* talk based on: *Electroweak Phase Transition in a Dark Sector with CP Violation*

by LB, Margarete Mühlleitner and Jonas Müller [2204.13425]

Electroweak Phase Transition in a **Dark Sector** with **CP Violation**

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8th Symposium on Prospects in the Physics of **DISCRETE** Symmetries, November 2022

Motivation

- *Electroweak baryogenesis* (EWBG) can generate observed *baryon asymmetry of the universe* (BAU) ($\eta \simeq 6.1 \times 10^{-10}$ [Planck, 2018]) if [A. D. Sakharov, 1967], [D. Morrissey, M. Ramsey-Musolf, 2012]

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  $\rightarrow$ *creation* of BAU: EW sphaleron transitions (triggered by LH fermion access) [F. R. Klinkhammer, N.S. Manton, 1984]

  - sufficiently strong departure from thermal equilibrium, $\xi_c \equiv \frac{v_c}{T_c} \gtrsim 1$ (*conservation* of BAU inside bubble) [M. Quiros, 1994] $\Rightarrow$ **SFOEWPT** (*strong first-order electroweak phase transition*)

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Now .. Can we generate an SFOEWPT within 'CP in the Dark'?

Can the 'hidden' CP violation be translated to the visible sector?

'CP in the Dark' [D. Azevedo, P. Ferreira, M. Mühleitner, S. Patel, R. Santos, J. Wittbrodt, 2018]

- N2HDM-like extended scalar sector, *one* discrete $\mathbb{Z}_2$ symmetry

$$\Phi_1 \to +\Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$$

- $SU(2)_L \times U(1)_Y$ and $\mathbb{Z}_2$-invariant tree-level potential:

$$\begin{aligned} V^{(0)} =\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 \\ & + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \end{aligned}$$

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↵ charge-breaking VEV, $\omega_{\mathrm{CB}} = 0$

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↳ CP-violating VEV

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$\Rightarrow$ **'CP in the Dark'** - CPV + DM + SFOEWPT (?)

Minimizing the One-Loop Corrected Effective Potential @ $T \neq 0$

- true vacuum state @ finite temperature (FT) including radiative corrections = global minimum of the **effective potential @ FT**

- general one-loop effective potential @ FT splits into temperature-dependent and independent part [L. Dolan, R. Jackiw, 1974]

↵ optional finite shift

$$V^{(1)}(\omega, T) = \underbrace{V^{(0)}(\omega)}_{\text{tree-level}} + \underbrace{V^{\text{CW}}(\omega)}_{T\text{-indep. Coleman-Weinberg potential}} + \underbrace{V^{T}(\omega, T)}_{T\text{-dep.}} + \underbrace{V^{\text{CT}}(\omega)}_{\text{finite shift of scalar masses and mixing angles}}$$

$V^{(0)}(\omega)$: tree-level

$V^{\text{CW}}(\omega)$: T-indep. *Coleman-Weinberg* potential, renormalized in $\overline{MS}$-scheme [S. Coleman, E. Weinberg, 1973]

$V^{T}(\omega, T)$: T-dep., UV finite, IR finite after resummation $m^2 \to m^2 + \Pi^{(1)}(0)$ [M. Carrington, 1992], [R. Parwani, 1992], [P. Arnold, O. Espinosa, 1993]

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- V^{CT} absorbs NLO scalar mass and angle shift [P. Basler et al., 2017]

$$0 = \partial_{\phi_i}(V^{\text{CW}} + V^{\text{CT}}|_{\vec{\omega}=\vec{\omega}_{\text{tree}}})$$
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BSMPT [P. Basler, M. Mühlleitner, J. Müller, 2018/20] `https://github.com/phbasler/BSMPT`

- global minimization of the one-loop corrected effective potential @ $T \in \{0, 300\}$ GeV in non-zero FT VEV space $\vec{\omega} \rightarrow$ get $(\overline{\omega}_1, \overline{\omega}_2, \overline{\omega}_{\text{CB}}, \overline{\omega}_{\text{CP}}, \overline{\omega}_S)$ @ T

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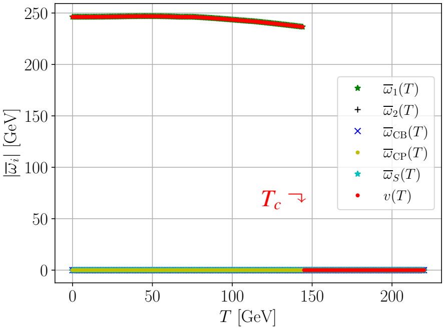

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- critical temperature T_c:
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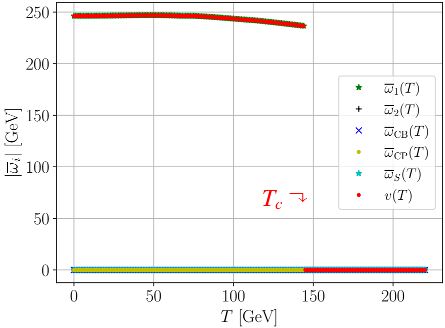

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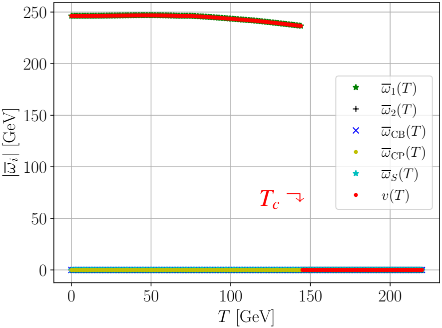

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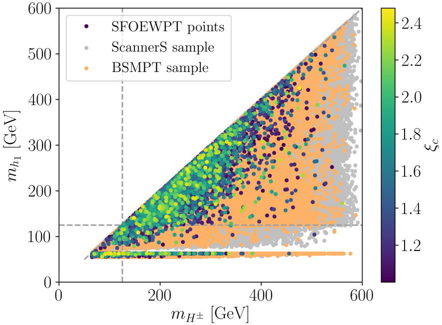
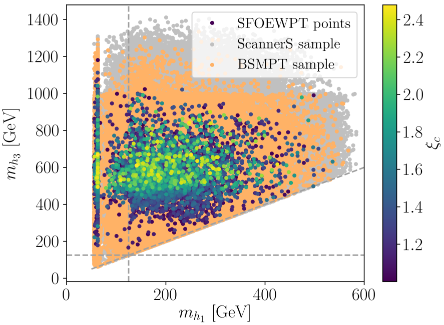
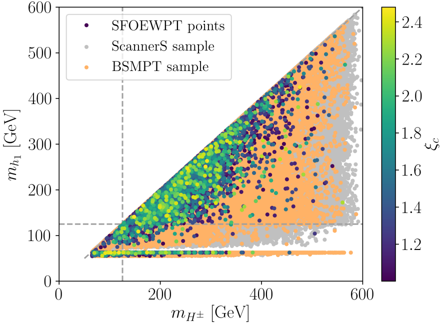
- *viable* parameter points
  - pass constraints imposed by: **ScannerS** [R. Coimbra et al., 2013] [M. Mühlleitner et al., 2020]
    BSMPT [P. Basler, M. Mühlleitner, J. Müller, 2018/20]
  - $\text{BR}(h \to \text{inv.}) < 0.11$ [M. Aaboud et al., 2019]
  - $\mu_{h\to\gamma\gamma} = 1.12 \pm 0.09$ [A. Sirunyan et al., 2021]

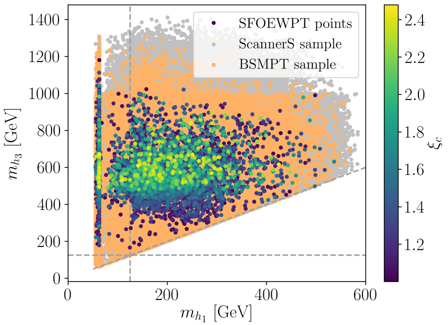
Results: Mass Parameter Distributions for an SFOEWPT





Results: Mass Parameter Distributions for an SFOEWPT





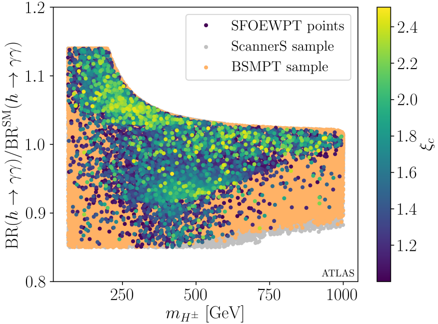
⇒ find SFOEWPT (and NLO-stable) points distributed all over allowed$^{(*)}$ parameter space

$^{(*)}$: by Higgs constraints, DM constraints, theoretical constraints.

- neither requirement of NLO-VEV stability nor SFOEWPT further constrains the parameter space
- restricted $m_{H^\pm}$-range due to $\mu_{\gamma\gamma}$ cut (see Slide 8)

Results: $\mathrm{BR}(h \to \gamma\gamma)$

$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.99^{+0.15}_{-0.14}$ [M. Aaboud et al., 2018]



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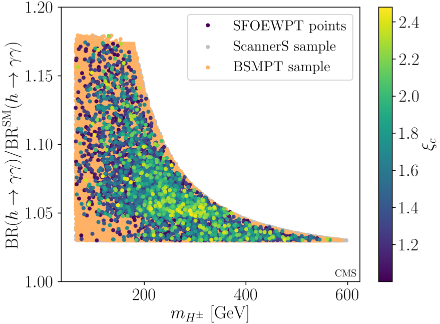

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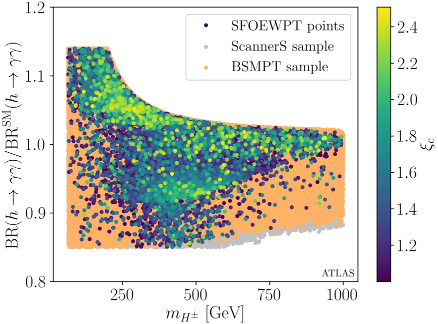

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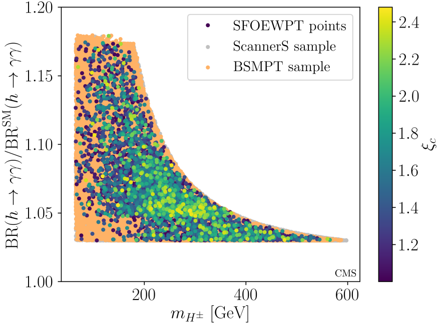

- tree-level couplings of h identical to those of SM Higgs boson
- *only* presence of dark particles can change $\mathrm{BR}(h \to \gamma\gamma)$

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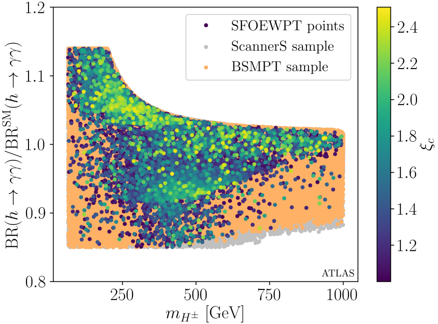

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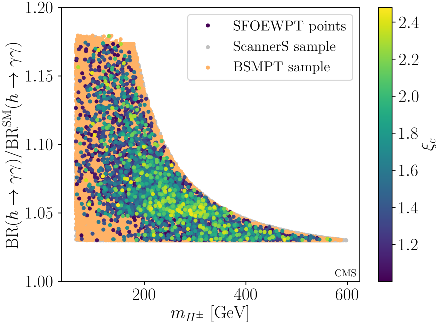

- tree-level couplings of h identical to those of SM Higgs boson
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  - $\to$ $H^\pm$-decay into photon pair
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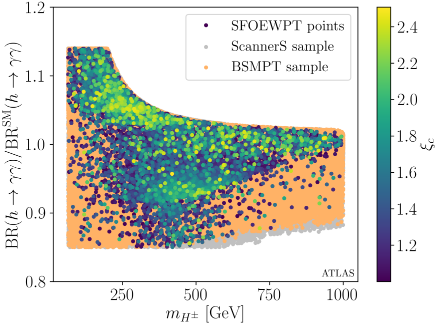

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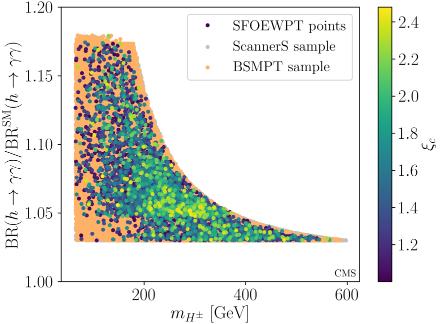

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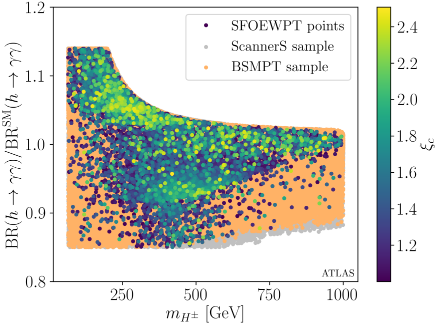

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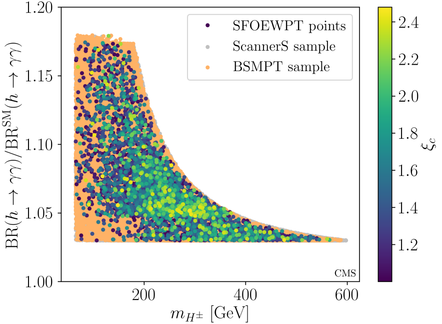

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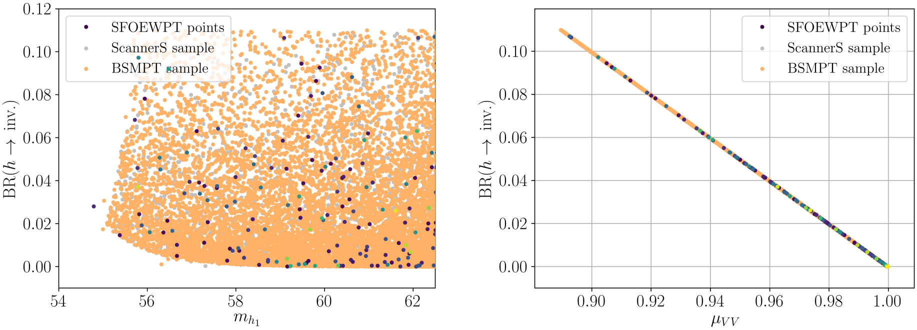
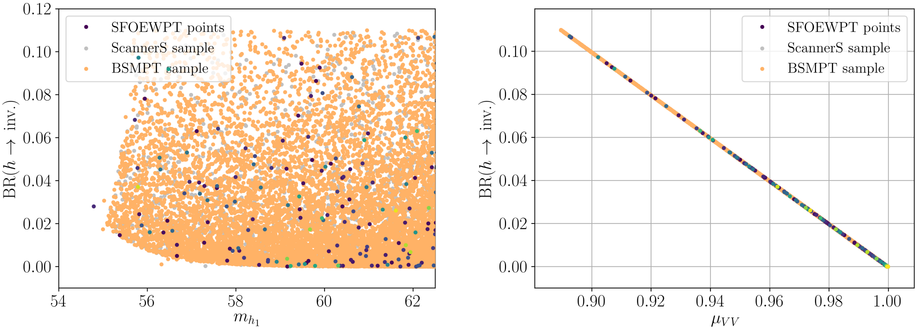
$\Rightarrow$ future increased precision on $\mu_{\gamma\gamma}$ can cut the parameter space on $m_{H^\pm}$ substantially

Results: BR($h \to$ inv.)



Results: $\mathrm{BR}(h \to \mathrm{inv.})$

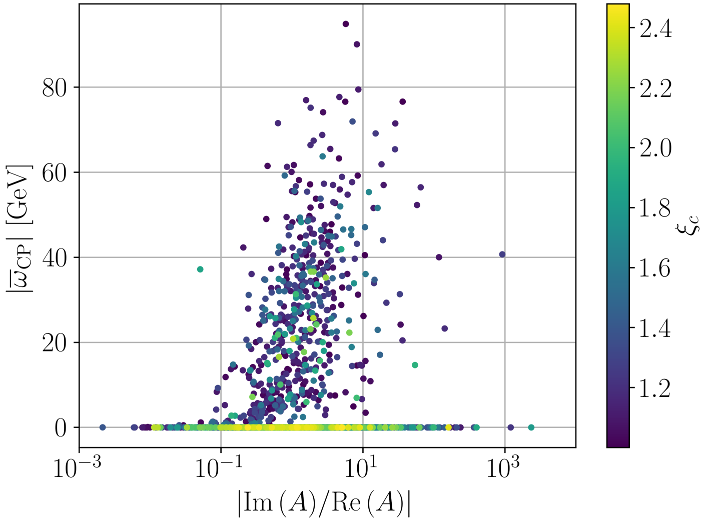


- SFOEWPT points scattered across allowed `ScannerS` parameter space
- $\mathrm{BR}(h \to \mathrm{inv.})$ strongly correlated with μ_{VV} ($V = Z, W$) (gauge boson signal strength), agree with results for *fully dark phase* of N2HDM [I. Engeln et al., 2020]

→ for $\mu_{VV} \to 1$, SM-like Higgs BR converges to SM value (invisible decay not allowed)

⇒ future precise measurements of $\mathrm{BR}(h \to \mathrm{inv.})$ and μ_{VV} can constrain parameter space, however *no* further insights into strength of the EWPT

Results: Spontaneous CPV at Finite Temperature



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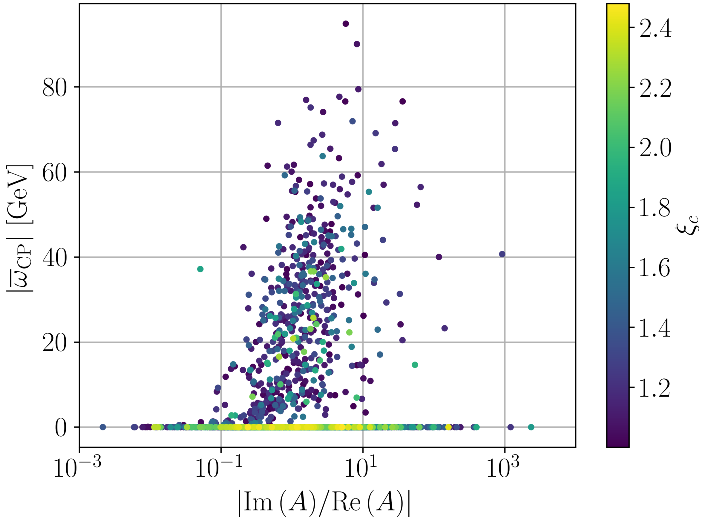
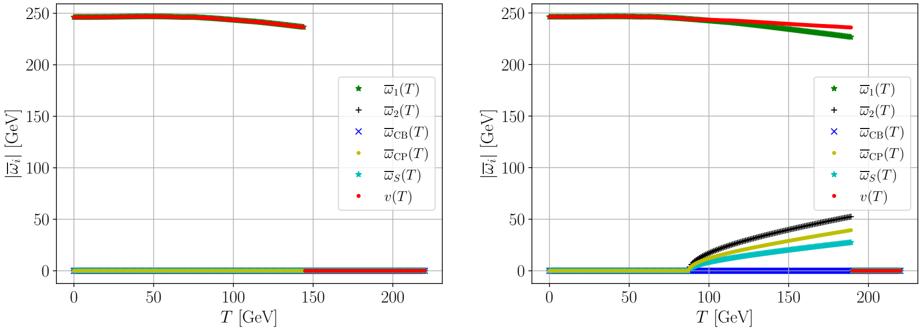


→ @ FT: $|\overline{\omega}_{\mathrm{CP}}| \neq 0$ possible for SFOEWPT points ⇔ @ $T = 0\,\mathrm{GeV}$: $\overline{\omega}_{\mathrm{CP}}\big|_{T=0\,\mathrm{GeV}} = 0$
→ CPV only possible explicitly ($\mathrm{Im}(A) \neq 0$)

→ no clear correlation - but: $|\overline{\omega}_{\mathrm{CP}}| > 0$ only for $\mathrm{Im}(A) \neq 0$

Results: Spontaneous CPV at Finite Temperature

- two different VEV patterns in detail:



⇓

only ω_1 develops non-zero values

⇓

dark VEVs (except $\omega_{\rm CB}$) participate in EWPT

spontaneous CPV!

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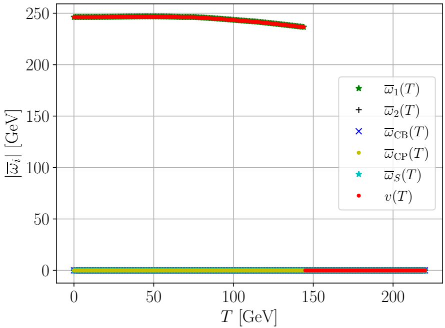
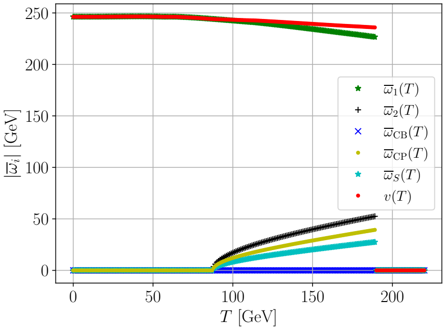




$\Downarrow$

only ω_1 develops non-zero values

$\Downarrow$

dark VEVs (except $\omega_{\rm CB}$) participate in EWPT

spontaneous CPV!

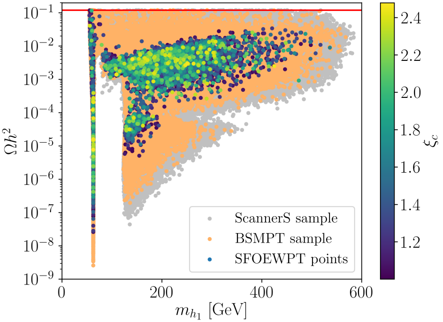
$\rightarrow$ @ FT: $\mathbb{Z}_2$ symmetry is broken $\rightarrow$ dark charge no longer conserved $\rightarrow$ dark sector **mixes** with SM-like particles

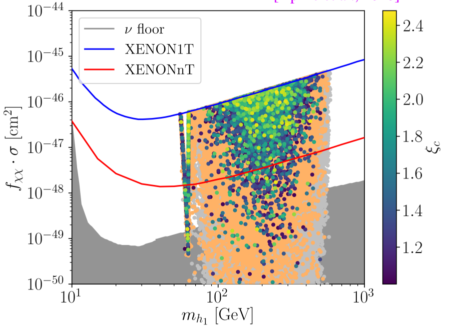
$\Rightarrow$ additional non-standard CPV transferred to the SM-like couplings to fermions @ FT!

Results: DM Observables

$\Omega_{\text{obs}} h^2 = 0.1200 \pm 0.0012$
[Aghanim et al., 2018]

[Billard et al., 2013],
[Aprile et al., 2018],
[Aprile et al., 2020]





$$f_{\chi\chi} \cdot \sigma_{\text{SI, DM-nucl.}} \equiv \frac{\Omega_{\text{prod}} h^2}{\Omega_{\text{obs}} h^2} \cdot \sigma_{\text{SI, DM-nucl.}}$$

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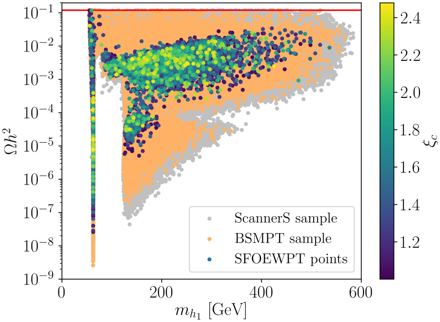

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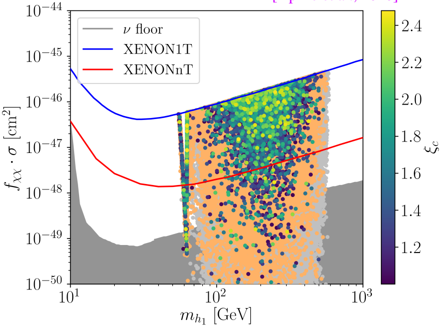

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Viable SFOEWPT parameter points

⇒ compatible with *relic density* ($< \Omega h^2$)

⇒ above neutrino floor

⇒ testable at future *direct detection* experiments

Conclusion

- dynamical generation of the baryon asymmetry of the universe (BAU) possible if *Sakharov conditions* fulfilled
- *electroweak baryogenesis*: fulfill Sakharov conditions with
  - BSM models
  - non-standard *CP-violation* (CPV)
  - *strong first-order electroweak phase transition* (SFOEWPT)
- 'CP in the Dark': special N2HDM + one discrete $\mathbb{Z}_2$ symmetry
  - dark sector with DM candidate h_1
  - explicit CPV in the dark sector at zero temperature

$\Rightarrow$ **BSMPT**: global minimization of the one-loop corrected effective potential at finite temperature

$\rightarrow$ **viable SFOEWPT** parameter points for 'CP in the Dark'

- within reach of future direct detection experiments

$\Rightarrow$ show **spontaneous CPV at finite temperature**!

$\rightarrow$ **Open question:** Can these points successfully generate the BAU?

Thanks for your attention!

Benchmark Points

All points have: $\lambda_1 \simeq 0.258$, $m_{11}^2 \simeq -7824\ \mathrm{GeV}^2$

point	m_{22}^2 [GeV^2]	m_S^2 [GeV^2]	Re (A) [GeV]	Im (A) [GeV]	λ_1	
no sponCPV	96 703.414	32 442.949	159.627	-325.391	3.532	
sponCPV	65 258.809	36 279.847	279.502	-326.645	3.660	
point	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
no spon CPV	-0.796	0.787	-0.055	10.446	7.596	4.683
spon CPV	-0.821	0.220	-0.371	4.715	7.760	14.781

point	$m_{H^\pm}$	m_{h_1}	m_{h_2}	m_{h_3}	T_c	v_c
no spon CPV	269.386	241.718	308.943	549.265	144.21	236.53
spon CPV	200.940	62.680	218.700	560.206	189.77	235.85
point	ξ_c	$\overline{\omega}_{\mathrm{CB}}$	$\overline{\omega}_1$	$\overline{\omega}_2$	$\overline{\omega}_{\mathrm{CP}}$	$\overline{\omega}_S$
no spon CPV	1.64	-8.977×10^{-7}	236.53	9.093×10^{-7}	-3.793×10^{-7}	4.604×10^{-7}
spon CPV	1.24	-2.212×10^{-5}	226.46	52.72	39.52	-27.58

Baryon Asymmetry of the Universe (BAU)

initial: *Big Bang* (symmetric universe) $\Leftrightarrow$ today: **BAU** (asymmetric universe)

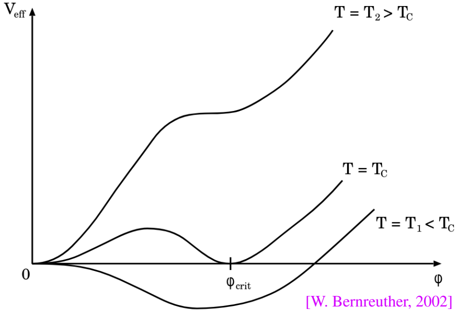
$$\eta \equiv \frac{n_b - \bar{n}_b}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck, 2018]

How can we generate a non-zero *baryon asymmetry of the universe*?

[Sakharov, 1967]: dynamical generation of a BAU with an initially symmetric state possible if

condition		
existence of B violating processes	$\Rightarrow$	sphaleron-mediated @ $T > T_{\mathrm{EW}} = 100\,\mathrm{GeV}$ [N. Manton, 1983], [F. Klinkhammer, N. Manton, 1984]
$\mathcal{C}$ and $\mathcal{CP}$ violation (CPV)	$\Rightarrow$	*Cabibbo-Kobayashi-Maskawa* mechanism (?) [N. Cabibbo, 1963], [M. Kobayashi, T. Maskawa, 1973]
departure from thermal equilibrium	$\Rightarrow$	electroweak phase transition (EWPT) [D. Kirznits, 1972], [L. Dolan, R. Jackiw, 1974]

Electroweak Baryogenesis (EWBG) [D. Morrissey, M. Ramsey-Musolf, 2012]



[W. Bernreuther, 2002]

- EWBG takes place around $T \sim T_{\mathrm{EW}}$
- EWPT happens and bubbles with non-zero vacuum expectation value (VEV) are created and expand
- necessary departure from thermal equilibrium achieved through ***strong*** *first-order* EWPT (SFOEWPT)

→ '*first-order*': discontinuity in VEV v at T_c:

$$V(v=0,T_c) = V(v\neq 0,T_c)$$

- How do we see this in the potential?
  → global minimum jumps from symmetric to broken minimum @ T_c

→ '**strong**': *conservation* of BAU through sufficient suppression of the sphaleron rate inside the bubbles

$$\Gamma^{\mathrm{sph}}_{\not{B}+\not{L}} \propto \exp -\frac{E_{\mathrm{sph}}(T)}{T} \quad \Rightarrow \quad \xi_c \equiv \frac{v_c}{T_c} \gtrsim 1$$

*baryon-wash-out condition** [M. Quiros, 1994]

⇒ EWPT in SM only *smooth cross-over* [K. Kajantie et al., 1996]

⇒ need BSM models that enable an SFOEWPT* + *non-standard CPV*