Electroweak Phase Transitions with BSM Fermions

[arXiv:2107.09617]

Martin Gabelmann, M. Margarete Mühlleitner, Jonas Müller | 26. August 2021

SUSY XXVIII 2021

1 Motivation

2 The 2HDM + Electroweakinos

3 Strength of the Electroweak Phase Transition in the 2HDM+EWinos

Experimental constraints on...

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Electroweakinos
(i.e. weak fermions)

$m_{\chi_1^0} \gtrsim$ 50-200 GeV

$m_{\chi_1^\pm} \gtrsim$ 94 GeV

Extended Higgs sectors
(e.g. MSSM inspired 2HDM)

$m_A \gtrsim$ 500-600 GeV

$\tan\beta \gtrsim 1 - 2$ [Bahl et. al]

Coloured Scalars
(e.g. stops)

$m_{\tilde{t}_1} \gtrsim$ 1-2 TeV

... suggest a hierachy between scalars and fermions ($\rightarrow$ split SUSY)

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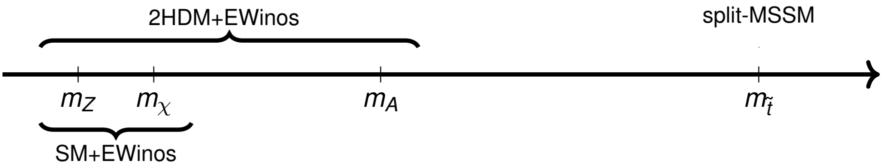

Electroweak Phase Transitions

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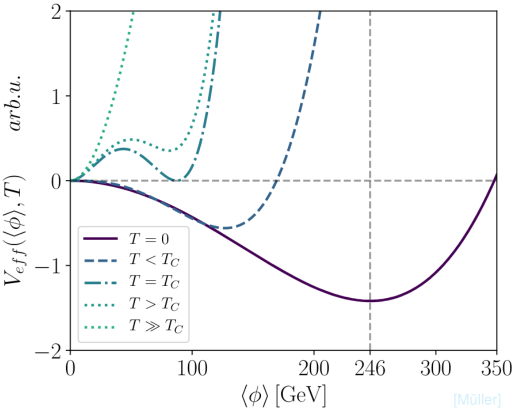
Strong first order EW phase transition (SFOEWPT):

- $\xi_c = {}^{v_C}/_{T_C} \gtrsim 1$ necessary requirement for baryogeneses [Sakharov]
- not possible in the SM ($m_h < 70\,\mathrm{GeV}$) [Kajantie et. al]
- extended Higgs sectors: many models favour light scalar masses (e.g. 2HDM [Basler et. al])



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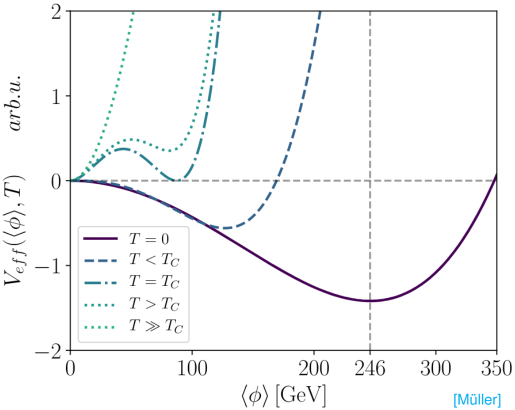

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Implications of Electroweak Phasetransitions

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(vanilla) **MSSM**

- scalar potential governed by gauge sector $\lambda_i \propto g_1^2, g_2^2$
- $\xi_c > 1$ requires $m_{\tilde{t}} < 115\,\mathrm{GeV}$

[Carena et. al]

(vanilla) **2HDM**

- $\xi_c > 1$ possible [Bochkarev et. al]
- increasing tension due to constraints on m_A, $m_{H^\pm}$, m_H

[Black et. al]

$\rightarrow$**Question:**

- Q1: can split-SUSY fermions relax tensions in the 2HDM?
- Q2: can it emerge from non-minimal split-SUSY?

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Scalar Sector

Type II 2HDM with a soft $\mathbb{Z}_2$-breaking term:

$$V_{2\text{HDM}} = \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \left(\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 - m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) + m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2$$

Spectrum after EWSB:

- 2 CP-even h_{SM} and H
- 1 CP-odd A
- 1 charged Higgs pair $H^\pm$

Fermion Sector

Similar to the MSSM, add triplet ($\tilde{W}$), singlet $\tilde{B}$ and two doublets ($\tilde{H}_u, \tilde{H}_d$):

$$V_{inos} = \frac{1}{\sqrt{2}} {H_u}^\dagger \left(g_{2u} \sigma_a \tilde{W}^a + g_{1u} \tilde{B} \right) \tilde{H}_u - \frac{1}{\sqrt{2}} {H_d}^\dagger \left(g_{2d} \sigma_a \tilde{W}^a + g_{1d} \tilde{B} \right) \tilde{H}_d + \frac{M_{\tilde{W}}}{2} \tilde{W}^a \tilde{W}^a + \frac{M_{\tilde{B}}}{2} \tilde{B} \tilde{B} + \mu \tilde{H}_u (i\sigma_2) \tilde{H}_d + h.c.$$

- 4 neutralinos $\chi^0_{1,\ldots,4}$
- 2 charginos $\chi^\pm_{1,2}$
- Yukawa couplings g_{ij} and Majorana masses $\mu, M_{\tilde{W}}, M_{\tilde{B}}$ are free input parameters

Isospin rotation:

$$H_u = \Phi_2, \qquad H_d = -i\sigma_2 \Phi_1^*$$

Effective Potential Approach at $T \neq 0$

$$V(T) = V_{\text{2HDM}}^{(\text{tree})} + V_{CW}^{(1)} + V_T + V_{CT}$$

- tree-level potential of the 2HDM
- one-loop effective potential $V_{CW}^{(1)}$ including effects of V_{inos}
- temperature corrections V_T (incl. V_{inos})
- Counterterm potential V_{CT}
- extended BSMPT [Basler et. al] to include the EW-ino contributions

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Q1:

Can split-SUSY fermions relax tensions in the 2HDM?

Example Point: 2HDM

Idea: start with 2HDM (without EWinos) and then turn-on fermion contributions.

$$m_h = 125.09\,\mathrm{GeV}, \qquad m_H = 637.37\,\mathrm{GeV},$$
$$m_A = 811.35\,\mathrm{GeV}, \qquad m_{H^\pm} = 839.90\,\mathrm{GeV},$$
$$\tan\beta = 6.15\ , \qquad \alpha = -0.1605\ ,$$

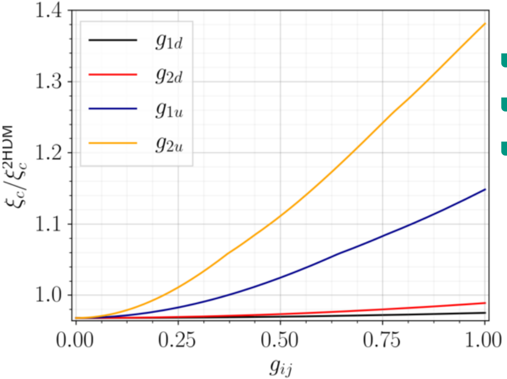
leads to

$$\xi_c^{\text{2HDM}} = 0.82 < 1 \quad \lightning$$

when considering the pure 2HDM type II.

Example Point: 2HDM+EWinos

$M_{\tilde{W}} = M_{\tilde{B}} = \mu = 250\,\mathrm{GeV}$



- up to 40% w.r.t. vanilla 2HDM
- up-type Yukawas dominant
- $SU(2)$ Yukawas dominant (more d.o.f)

Backup-slides → general feature of EWinos!

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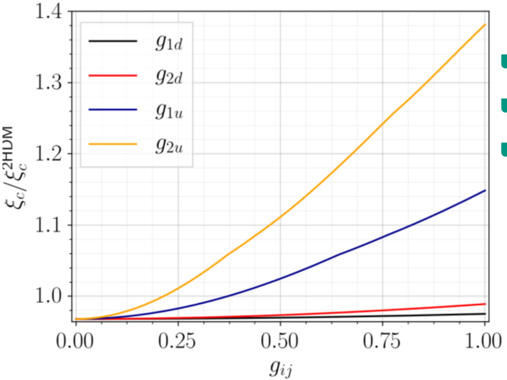

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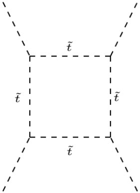
Backup-slides $\rightarrow$ general feature of EWinos!

Q2:

Can it emerge from non-minimal split-SUSY?

Matching the 2HDM+EWinos to the MSSM

- MSSM:
  - $\lambda_{1,2,3,4} = \mathcal{O}(g_1^2, g_2^2) + \frac{1}{(4\pi)^2}\mathcal{O}(\frac{A_t}{m_{\tilde{t}}})$
  - $\lambda_{5,6,7} = 0 + \frac{1}{(4\pi)^2}\mathcal{O}(\frac{A_t}{m_{\tilde{t}}})$
  - A_t is a low-scale parameter



$\propto \frac{1}{(4\pi)^2}\frac{A_t^4}{m_{\tilde{t}}^4}$

- our scan requires:
  $\lambda_5 > 0.1$ to reach $\xi_c > 1$ ↯

alternatives:

- add light singlet (split-NMSSM) [Demidov et. al] [Athron et. al]
  $\rightarrow$ singlet couplings enable SFOEWPT
- integrate out heavy singlet
  NMSSM $\rightarrow$ MSSM $\rightarrow$ 2HDM+EWinos

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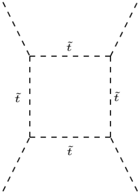

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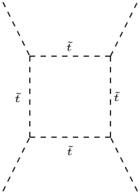

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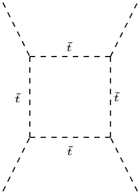

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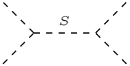

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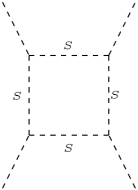

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Conclusion

Summary:

- studied impact on EWPT of additional fermions in a 2HDM
- $SU(2)$ doublets/triplets beneficial *i.e.* strengthen the EWPT
- re-opens parameter space which is forbidden in the default 2HDM
- not possible to be embedded in minimal split-MSSM
  $\rightarrow$ requires at least an NMSSM with heavy singlet

Outlook:

- study impact in non-minimal SUSY
- impact on collider/flavour phenomenology

Backup

Global View: reopen parameter space with **large** masses

- random parameter scan using ScannerS [Coimbra et al.]
- scan with default 2HDM allowing for all ξ_c
- re-evaluate using 2HDM+EWinos:
  - $g_{1u} = g_{1d} = g_1^{\text{SM}}$
  - $g_{2u} = g_{2d} = g_2^{\text{SM}}$
  - $M_{\tilde{B}} = M_{\tilde{W}} = \mu = 200\,\text{GeV}$
- compare ξ_c with ξ_c^{2HDM}
- large-mass points which were forbidden in the 2HDM are now allowed!

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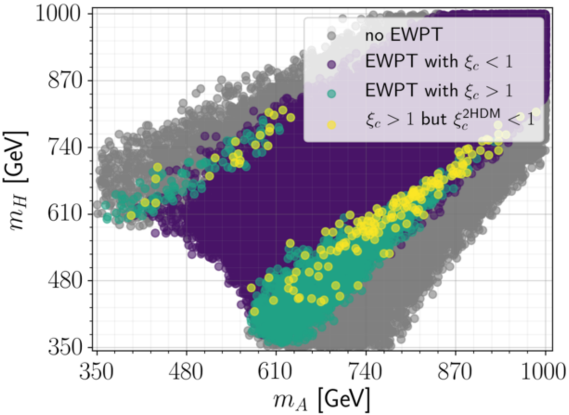

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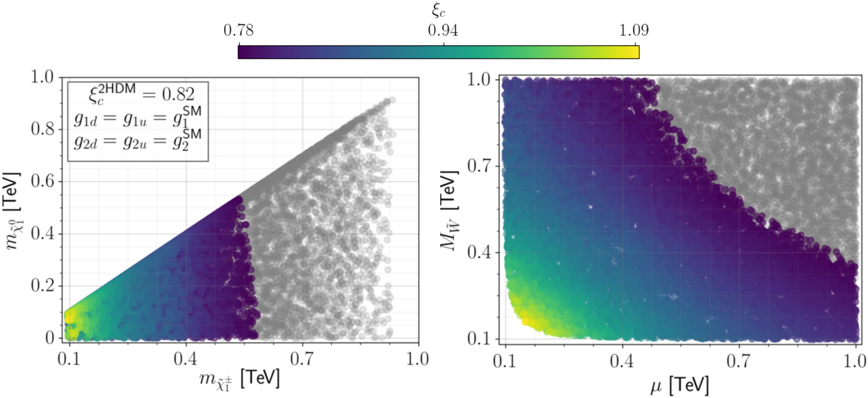
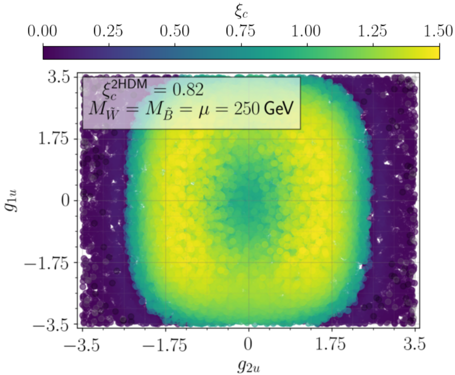


$g_{1i} = g_1^{SM}$, $g_{2i} = g_2^{SM}$ fix

μ, $m_{\tilde{B}}$, $m_{\tilde{W}}$ varied independently

Global Yukawa Scan



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- extended to incorporate corrections from fermions in arbitrary model
  - $V_{CW}^{(1)}\big|_{inos}$
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- calculates all ingredients for $V(T)$
- V_{CT}: achieves equal scalar tree-level and one-loop masses/mixings
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