The CP-Violationg 2HDM in Light of a Strong First Order Phase Transition - Implications for Higgs Physics

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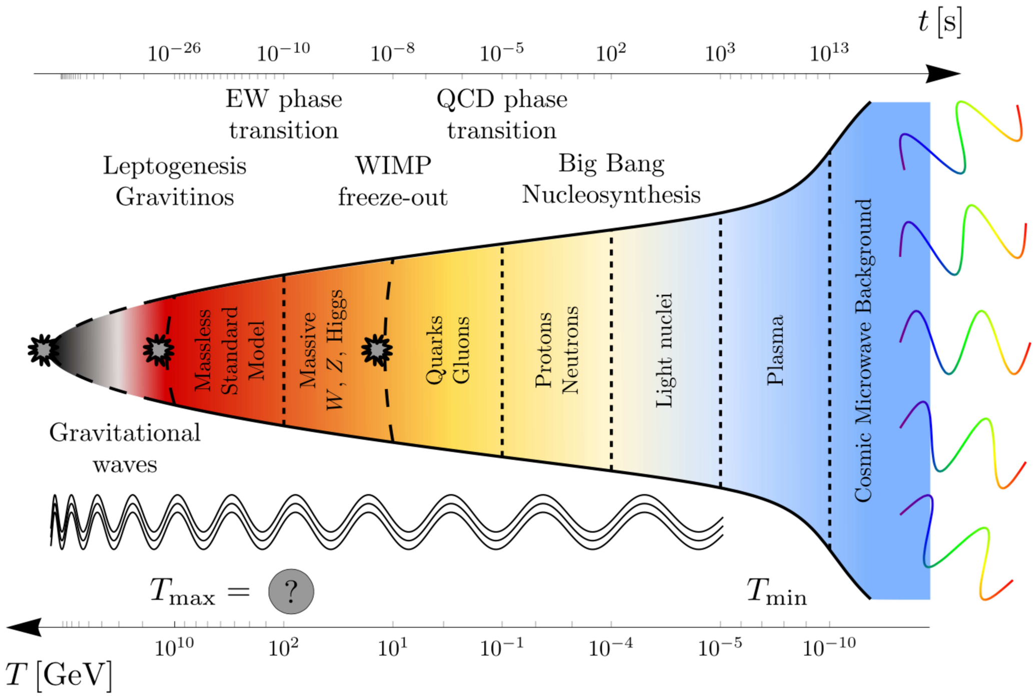
Outline

◇ Introduction

◇ The C2HDM

◇ Results

◇ Conclusions



From K. Schmitz, DESY-THESIS-2012-039

Introduction

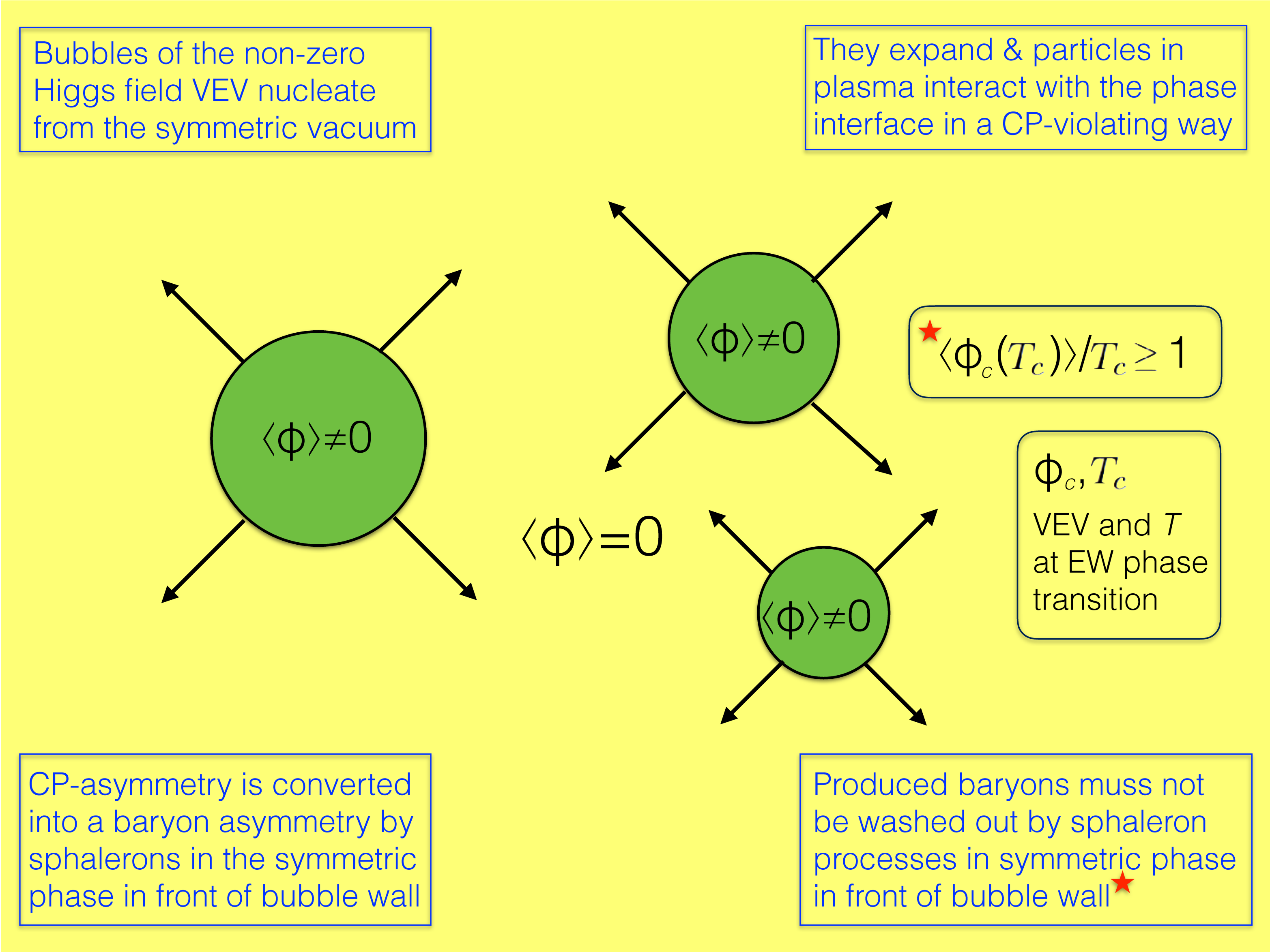
$\mathcal{M}$otivation

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

$\mathcal{B}$aryogenesis in a $\mathcal{N}$utshell



[adapted from Morrissey, Ramsey-Musolf '12]

$\mathcal{M}$otivation

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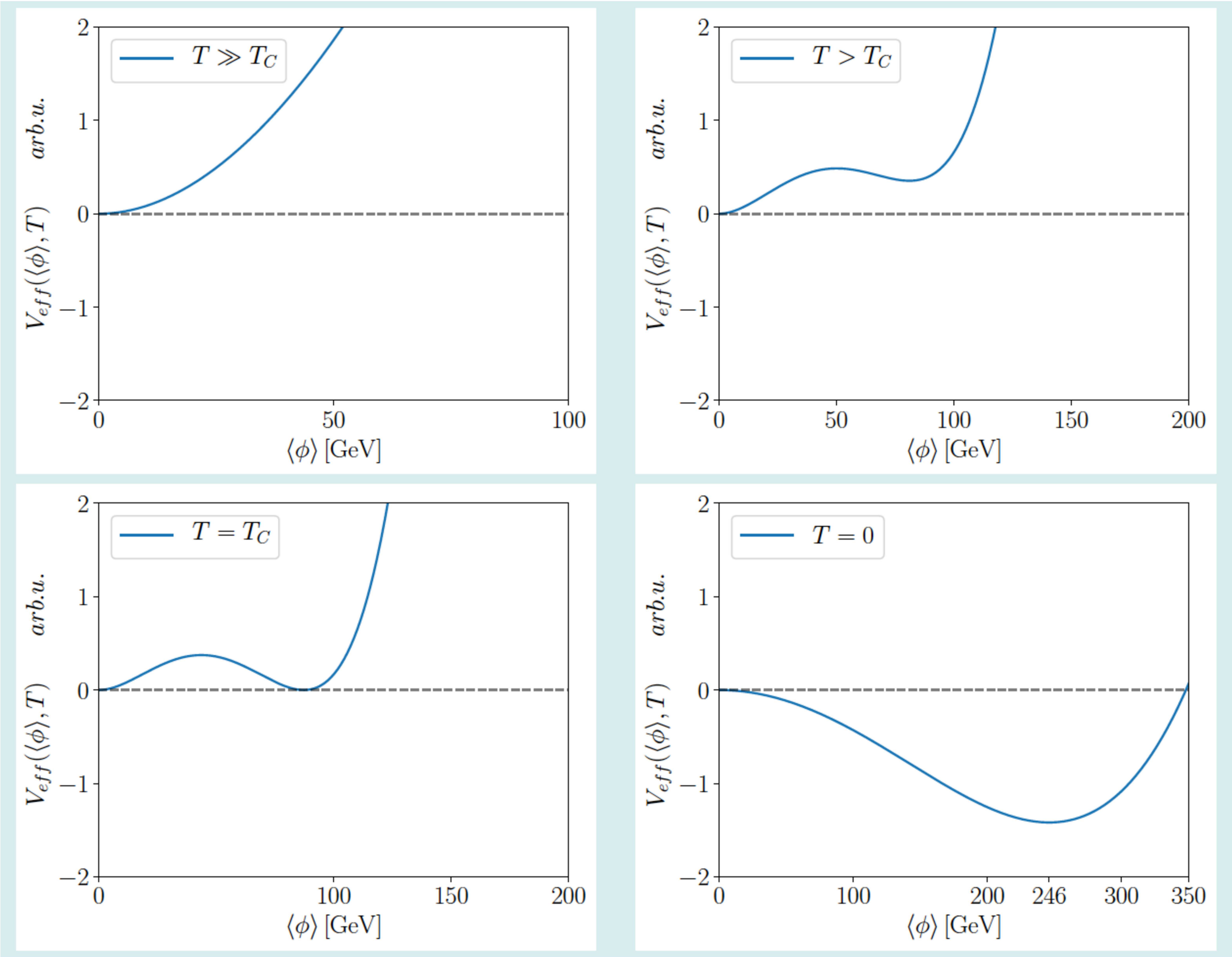
- **Sakharov Conditions:** [Sakharov '67]
  - * (i) B number violaton (sphaleron processes)
  - * (ii) C and CP violation
  - * (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

Strong First Order Electroweak Phase Transition



$\mathcal{M}$otivation

- **Electroweak Baryogenesis in the Standard Model:**
  - ∗ all ingredients required for EWBG contained in the SM, but
  - ∗ EW phase transition of strong first order only if $m_H \lesssim 70$ GeV

    [Bochkarev,Shaposhnikov '87; Kajantje eal '95; Fodor eal '96]
  - ∗ CP violation induced by CKM phase not sufficient to generate large enough chiral asymmetries

    [Gavela eal '93,'94; Huet,Sather '94]

$\Rightarrow$ consider extended Higgs sectors

- **Extended Higgs sectors:**
  - ∗ additional scalar degrees of freedom can strengthen the PT:
    - additional massive particles
    - enhanced Higgs self-couplings
  - ∗ additional sources of CP violation

$\mathcal{T}$he $\mathcal{C}$2HDM

$\mathcal{B}$aryogensis in the C2HDM

- **EWPT in the 2HDM:**
  [Bochkarev eal; McLerran eal; Turok eal; Cohen eal; Nelson eal; Funakubo eal; Davies eal; Cline eal; Dorsch eal; Fromme eal; Haarr eal; Basler eal; Gorda eal; Laine,Rummukainen; Bernon eal; Andersen eal]

- **This talk:** based on
  2HDM: [Basler,Krause,MM,Wittbrodt,Wlotzka, JHEP 1702 (2017) 121]
  C2HDM: [Basler,MM,Wittbrodt, JHEP 1803 (2018) 061]

- **Features:**
  - ∗ Inclusion of theoretical and newest experimental constraints
  - ∗ 'On-shell' renormalization
  - ∗ Inclusion of CP violation - investigation of possible spontaneously generated CP violation
  - ∗ Detailed analysis of implications on collider observables

The Tree-Level Higgs Potential

- **The tree-level Higgs potential:**

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] .$$

- **CP Violation:** m_{12}^2, λ_5 can be complex (all others real); $m_{12}^2 \neq \lambda_5 \rightsquigarrow$ CP violation

- **Higgs fields after EWSB:** at $T \neq 0$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \omega_1 + \zeta_1 + i\psi_1 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_{\text{CB}} + \rho_2 + i\eta_2 \\ \omega_2 + i\omega_{\text{CP}} + \zeta_2 + i\psi_2 \end{pmatrix}$$

includes possibility of (unphysical) charge breaking ω_{CB} and CP breaking ω_{CP} minima

The Tree-Level Higgs Potential

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$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] .$$

- **CP Violation:** m_{12}^2, λ_5 can be complex (all others real); $m_{12}^2 \neq \lambda_5 \rightsquigarrow$ CP violation

- **Higgs fields after EWSB:** at $T = 0$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ v_1 + \zeta_1 + i\psi_1 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} +\rho_2 + i\eta_2 \\ v_2 + \zeta_2 + i\psi_2 \end{pmatrix}$$

$T = 0$: $\omega_{\text{CP}}, \omega_{\text{CB}} \to 0$, $\omega_1 \to v_1$, $\omega_2 \to v_2$ $\quad$ $v_1^2 + v_2^2 = (246 \text{ GeV})^2$, $\tan\beta \equiv \frac{v_2}{v_1}$

The Tree-Level Higgs Potential

- **Particle content:**

  3 neutral CP-mixing Higgs bosons H_1, H_2, H_3

  1 charged Higgs pair $H^\pm$

- **Flavour-Changing Neutral Currents (FCNC) at tree-level:** forbidden by $\mathbb{Z}_2$ symmetry

$$\Phi_1 \to \Phi_1 \; , \qquad \Phi_2 \to -\Phi_2 \; .$$

$\rightsquigarrow$ 4 types of 2HDM

- **Classification of the Yukawa sector:**

	Type I	Type II	Lepton-Specific	Flipped
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Leptons	Φ_2	Φ_1	Φ_1	Φ_2

$\mathcal{T}$he $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{E}$ffective $\mathcal{P}$otential at $\mathcal{F}$inite $\mathcal{T}$emperature

- **Investigate phase transition:** determine

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c}$$

for C2HDM taking into account all theoretical and experimental constraints

- **Effective potential at finite temperature:**

$$V_{\text{eff}}^{(1)}(\vec{\omega}, T) = V_{\text{tree}}(\vec{\omega}) + V_{\text{CW}}(\vec{\omega}) + V_{\text{CT}}(\vec{\omega}) + V_T(\vec{\omega}, T)$$

- $T = 0$ **1-loop contribution:** Coleman-Weinberg contribution [Coleman,Weinberg '73]

$$V_{\text{CW}} = \sum_i \frac{n_i}{64\pi^2}(-1)^{2s_i} m_i^4(\vec{\omega}) \left[\ln\left(\frac{m_i^2(\vec{\omega})}{\mu^2} \right) - c_i \right]$$

n_i number of degrees of freedom
μ renormalization scale, set to VEV $v \approx 246$ GeV
$\overline{\text{MS}}$ renormalization constants $c_i = 5/6$ for bosons, $c_i = 3/2$ otherwise

$\mathcal{T}$he $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{E}$ffective $\mathcal{P}$otential at $\mathcal{F}$inite $\mathcal{T}$emperature

- **The counterterm potential:**
  Choose V_{CT} such that the minimum, the masses and the mixing angles at $T = 0$ remain the same at one-loop level [Basler,Krause,MM,Wittbrodt,Wlotzka '16]

$$\begin{aligned} 0 &= (\partial_{\phi_i} V_{\mathsf{CT}} + \partial_{\phi_i} V_{\mathsf{CW}})|_{\langle\phi\rangle_{T=0}} \\ 0 &= (\partial_{\phi_i}\partial_{\phi_j} V_{\mathsf{CT}} + \partial_{\phi_i}\partial_{\phi_j} V_{\mathsf{CW}})|_{\langle\phi\rangle_{T=0}} \end{aligned}$$

- **$T \neq 0$ contribution:**
  - Thermal loops (fermionic (+) and bosonic (−) integral $J_\pm$) [Carena eal '08]

$$V_T = \sum_i n_i \frac{T^4}{2\pi^2} J_\pm(m_i^2(\vec{\omega})/T^2)$$

  - Thermal mass corrections [Arnold,Espinosa '94]

$$J_-\left(\frac{m_i^2}{T^2}\right) \to J_-\left(\frac{m_i^2}{T^2}\right) - \frac{\pi}{6}(\overline{m}_i^3 - m_i^3)\,, \qquad i = W_L^\pm, Z_L, \gamma_L, \Phi^0, \Phi^\pm$$

  with the thermal masses $\overline{m}_i$

$\mathcal{P}$arameter $\mathcal{S}$can

- **Scan over parameter space:**
  with `ScannerS`, checks for: [Coimbra,Sampaio,Santos '13; Ferreira,Guedes,Sampaio,Santos '14]

- **Theoretical constraints:**
  boundedness from below, tree-level perturbative unitarity, EW vacuum is global minimum of tree-level potential at $T = 0$

- **Experimental constraints::**
  * S, T, U parameters for EW precision observables [Baak eal '14]
  * $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{ hadrons})$ and $B \to X_s\gamma$ [Haber,Logan '99;Deschamps eal '09; Mahmoudi,Stal '09; Steinhauser eal '17]
  * Higgs exclusion bounds by `HiggsBounds` [Bechtle eal '08,'11,'13]
  * Higgs rates checked via `SUSHI` and `C2HDM_HDECAY` [Harlander eal; Fontes eal]
  * Electric dipole moment of the electron [The ACME Collaboration]

- **Calculation of the global electroweak minimum:**
  as function of T to determine $\xi_c \leftarrow$ use of code `BSMPT` [Basler,MM '18]

$\mathcal{B}$SMPT

- **BSMPT - Beyond the Standard Model Phase Transitions:** [Basler,MM '18]
  A C++ tool for the electroweak phase transition in extended Higgs sectors
  Computation of loop-corrected effective potential at $T \neq 0$ including the thermal masses
  Renormalization based on physical conditions (see previous slides)

- **Features:**

  * Computation of $\xi_c = v_c/T_c$
  * Calculation of evolution of the VEV(s) with T
  * Calculation of the global minimum of the 1-loop-corrected potential at $T = 0$
  * Computation of the loop-corrected trilinear Higgs self-couplings in the "on-shell" scheme

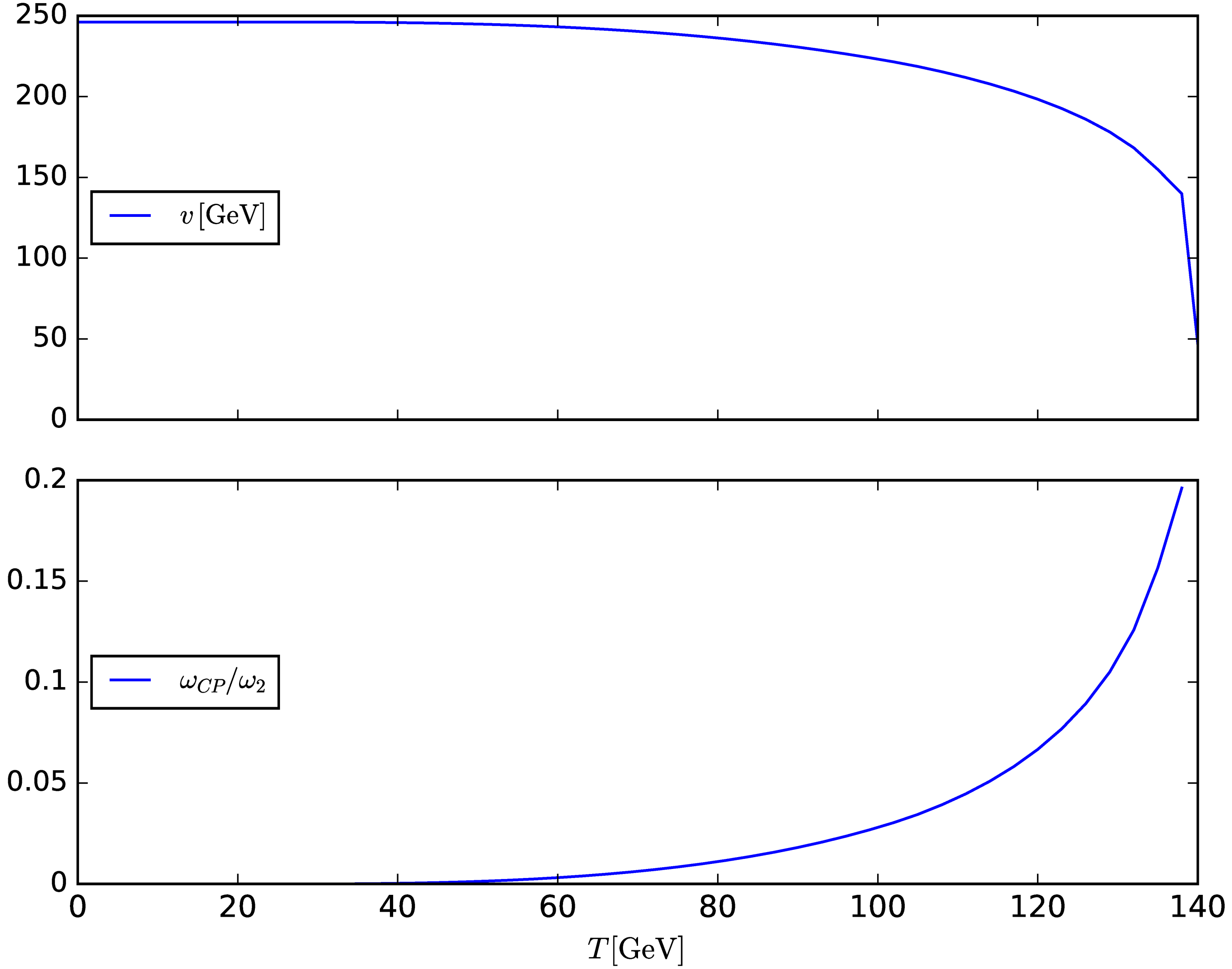
- **Models:** generic code allows for easy implementation of new models
  implemented models: 2HDM, C2HDM, N2HDM

- **Webpage:** https://github.com/phbasler/BSMPT

Results

$\mathcal{E}$volution of the $\mathcal{V}$acuum

[Basler,MM,Wittbrodt '17]



Type I

$m_{H_1} = 125.09\,\mathrm{GeV}$

$m_{H_2} = 236.99\,\mathrm{GeV}$

$m_{H_3} = 542.95\,\mathrm{GeV}$

$m_{H^\pm} = 223.76\,\mathrm{GeV}$

$\tan\beta = 6.95$

$\mathrm{Re}(m_{12}^2) = 8044.9\,\mathrm{GeV}^2$

$\alpha_1 = 0.41\pi$

$\alpha_2 = -0.016\pi$

$\alpha_3 = 0.041\pi$

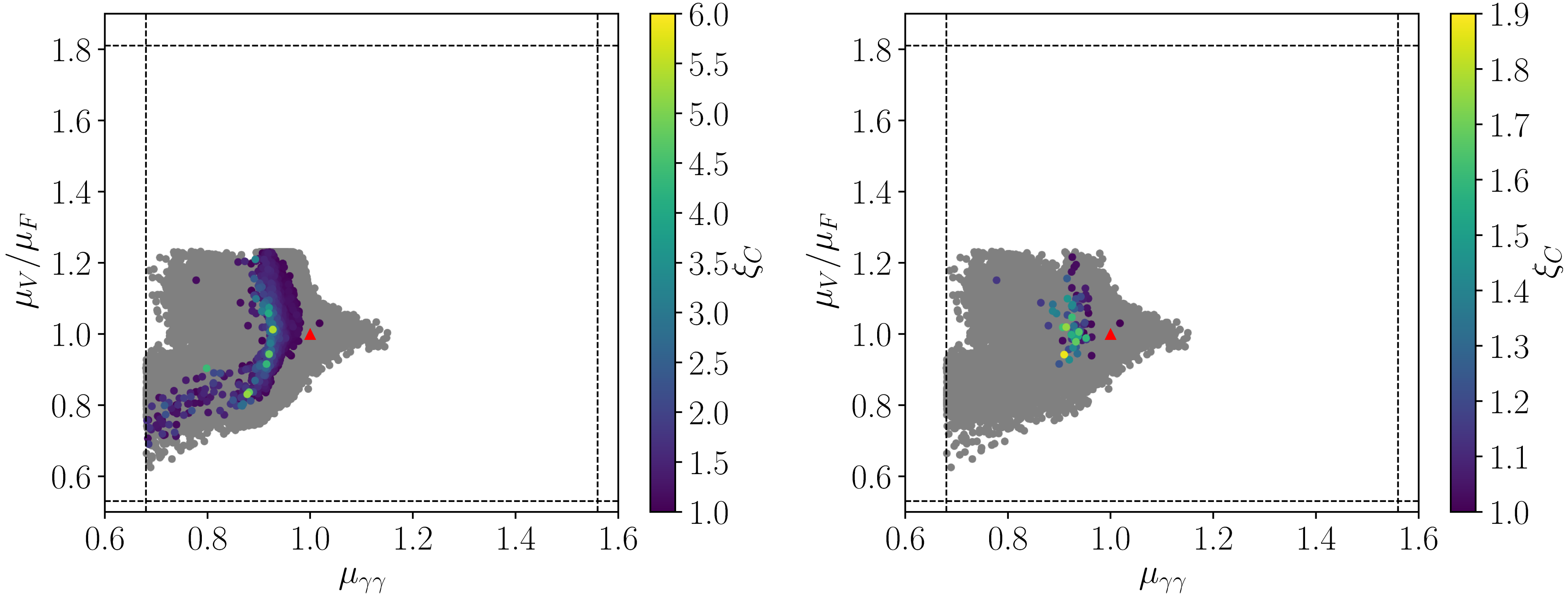
$v_c = 139.274\,\mathrm{GeV}$

$T_c = 138.913\,\mathrm{GeV}$

$\xi_c = 1.0026\,\mathrm{GeV}$

$\mathcal{S}$ignal $\mathcal{R}$ates at the $\mathcal{L}$HC

Type I, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17]



* $\mu_F = \sigma_{\text{C2HDM}}(ggF + bbF)/\sigma_{\text{SM}}(ggF)$ and $\mu_V = \sigma_{\text{C2HDM}}(VBF + VH)/\sigma_{\text{SM}}(VBF + VH)$

* Signal rates: $(H_i = h_{125})$

$$\mu_{xx} = \mu_F \times \frac{\text{BR}_{\text{C2HDM}}(H_i \to xx)}{\text{BR}_{\text{SM}}(H_i \to xx)}$$

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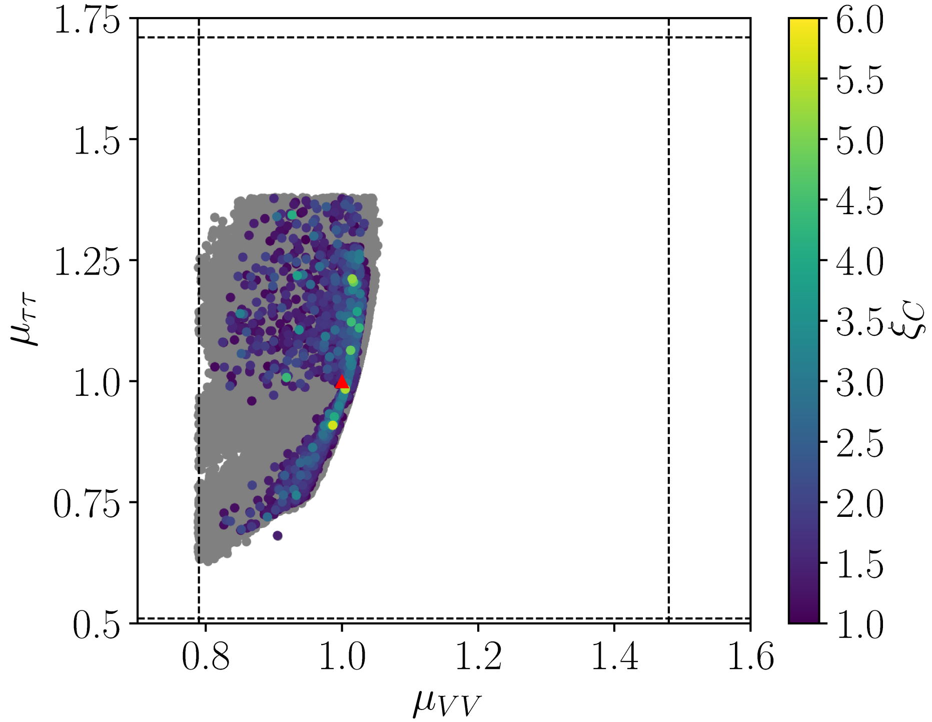
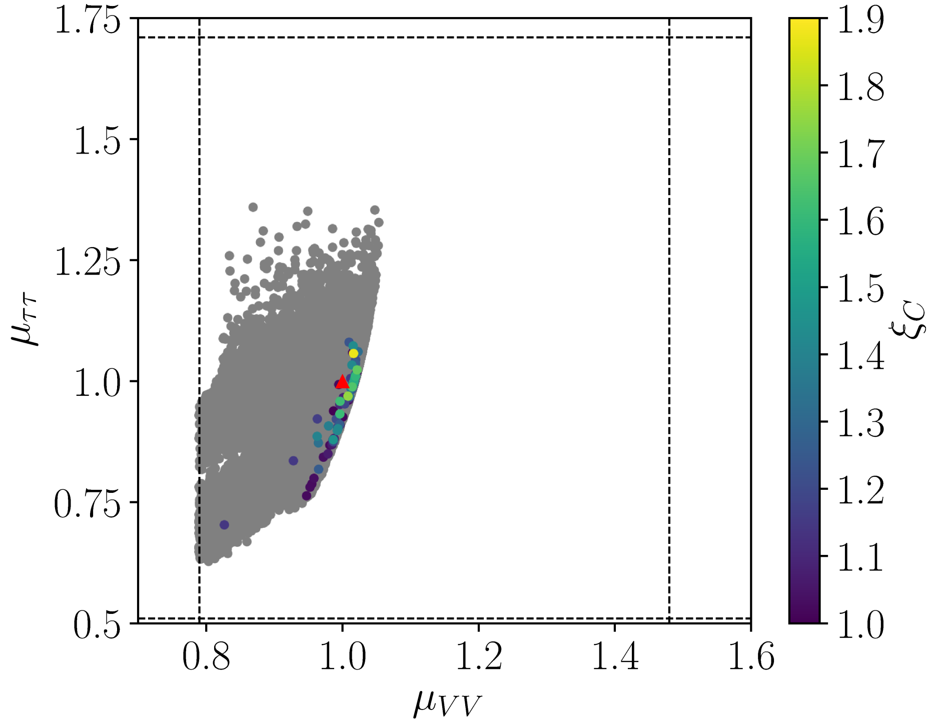


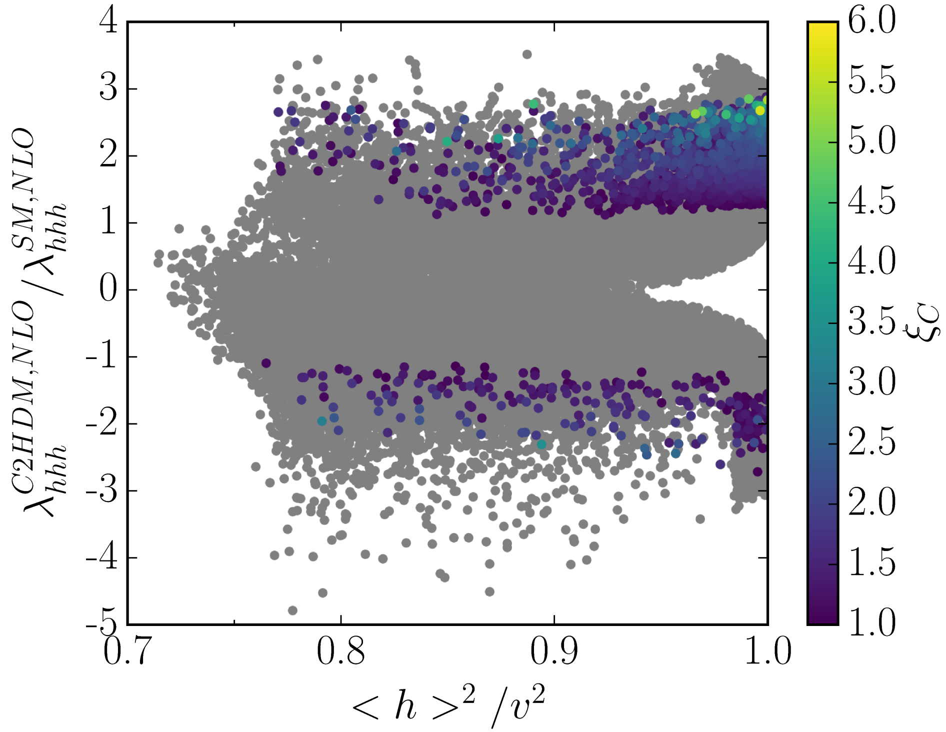


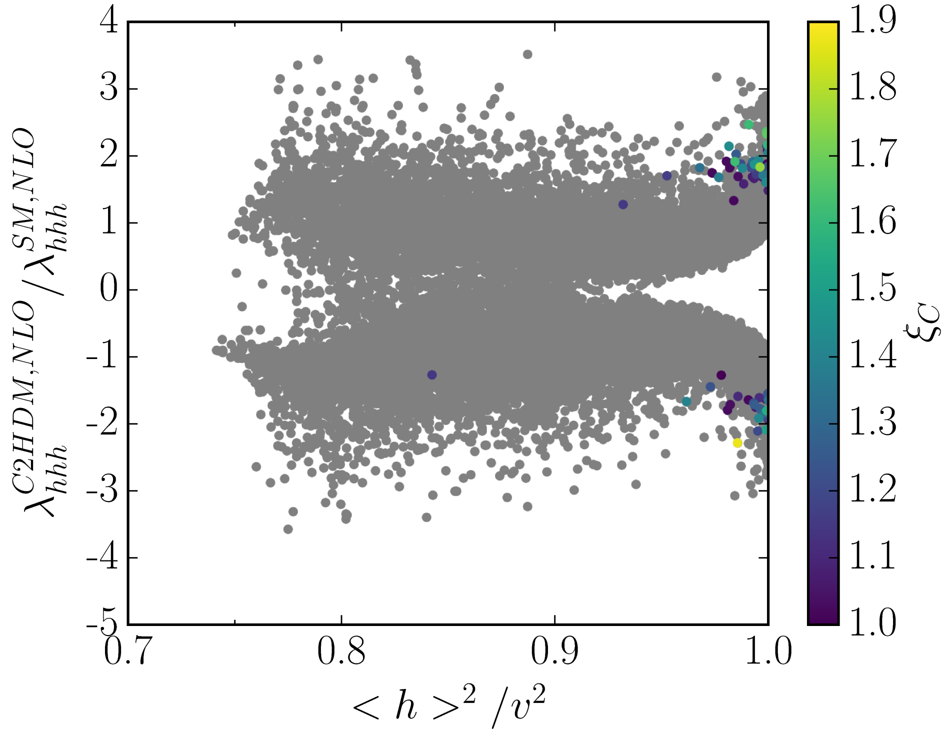
$*$ Signal rates: $(H_i = h_{125})$

$$\mu_{xx} = \mu_F \times \frac{\text{BR}_{\text{C2HDM}}(H_i \to xx)}{\text{BR}_{\text{SM}}(H_i \to xx)}$$

$\mathcal{E}$ffects on the $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

Type I, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17]





- Plots include unitarity constraints
- $1.1 \lesssim \left| \frac{\lambda_{hhh}^{\text{C2HDM,NLO}}}{\lambda_{hhh}^{\text{SM,NLO}}} \right| \lesssim 2.9$

- Most CP-violating points require $\frac{<h>^2}{v^2} \gtrsim 0.95$
- CP-odd part of $h \lesssim 24\% \xrightarrow{\text{EWPT}} \sim 2.5\%$

$\mathcal{B}$enchmark $\mathcal{P}$oint

m_{H_1} [GeV]	125.09
m_{H_2} [GeV]	291.49
$m_{H^\pm}$ [GeV]	543.30
Re(m_{12}^2) [GeV^2]	15590
α_1	1.366
α_2	-0.028
α_3	0.086
$\tan\beta$	5.08
m_{H_3} [GeV]	548.97
ξ_c	1.52
R_{13}^2	$7.641 \cdot 10^{-4}$
R_{23}^2	$7.436 \cdot 10^{-3}$
R_{33}^2	0.992
σ_{hh}^{NLO} [fb]	217.95

BR(H_2)	BR$(H_2 \to H_1 H_1)$ = 0.400
	BR$(H_2 \to Z H_1)$ = 0.294
	BR$(H_2 \to WW)$ = 0.156
BR(H_3)	BR$(H_3 \to Z H_2)$=0.940
	BR$(H_3 \to t\bar{t})$=0.056
	BR$(H_3 \to WW)$=0.002
BR$(H^\pm)$	BR$(H^\pm \to W H_2)$=0.943
	BR$(H^+ \to t\bar{b})$=0.054
	BR$(H^\pm \to W H_1)$=0.002

Combination of rates to identify CP violation:

* type I, H_1 SM-like, mostly CP-even
* $H_2 \to Z H_1 \wedge H_2 \to WW$
  forbidden w/o CP violation

see also, [Branco eal '99;Fontes eal '15,King eal '15]

$\mathcal{C}$onclusions

* Detailed phenomenological analysis taking into account recent bounds and constraints
* Strong first order EWPT possible in the C2DHM
* Overall $\xi_c = v_c/T_c$ smaller than in CP-conserving 2HDM
* Explicit CP violation at $T = 0$ induces spontaneous CP violation at the EWPT
* Trilinear Higgs self-coupling larger than in SM
* μ-values of SM-like Higgs boson in C2HDM with strong PT more restricted than in CP-conserving 2HDM
* Like in 2HDM, strong PT prefers hierarchy with mass gap between the non-SM-like Higgs bosons, but: also approximately mass degenerate scenarios possible

Successful link between cosmology and collider phenomenology

Thank You For Your Attention!

$\mathcal{I}$nput $\mathcal{P}$arameters

- **Tadpole conditions:**

$$
\begin{aligned}
m_{11}^2 &= \mathrm{Re}(m_{12}^2)\frac{v_2}{v_1} - \frac{v_1^2}{2}\lambda_1 - \frac{v_2^2}{2}\lambda_{345} \\
m_{22}^2 &= \mathrm{Re}(m_{12}^2)\frac{v_1}{v_2} - \frac{v_2^2}{2}\lambda_2 - \frac{v_1^2}{2}\lambda_{345} \\
2\,\mathrm{Im}(m_{12}^2) &= v_1 v_2\,\mathrm{Im}(\lambda_5)\ ,
\end{aligned}
$$

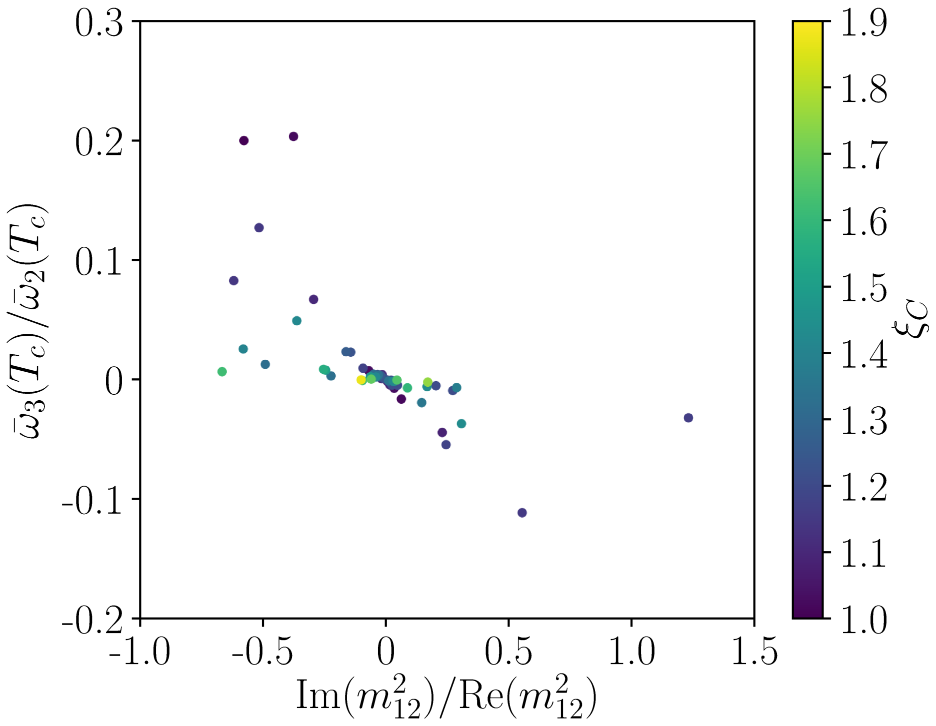
fix one of the parameters

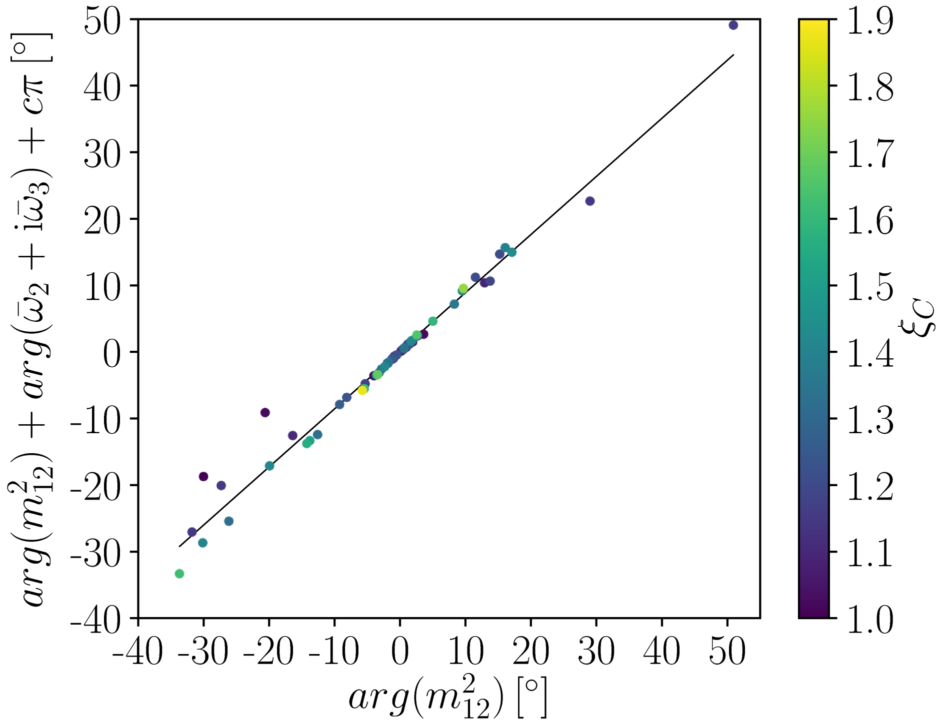
- **Input parameters:**

$$
v\ , \quad t_\beta\ , \quad \alpha_{1,2,3}\ , \quad m_{H_i}\ , \quad m_{H_j}\ , \quad m_{H^\pm} \quad \text{and} \quad \mathrm{Re}(m_{12}^2)\ .
$$

Type I, $H_1 = h$

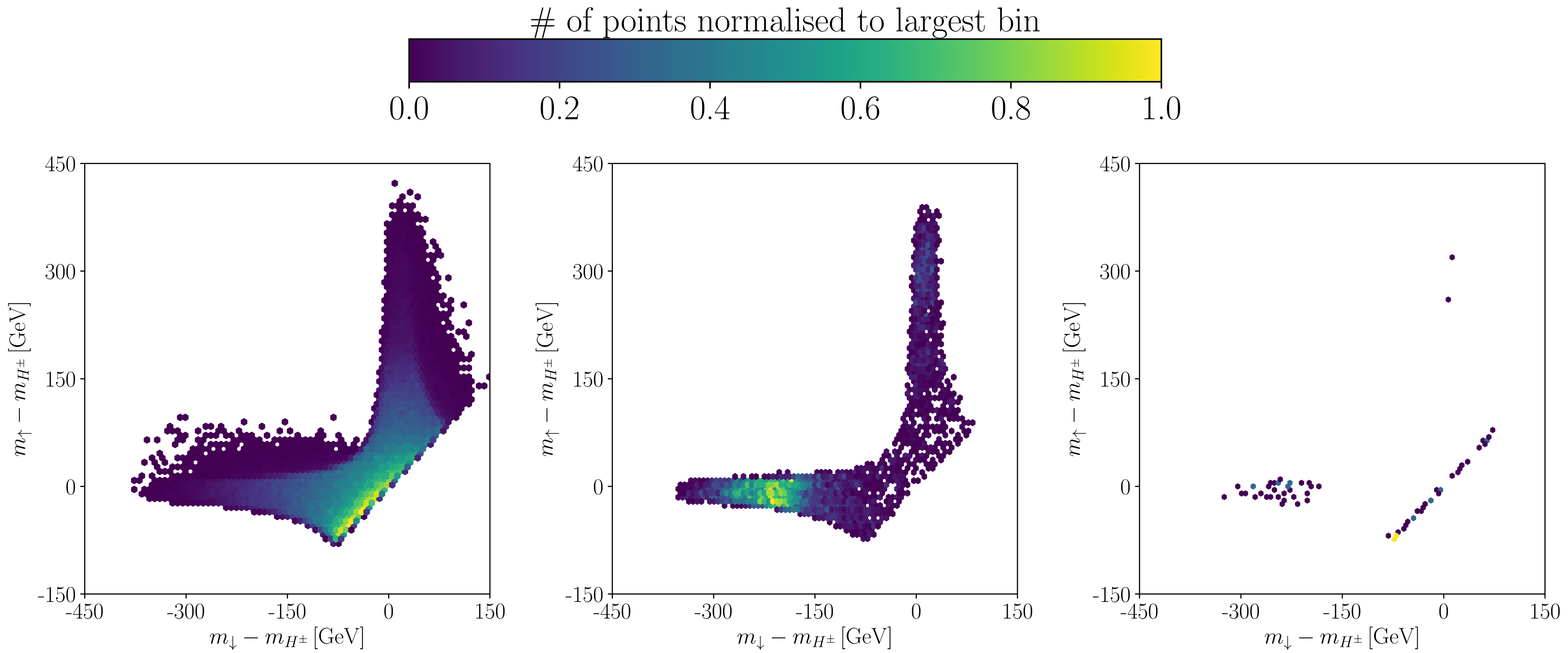
[Basler,MM,Wittbrodt '17]





$\mathcal{M}$ass $\mathcal{D}$ifferences

Type I, $H_1 = h$ [Basler,MM,Wittbrodt '17]



left: all points passing the constraints; middle: all points with a strong PT and CP conservation; right: all points with $\xi_c > 1$ and explicit CP violation

$\mathcal{C}$orrections to the $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

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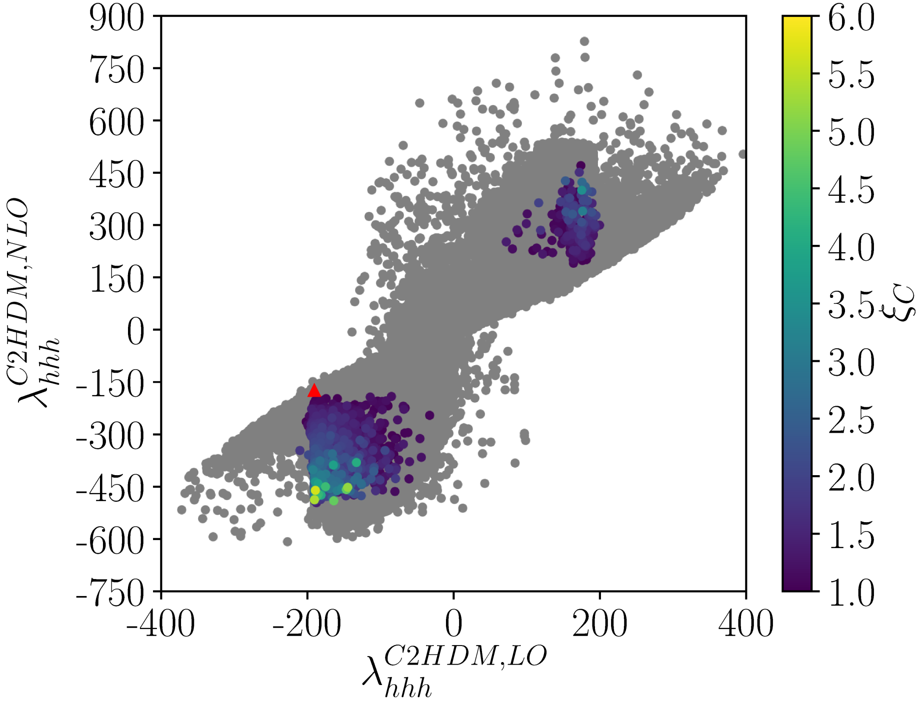
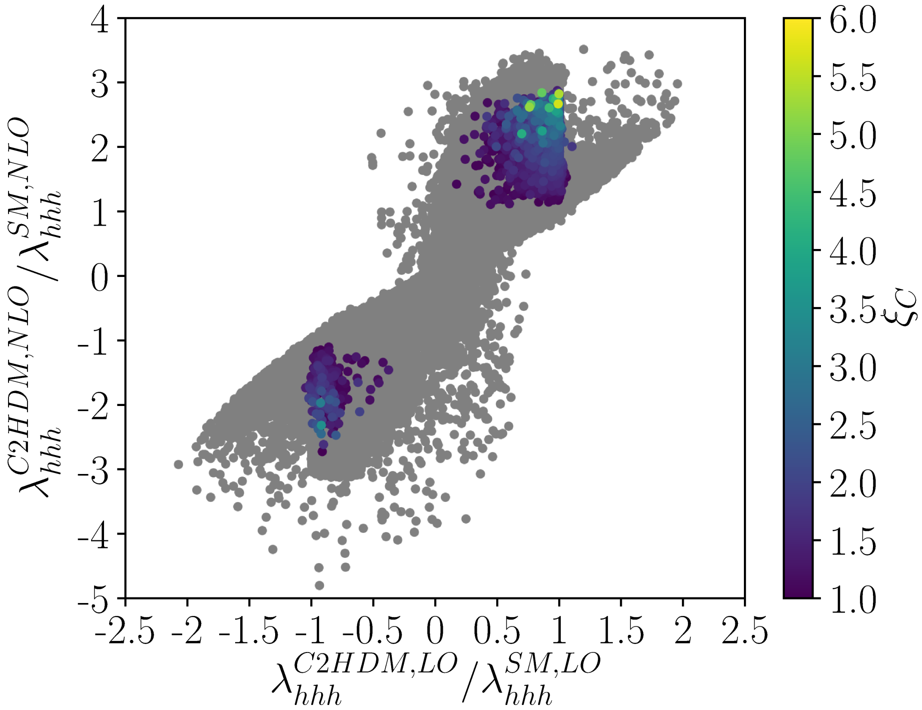
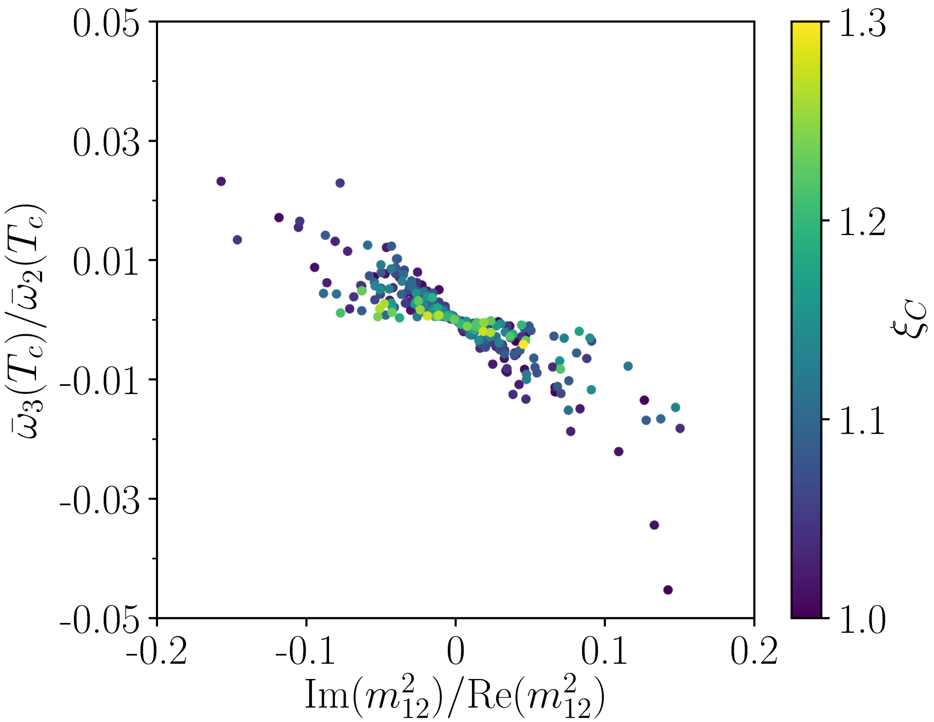


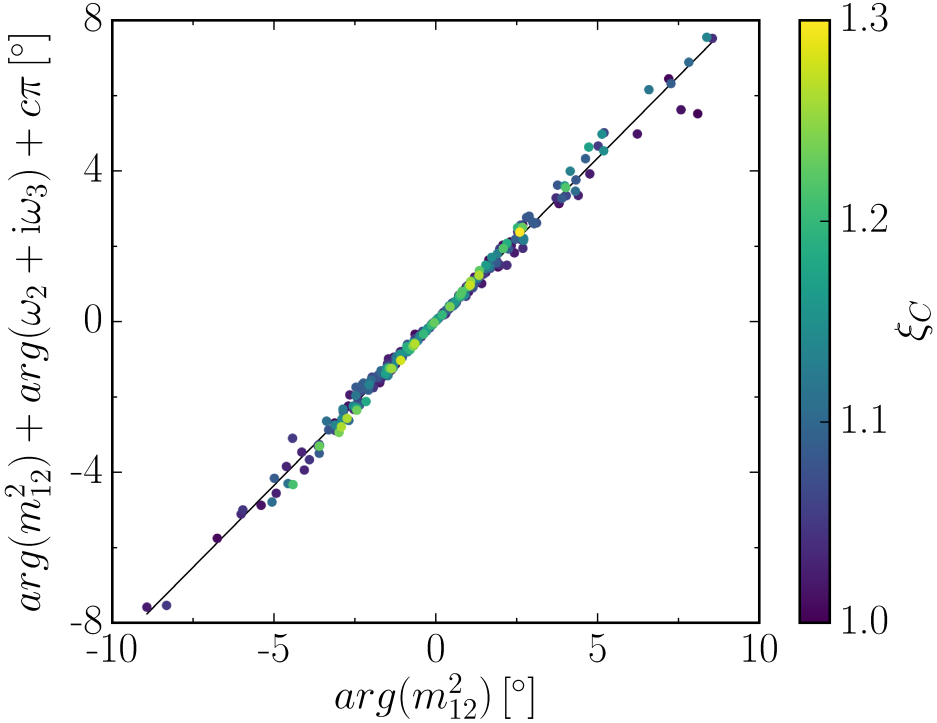


red triangle: SM point; coloured points $\xi_c > 1$

$\mathcal{S}$pontaneous $\mathcal{G}$eneration of a $\mathcal{CP}$-$\mathcal{V}$iolating $\mathcal{P}$hase

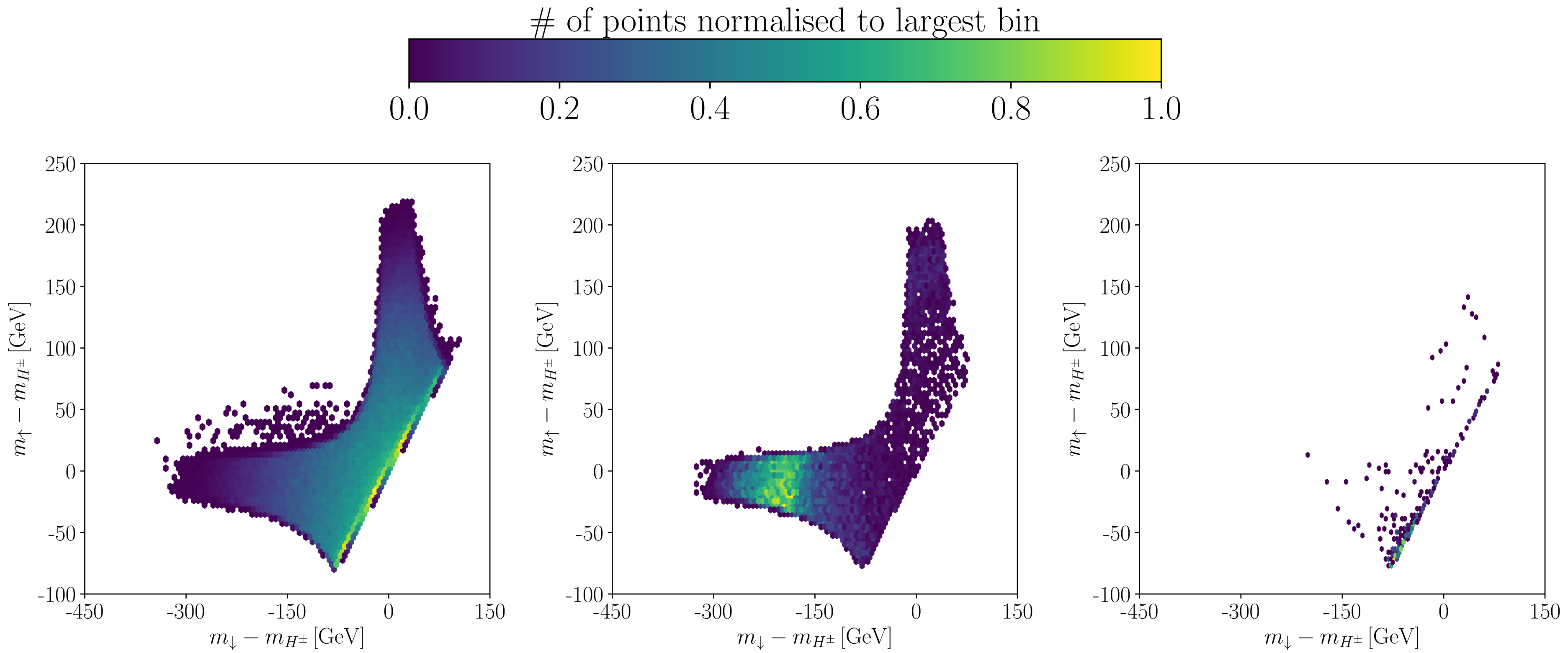
Type II, $H_1 = h$ [Basler,MM,Wittbrodt '17]





$\mathcal{M}$ass $\mathcal{D}$ifferences

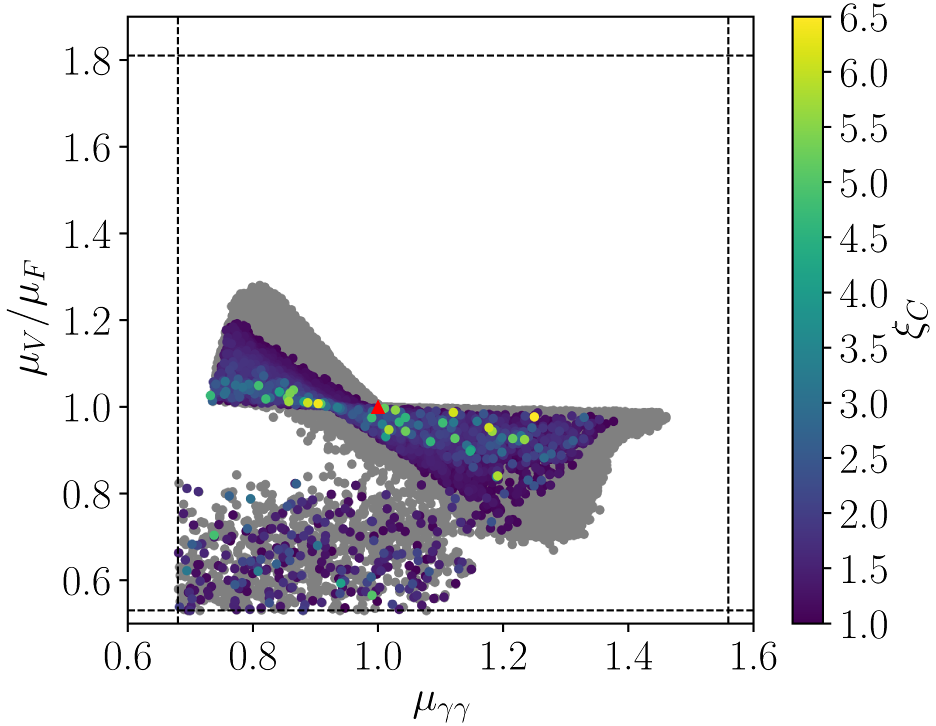
Type II, $H_1 = h$ [Basler,MM,Wittbrodt '17]

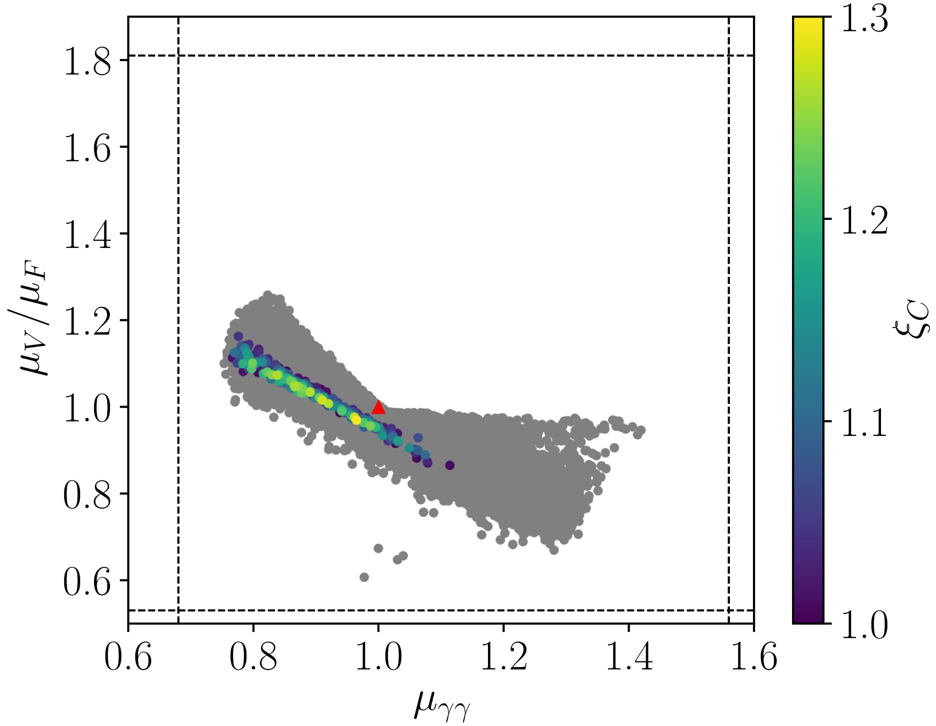


left: all points passing the constraints; middle: all points with a strong PT and CP conservation; right: all points with $\xi_c > 1$ and explicit CP violation

$\mathcal{S}$ignal $\mathcal{R}$ates at the $\mathcal{L}$HC

Type II, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17]





* $\mu_F = \sigma_{\text{C2HDM}}(ggF + bbF)/\sigma_{\text{SM}}(ggF)$ and $\mu_V = \sigma_{\text{C2HDM}}(VBF + VH)/\sigma_{\text{SM}}(VBF + VH)$

* Signal rates: $(H_i = h_{125})$

$$\mu_{xx} = \mu_F \times \frac{\text{BR}_{\text{C2HDM}}(H_i \to xx)}{\text{BR}_{\text{SM}}(H_i \to xx)}$$

$\mathcal{S}$ignal $\mathcal{R}$ates at the $\mathcal{L}$HC

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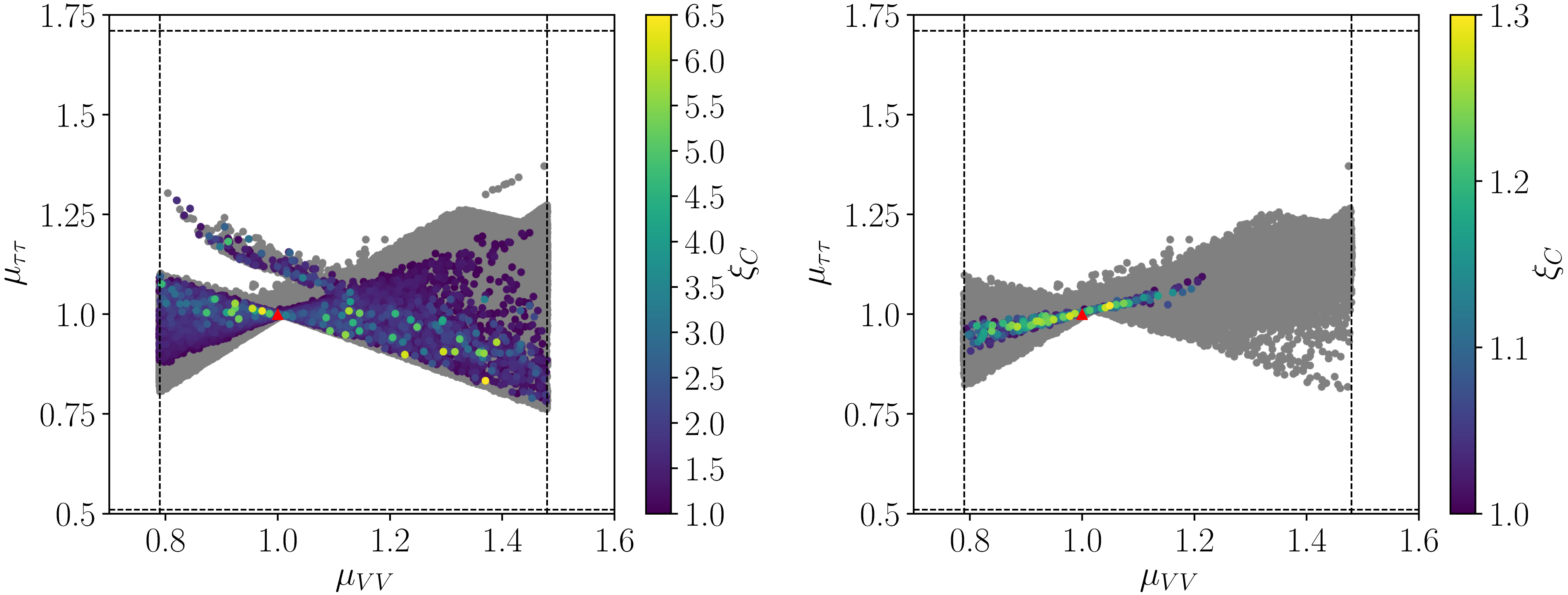

$*$ Signal rates: $(H_i = h_{125})$

$$\mu_{xx} = \mu_F \times \frac{\text{BR}_{\text{C2HDM}}(H_i \to xx)}{\text{BR}_{\text{SM}}(H_i \to xx)}$$

$\mathcal{T}$he $\mathcal{D}$ifferent $\mathcal{C}$ontributions to the $\mathcal{E}$DM

[Fontes,MM,Romao,Santos,Silva,Wittbrodt '17]