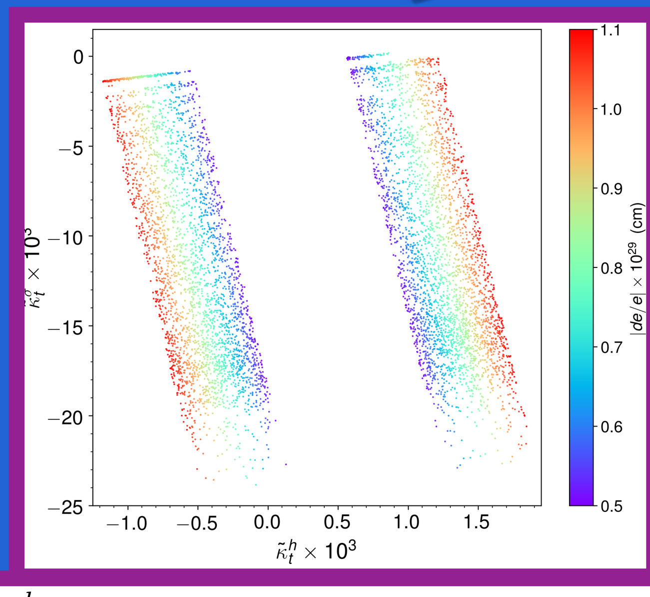


Values of $\text{Im}[c_i^t]/y_t$ for the points of our MLσM parameter scan

Weaker than EFT approach due to cancellations induced by correlations

b) $\tilde\kappa_t^{h,\sigma}$ values

Price of cancellation: fine-tuning in α_2 of the order of 10% to 1%



Values of $\tilde\kappa_t^{h,\sigma}$ for the points of our MLσM parameter scan

$\tilde\kappa_t^\sigma \gg \tilde\kappa_t^h$ due to cancellations

Weaker than SMEFT alone ($\tilde\kappa_t \lesssim 0.0012$ [4])

c) NP scale: lightest VLQ mass ~ 3 TeV

$\Lambda \sim \mathcal{O}(1)$, smaller than in EFT approach

[2] J. Brod, U. Haisch, and J. Zupan, [arXiv:1310.1385]

[3] J. Aguilar-Saavedra, JAG, L. Merlo, and J. No, [arXiv:1911.10202]

[4] E. Fuchs, M. Losada, Y. Nir, and Y. Viernik, [arXiv:2003.00099]

5. EWPhT

Successful EWBG requires a strong enough EWPhT: $v_{h,c}/T_c > 0.6-1.6$

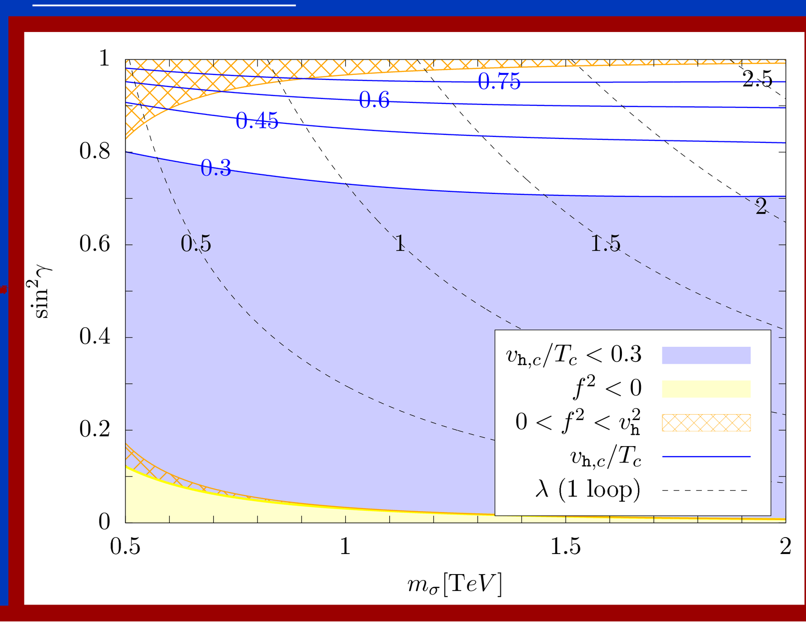
T_c: T where 2 degenerate minima $\exists$

$v_{h,c}$: Higgs VEV at $T = T_c$

In the MLσM, $v_{h,c}/T_c \gtrsim 0.6$ for $\sin^2\gamma \gtrsim 0.9$

Completely excluded by LHC Higgs data ($\sin^2\gamma \lesssim 0.09$)

No EWBG in the MLσM!!



Strength of the EWPhT ($v_{h,c}/T_c$) as function of m_σ and $\sin^2\gamma$