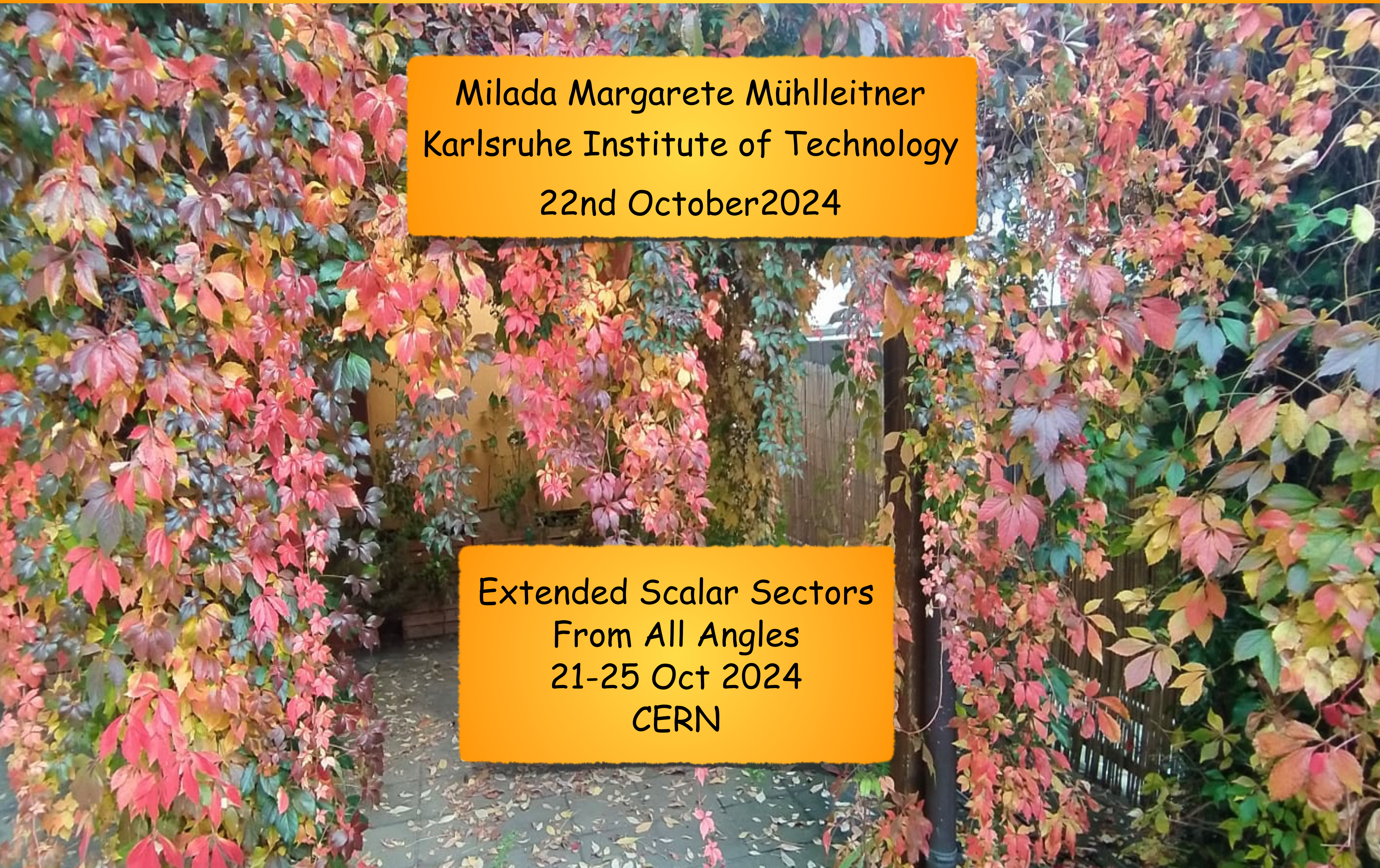
CP Violation in Extended Scalar Sectors



Milada Margarete Mühlleitner
Karlsruhe Institute of Technology

22nd October2024

Extended Scalar Sectors
From All Angles
21-25 Oct 2024
CERN

Outline

- ✦ Introduction
- ✦ The C2HDM
- ✦ Measurements of CP-Violation
- ✦ CP-Violation in the NMSSM
- ✦ CP-Violation and Electroweak Baryogenesis
- ✦ Conclusions

Introduction

Why CP violation?

✏ Sizable CP-violation, CP-violation in Higgs sector: sign of physics beyond the Standard Model

✏ Sizable CP-violation required for Electroweak Baryogenesis

- **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

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

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

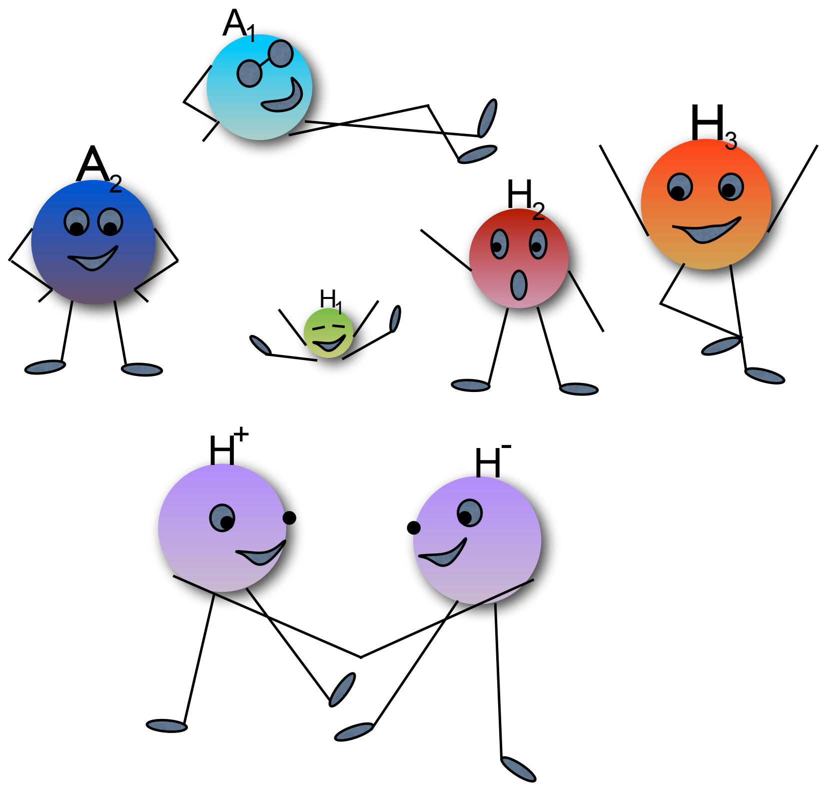
$\langle \Phi_c \rangle$ and T_c field configuration and temperature at phase transition

Extended Higgs Sectors

Why extended Higgs sectors?

* many new physics models require extended Higgs models
* fermion/gauge sectors not minimal - why should the Higgs sector be minimal?
* extended Higgs sectors:

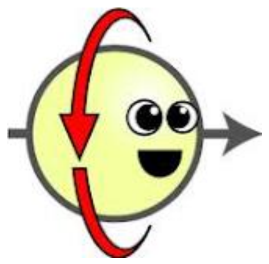
  - provide DM candidate
  - new sources of CP-violation
  - alleviate metastability
  - allow for strong first-order phase transition
  - change di-Higgs cross section
  - enlarged Higgs spectrum -> interesting phenomenology



Higgs Spin and CP Quantum Numbers

❖ Quantum numbers of the Higgs boson: J^{PC}

- J spin
- P parity
- C charge conjugation



✻ γγ→H or H→γγ ~> J ≠ 1

❖ CP properties:

✻ SM Higgs $J^{CP} = 0^{++}$; beyond the SM (BSM):

- more than one spin-0 particle possible
- CP-even, CP-odd, CP-violating Higgs states

✻ Study of CP properties ~> insights in beyond-SM (BSM) physics

✻ existing and future colliders:
establish CP properties, determine amount of CP-mixing

Determination of Higgs Quantum Numbers

✏ Quantum numbers of the Higgs boson:

➢ angular correlations in production: Hjj in vector boson fusion [Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld]

gluon gluon fusion [Odagiri; Klänge,Zeppenfeld; Campanario eal; Del Duca eal; Andersen eal]

➢ Higgs decays into W and Z pairs [Dell'Aquila,Nelson; Barger eal; Kramer,Kühn,Stong,Zerwas; Skjold,Osland; Choi,Kalinowski,Liao,Zerwas; Miller,MM,Zerwas; Bluj; Dova eal; Buszello, Fleck,Marquard,van der Bij; Gao eal; Englert eal; Sancti eal]

➢ gamma gamma collisions [Grzadkowski,Gunion; Asakawa,Choi,Hagiwara; Godbole,Rindani,Singh; Godbole,Kraml,Rindani,Singh]

✏ CP-Violation:

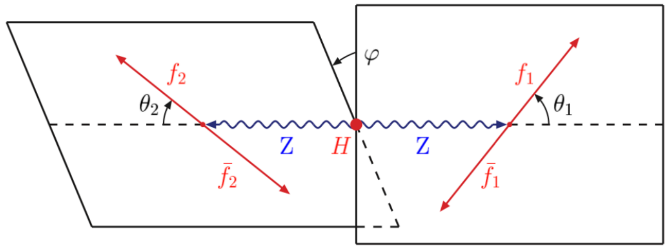
➢ angular or other CP-sensitive observables [Gunion,He; Chang eal; Skjold,Osland; Choi eal; Niezurawski, Zarnecki,Krawczyk; Godbole,Kraml; Rindani,Singh; Godbole, Miller,MM, De Rujula eal]

➢ Combination of three decays into bosons [Grzadkowski,Gunion,PLB350(1995)218] [Fontes,Romao,Santos,Silva,Phys.Rev.D92(2015)5,055014] [Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

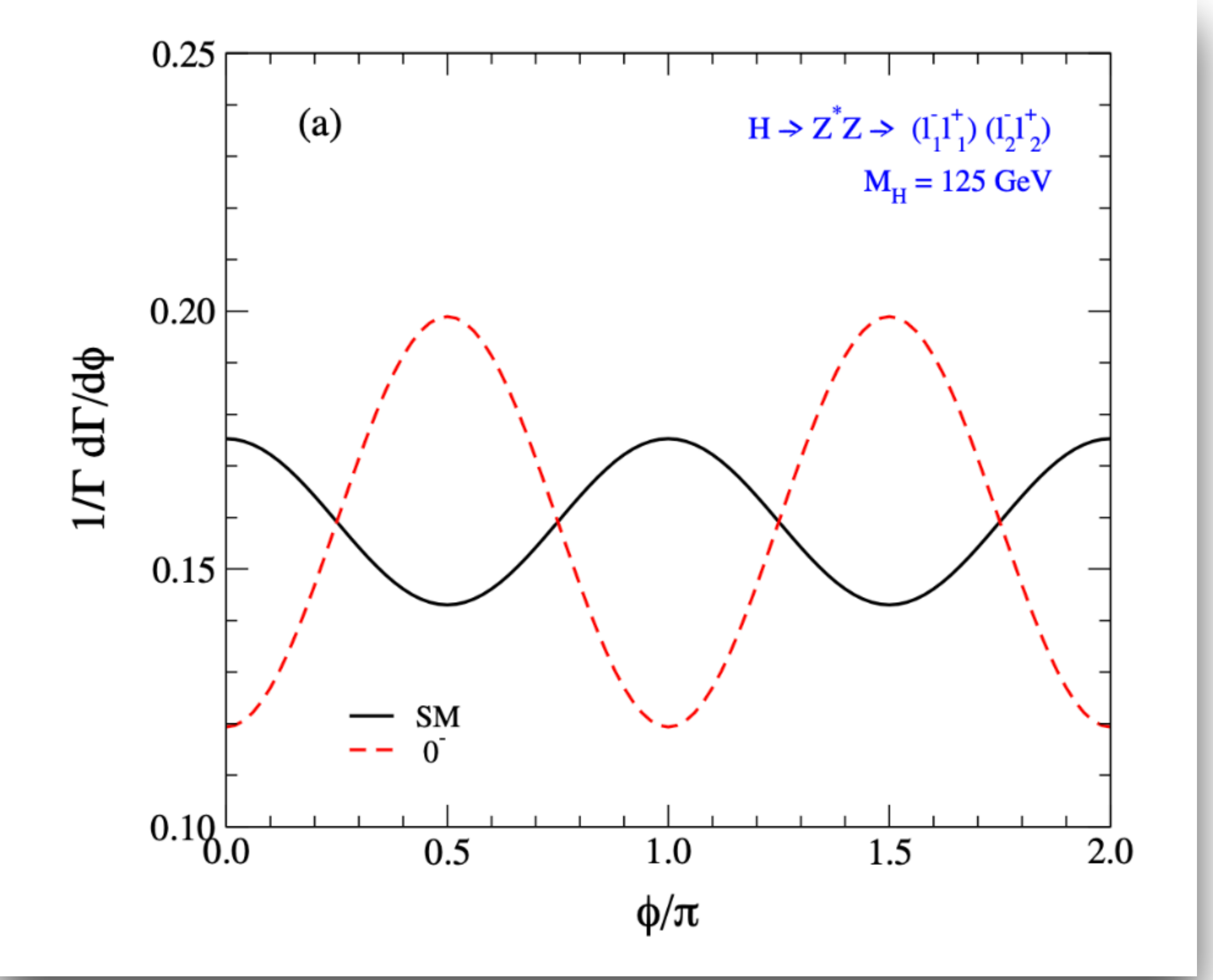
➢ „2-guise CP": CP-odd and CP-even decays at the same time [Fontes,Romao,Santos,Silva,JHEP06(2015)060] [Fontes,MM,Romao,Santos,Silva,Wittbrodt,JHEP 02 (2018) 073] [Biekötter,Fontes,MM,Romao,Santos,Silva, JHEP 05 (2024) 127]

Extraction of Higgs Quantum Numbers

❖ Higgs Decay into Z boson pair: $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$

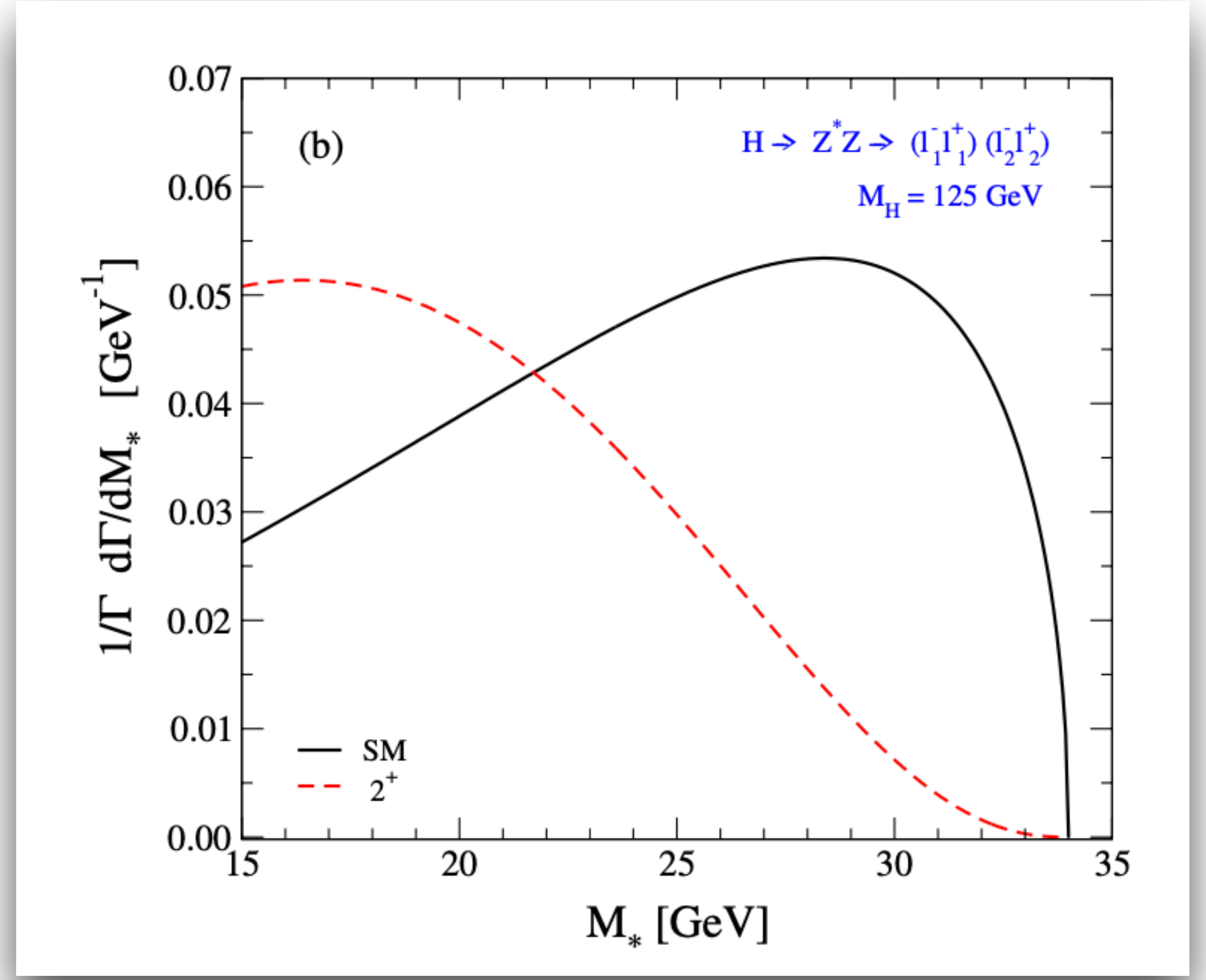


CP-even or CP-odd



[Adapted from Choi,Miller,MM,Zerwas,´03]

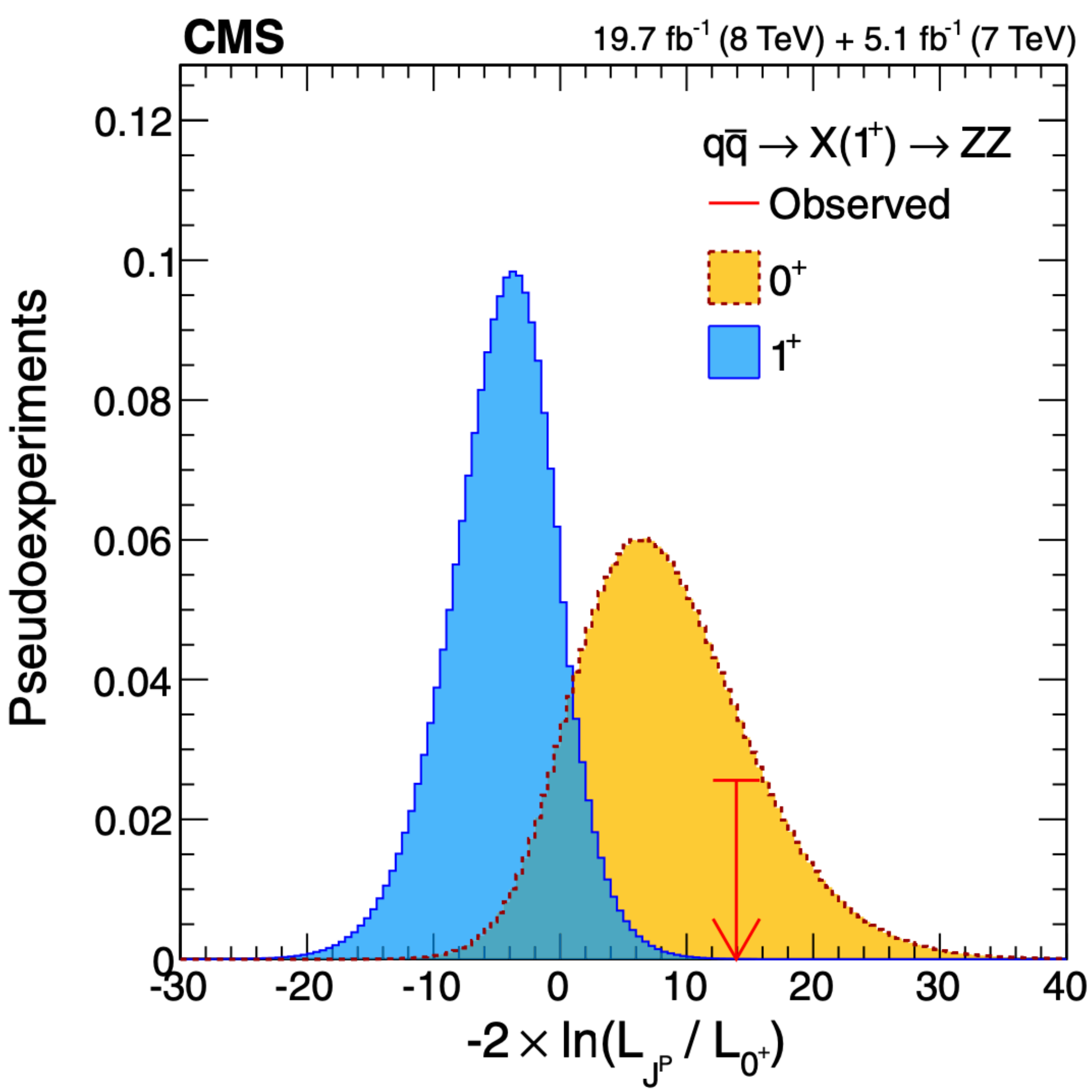
Spin 0 or Spin 2



[Adapted from Choi,Miller,MM,Zerwas,´03]

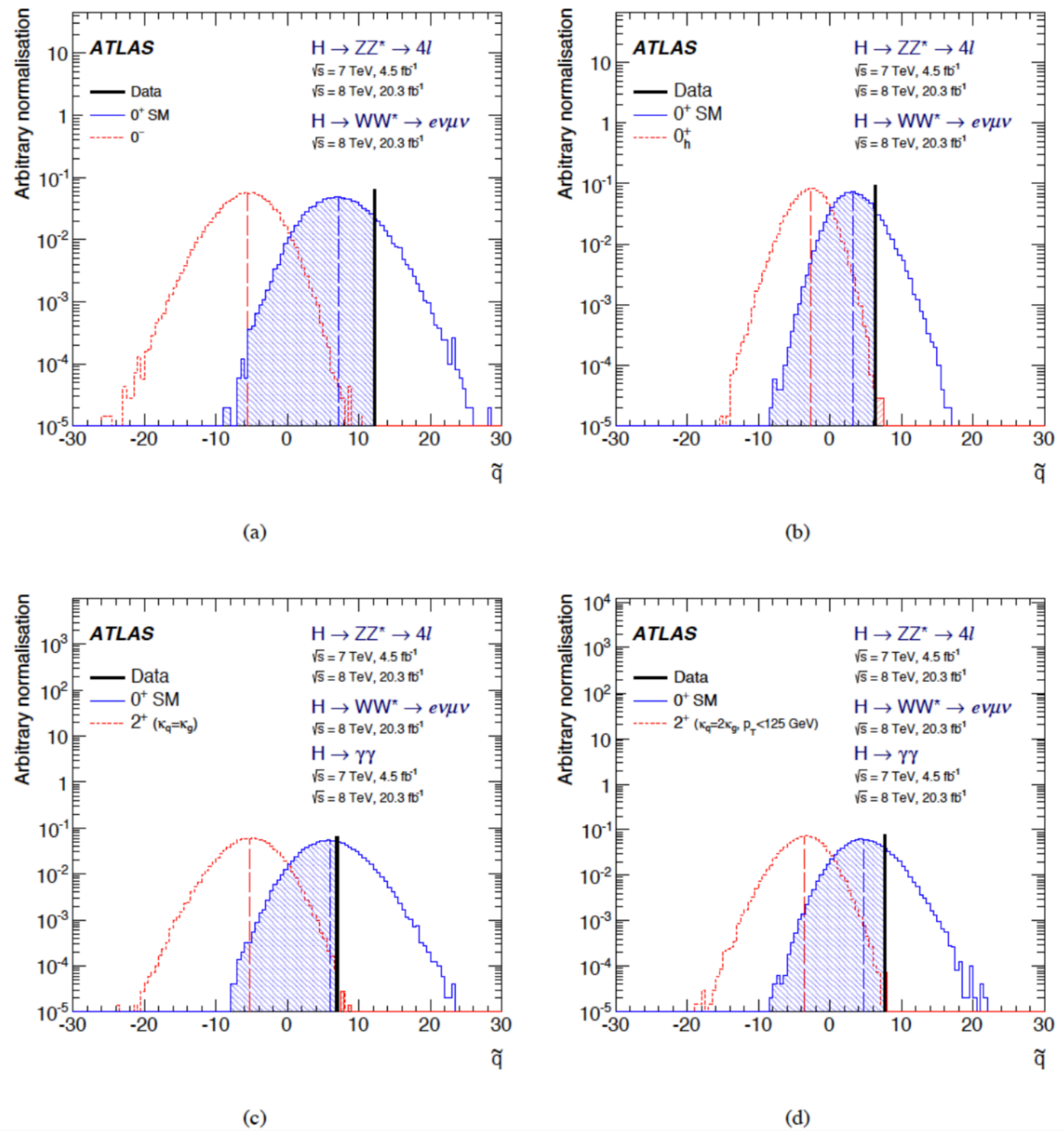
Experiment: Hypothesis Test

[CMS,PhysRevD.92.012004(2015)]



The expectation for the SM Higgs boson is represented by the yellow histogram on the right and the alternative JP hypothesis by the blue histogram on the left. The red arrow indicates the observed q value.

[ATLAS,1506.05669]



Observed (expected) values: vertical solid (dashed) lines; shaded areas ≙ integrals of the expected distributions to compute the p-values for the rejection of each hypothesis.

Vast New Physics Landscape

Sample Benchmark Model: The C2HDM

The CP-Violating 2HDM (C2HDM)

❖ C2HDM Higgs potential: w/ softly broken $\mathbb{Z}_2$ symmetry $(\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2)$

allows for a decoupling limit [Ginzburg,Krawczyk,Osland,'02]

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

All parameters are real except for m_{12}^2 and λ_5: $m_{12}^2 = |m_{12}^2| e^{i\phi(m_{12}^2)}, \quad \lambda_5 = |\lambda_5| e^{i\phi(\lambda_5)}$

The two complex phases are not independent of each other

$$2\mathrm{Re}(m_{12}^2) \tan\phi(m_{12}^2) = v_1 v_2 \, \mathrm{Re}(\lambda_5) \tan\phi(\lambda_5)$$

Ensure explicit CP violation (both phases cannot be removed simultaneously) by choosing:

$$\phi(\lambda_5) \neq 2\,\phi(m_{12}^2)$$

* For CP violation in the 3HDM, cf. talk by M. Rebelo Monday afternoon.

* For CP violation in BSM w/ natural alignment, cf. talk by A. Pilaftsis, Tuesday afternoon.

The CP-Violating 2HDM (C2HDM)

❖ Mass spectrum and mixing:

$v_2 = 0 \rightsquigarrow$ DM: inert doublet model (IDM)

Insert $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}$ $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$ in Higgs potential, collect bilinear field terms

Diagonalize obtained mass matrix with

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \qquad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

$(\rho_3 = -s_\beta \eta_1 + c_\beta \eta_2)$

$$-\pi/2 < \alpha_1 \leq \pi/2, \qquad -\pi/2 < \alpha_2 \leq \pi/2, \qquad -\pi/2 < \alpha_3 \leq \pi/2$$

Leads to mass eigenstates H_i, i=1,2,3, with $m_{H_1} \leq m_{H_2} \leq m_{H_3}$

only two masses are independent: $m_{H_3}^2 = \dfrac{m_{H_1}^2 R_{13}(R_{12}\tan\beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$

The CP-Violating 2HDM (C2HDM)

- Mass spectrum: CP violation ~> neutral formerly CP-even (h,H) and CP-odd (A) states mix to mass eigenstates H_i $(i = 1,2,3)$ with indefinite CP quantum number. Charged Higgs sector is unchanged.

> 3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3,
> with $m_{H_1} \leq m_{H_2} \leq m_{H_3}$
> 2 charged Higgs bosons: H^+, H^-

- Allowed amount of CP violation: stringently constrained by EDM measurements

Couplings of the SM-Like Higgs Boson

- C2HDM case with: SM-like Higgs boson $H_1 \equiv h$, $m_h = 125$ GeV

- Couplings to gauge bosons:

  Higgs couplings to gauge bosons have the same Lorentz structure;
  they are simply multiplied by a numerical factor

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha) g_{SM}^{hVV}$$

$$g_{C2HDM}^{hVV} = \cos\alpha_2 \, g_{2HDM}^{hVV}$$

C2HDM

„pseudoscalar" component

$|\sin\alpha_2| = 0 \rightsquigarrow h_1$ pure scalar

$|\sin\alpha_2| = 1 \rightsquigarrow h_1$ pure pseudoscalar

Couplings of the SM-Like Higgs Boson

❖ Yukawa sector: avoid flavour-changing-neutral couplings (FCNCs) by transferring $\mathbb{Z}_2$ symmetry to Yukawa sector ⇝ four 2HDM types

	u-type	d-type	leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-Specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

❖ Yukawa coupling modifiers $Y_{2HDM} \equiv \kappa$:

Type I: $\kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

Type II: $\kappa_U^{II} = \dfrac{\cos\alpha}{\sin\beta}\,, \quad \kappa_D^{II} = \kappa_L^{II} = -\dfrac{\sin\alpha}{\cos\beta}$

Type F(Y): $\kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta}\,, \quad \kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

Type LS(X): $\kappa_U^{LS} = \kappa_D^{LS} = \dfrac{\cos\alpha}{\sin\beta}\,, \quad \kappa_L^{LS} = -\dfrac{\sin\alpha}{\cos\beta}$

❖ Higgs Yukawa coupling in the C2HDM:

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta(1/\tan\beta)$$

Higgs Couplings in Scalar Extensions

❖ Yukawa

$$Y_{BSM} = f_Y(\alpha_i) Y_{SM} \pm i\gamma_5 g_Y(\alpha_i)$$

$f_Y(\alpha_i)$ and $g_Y(\alpha_i)$ are numbers functions of mixing angles and (maybe) other parameters

CP-conserving limit: $f_Y(\alpha_i)$ and $g_Y(\alpha_i)$ not simultaneously non-zero

❖ Gauge

$$g_{BSM} = f_g(\alpha_i) g_{SM}$$

$f_g(\alpha_i)$ is a number function of mixing angles and (maybe) other parameters;

$f_g(\alpha_i) = 0$ for pseusodscalar in CP-conserving limit

❖ Scalar

$$\lambda_{BSM} = f_\lambda(\alpha_i) \lambda_{SM}$$

Like for the couplings with gauge bosons: existence of combined terms shows that CP is broken

❖ Alignment limit: limit where all couplings of the SM-like Higgs are exactly the SM ones; e.g.

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha) g_{SM}^{hVV} \qquad \sin(\beta - \alpha) = 1 \qquad g_{2HDM}^{hVV} = g_{SM}^{hVV}$$

*adapted from Rui Santos

Measurements of CP-Violation

Combination of Decays

❖ Combination of three decays:

$h_{SM} \to ZZ \quad CP(h_{SM}) = 1$ $\quad$ $h_2 \to ZZ \quad CP(h_2) = 1$ $\quad$ $h_2 \to h_1 Z \quad CP(h_2) = -CP(h_1)$

forbidden in exact alignment limit

Away from alignment limit: many other combinations possible

❖ Combinations involving three Higgs bosons: [Fontes,Romao,Santos,Silva,PRD92(2015)5,055014]

$$h_1 \to ZZ \Leftarrow CP(h_1) = 1 \quad \rightsquigarrow \quad h_3 \to h_2 h_1 \Rightarrow CP(h_3) = CP(h_2)$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

* For test through loops, cf. talk by Rui Santos on Monday morning.

Example Benchmark C2HDM

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis
- Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\mathrm{NLO}}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\mathrm{tot}}_{H_1}$ [GeV]	$\Gamma^{\mathrm{tot}}_{H_2}$ [GeV]	$\Gamma^{\mathrm{tot}}_{H_3}$ [GeV]	$\Gamma^{\mathrm{tot}}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\mathrm{NNLO}}_{H_1}$ [pb]	$\sigma^{\mathrm{NNLO}}_{H_2}$ [pb]	$\sigma^{\mathrm{NNLO}}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$
\begin{aligned}
\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) &= 191 \text{ fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to WW) &= 254 \text{ fb}\\
\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) &= 109 \text{ fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) &= 122 \text{ fb}\\
\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) &= 235 \text{ fb}\,, & \sigma(H_3)\times \mathrm{BR}(H_3\to WW) &= 315 \text{ fb}\\
\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) &= 136 \text{ fb}\,, & \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) &= 76 \text{ fb}\,.
\end{aligned}
$$

Benchmark point compatible w/ all relevant theor. & exp. constraints (also di-Higgs constraints)

Example Benchmark C2HDM

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis
- Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\begin{array}{llll}
\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) = 191\ \mathrm{fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to WW) = 254\ \mathrm{fb} \\
\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) = 109\ \mathrm{fb}\,, & \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) = 122\ \mathrm{fb} \\
\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) = 235\ \mathrm{fb}\,, & \sigma(H_3)\times \mathrm{BR}(H_3\to WW) = 315\ \mathrm{fb} \\
\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) = 136\ \mathrm{fb}\,, & \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) = 76\ \mathrm{fb}\,.
\end{array}$$

CP-even

Example Benchmark C2HDM

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis
- Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	Re(m_{12}^2) [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\begin{aligned}
\sigma(H_2)\times{\rm BR}(H_2\to H_1H_1) &= 191\ {\rm fb}\,, & \sigma(H_2)\times{\rm BR}(H_2\to WW) &= 254\ {\rm fb}\\
\sigma(H_2)\times{\rm BR}(H_2\to ZZ) &= 109\ {\rm fb}\,, & \sigma(H_2)\times{\rm BR}(H_2\to ZH_1) &= 122\ {\rm fb}\\
\sigma(H_3)\times{\rm BR}(H_3\to H_1H_1) &= 235\ {\rm fb}\,, & \sigma(H_3)\times{\rm BR}(H_3\to WW) &= 315\ {\rm fb}\\
\sigma(H_3)\times{\rm BR}(H_3\to ZZ) &= 136\ {\rm fb}\,, & \sigma(H_3)\times{\rm BR}(H_3\to ZH_1) &= 76\ {\rm fb}\,.
\end{aligned}$$

CP-even

CP-odd

Example Benchmark C2HDM

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis
- Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	Re(m_{12}^2) [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{tot}_{H_1}$ [GeV]	$\Gamma^{tot}_{H_2}$ [GeV]	$\Gamma^{tot}_{H_3}$ [GeV]	$\Gamma^{tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{NNLO}_{H_1}$ [pb]	$\sigma^{NNLO}_{H_2}$ [pb]	$\sigma^{NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) = 191\ \mathrm{fb}\,,\quad \sigma(H_2)\times \mathrm{BR}(H_2\to WW) = 254\ \mathrm{fb}$$
$$\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) = 109\ \mathrm{fb}\,,\quad \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) = 122\ \mathrm{fb}$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) = 235\ \mathrm{fb}\,,\quad \sigma(H_3)\times \mathrm{BR}(H_3\to WW) = 315\ \mathrm{fb}$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) = 136\ \mathrm{fb}\,,\quad \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) = 76\ \mathrm{fb}\,.$$

CP-even

Example Benchmark C2HDM

[Abouabid, Arhrib,Azevedo,El Falaki, Ferreira, MM,Santos,´21]

- CP-violating 2HDM (C2HDM): BSM CP violation required in electroweak baryogenesis

- Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\text{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\text{NLO}}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\text{tot}}_{H_1}$ [GeV]	$\Gamma^{\text{tot}}_{H_2}$ [GeV]	$\Gamma^{\text{tot}}_{H_3}$ [GeV]	$\Gamma^{\text{tot}}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\text{NNLO}}_{H_1}$ [pb]	$\sigma^{\text{NNLO}}_{H_2}$ [pb]	$\sigma^{\text{NNLO}}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times \text{BR}(H_2 \to H_1H_1) = 191 \text{ fb}\,, \quad \sigma(H_2)\times \text{BR}(H_2 \to WW) = 254 \text{ fb}$$
$$\sigma(H_2)\times \text{BR}(H_2 \to ZZ) = 109 \text{ fb}\,, \quad \sigma(H_2)\times \text{BR}(H_2 \to ZH_1) = 122 \text{ fb}$$
$$\sigma(H_3)\times \text{BR}(H_3 \to H_1H_1) = 235 \text{ fb}\,, \quad \sigma(H_3)\times \text{BR}(H_3 \to WW) = 315 \text{ fb}$$
$$\sigma(H_3)\times \text{BR}(H_3 \to ZZ) = 136 \text{ fb}\,, \quad \sigma(H_3)\times \text{BR}(H_3 \to ZH_1) = 76 \text{ fb}\,.$$

CP-even

CP-odd

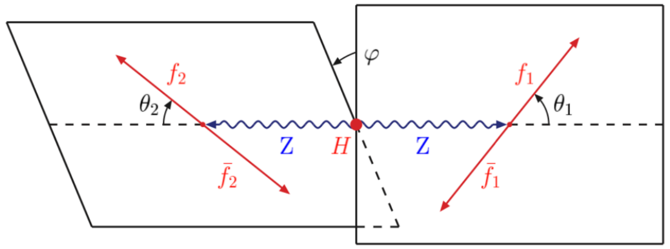
Asymmetries & Kinematic Distributions

❖ Higgs Decay $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$: (spin-0 assumed for H) [Godbole,Miller,MM,JHEP 12 (2007) 031]

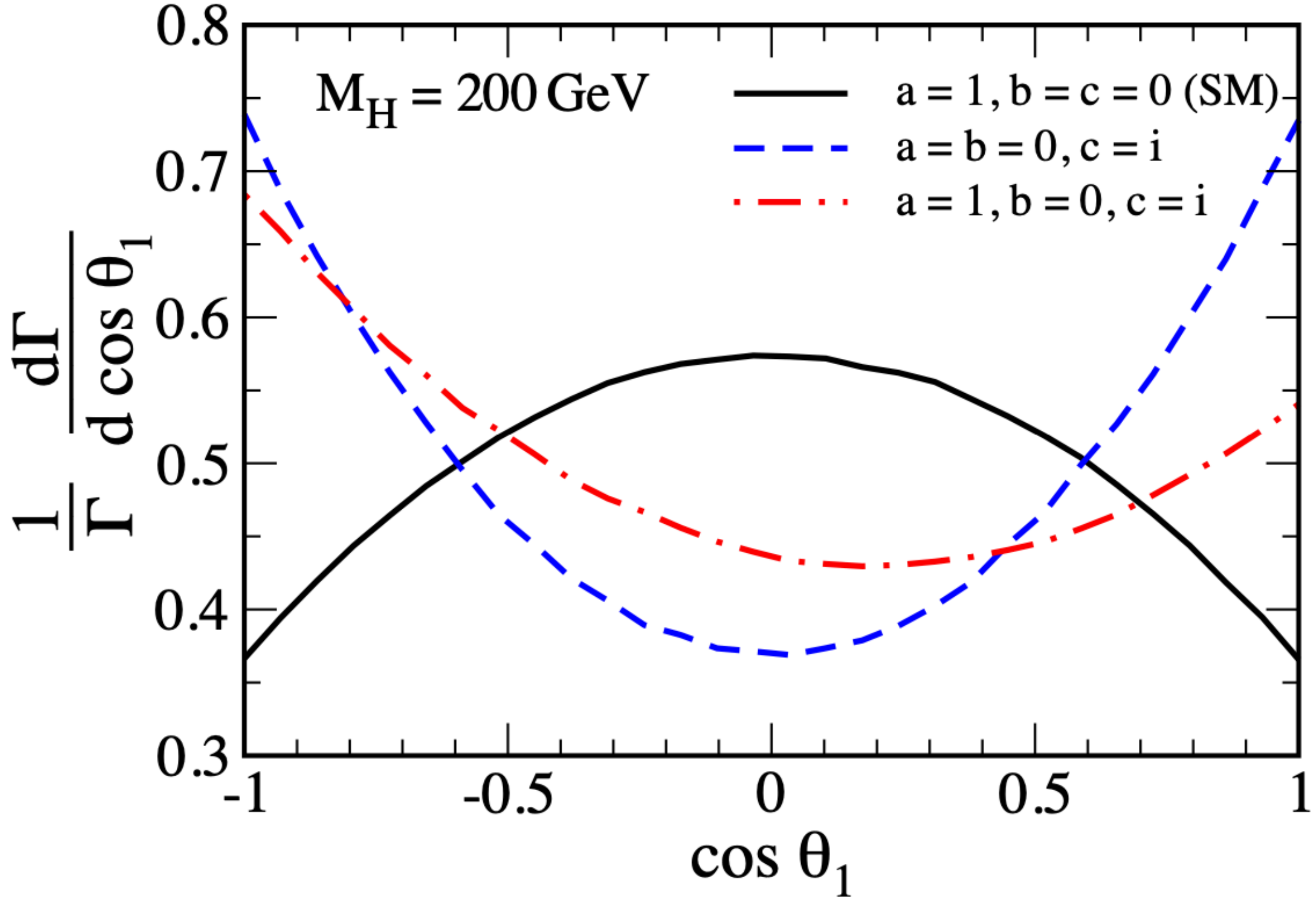
$$V_{HZZ}^{\mu\nu} = \frac{igm_Z}{\cos\theta_W}\left[a\,g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\frac{p^\alpha k^\beta}{m_Z^2}\right]$$

CP violation: $(a \neq 0$ and/or $b \neq 0)$ and $c \neq 0$

❖ CP-sensitive asymmetry: sensitive to Im(c)



normalized distribution



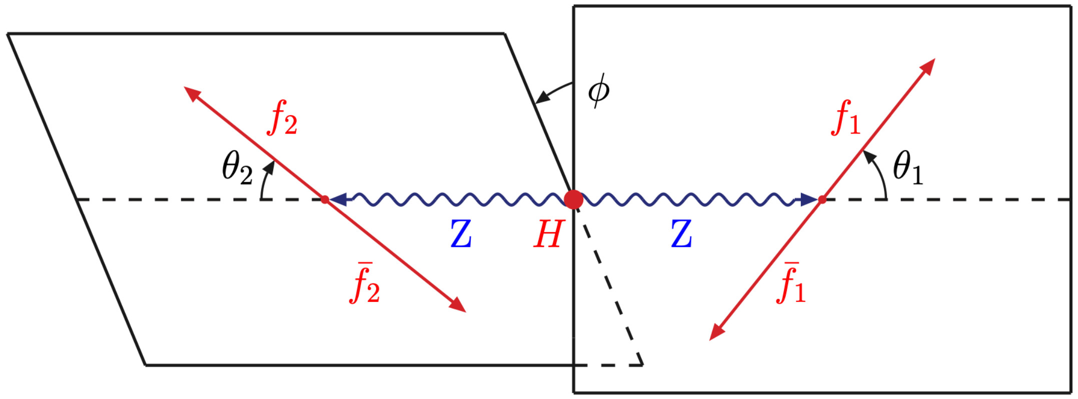
$$O_1 \equiv \frac{(\vec{p}_{2Z} - \vec{p}_{1Z}) \cdot (\vec{p}_{3H} + \vec{p}_{4H})}{|\vec{p}_{2Z} - \vec{p}_{1Z}||\vec{p}_{3H} + \vec{p}_{4H}|}$$

$$O_1 = \cos\theta_1$$

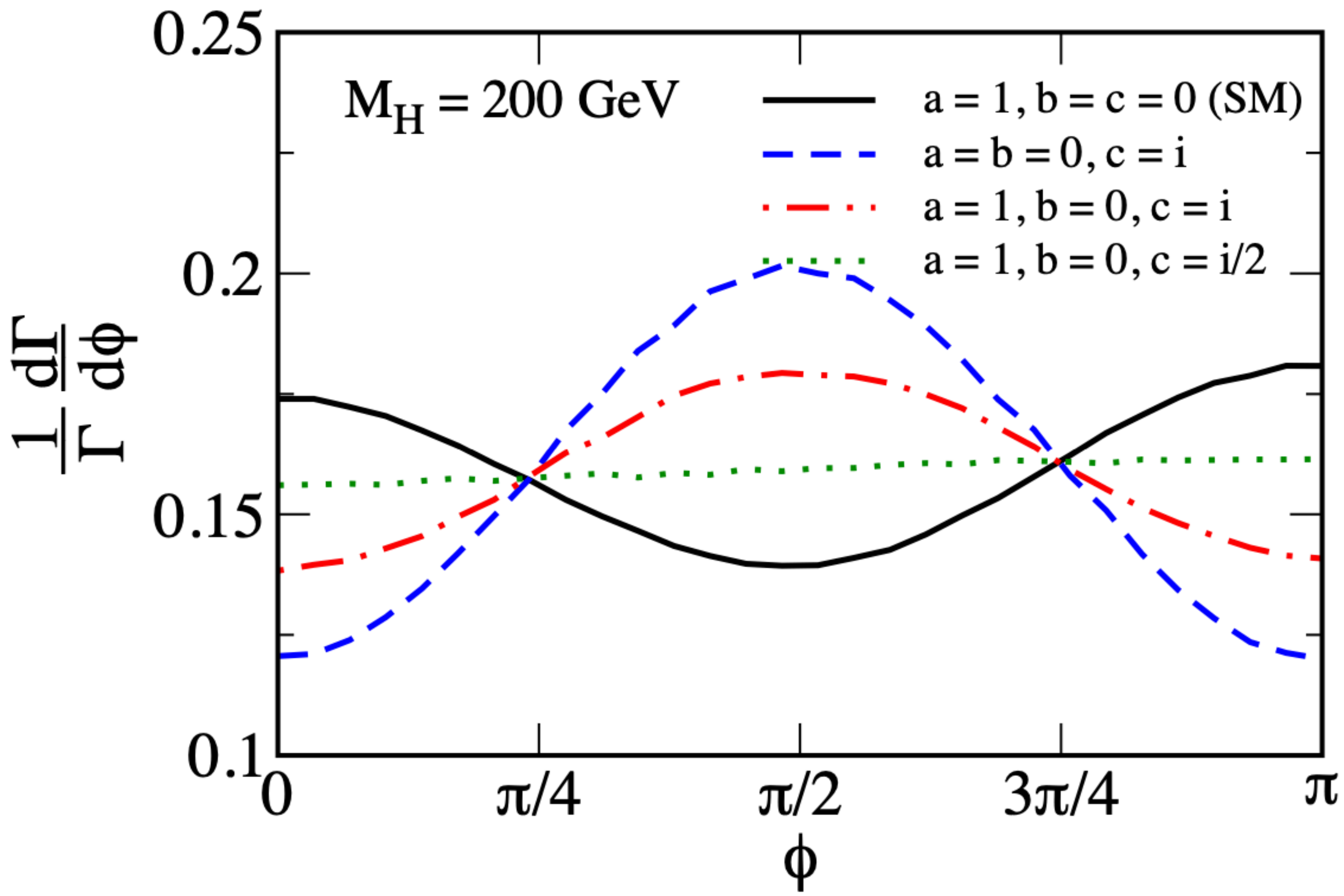
❖ Higgs Decay $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$: (spin-0 assumed for H) [Godbole,Miller,MM,JHEP 12 (2007) 031]

$$V^{\mu\nu}_{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[a\, g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\frac{p^\alpha k^\beta}{m_Z^2}\right]$$

CP violation: $(a \neq 0$ and/or $b \neq$) and $c \neq 0$



❖ Angular distribution in ϕ:



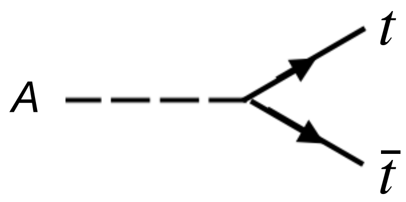
normalized distribution

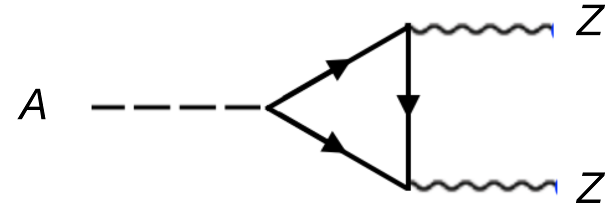
effect washed out for large M_H

Caveat: degenerate CP-even + CP-odd Higgs in CP-conserving theory could mimic effect

Another Caveat

❖ CP-conserving theory: pseudoscalar A (tree-level $A \to ZZ$ forbidden)

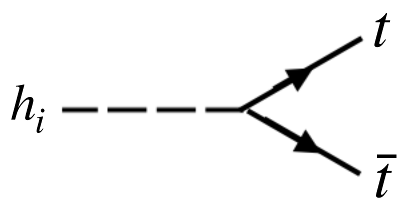


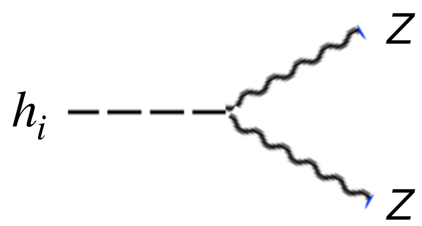


If tree-level coupling $h_i ZZ$ coupling is very small, of the order of the loop induced coupling ⇝ impossible to distinguish the models

cf. e.g. [Arhrib,Benbrik,El Falaki,Sampaio, Santos,Phys.Rev.D 99 (2019) 3, 035043]

❖ CP-violating theory: CP-mixing state h_i





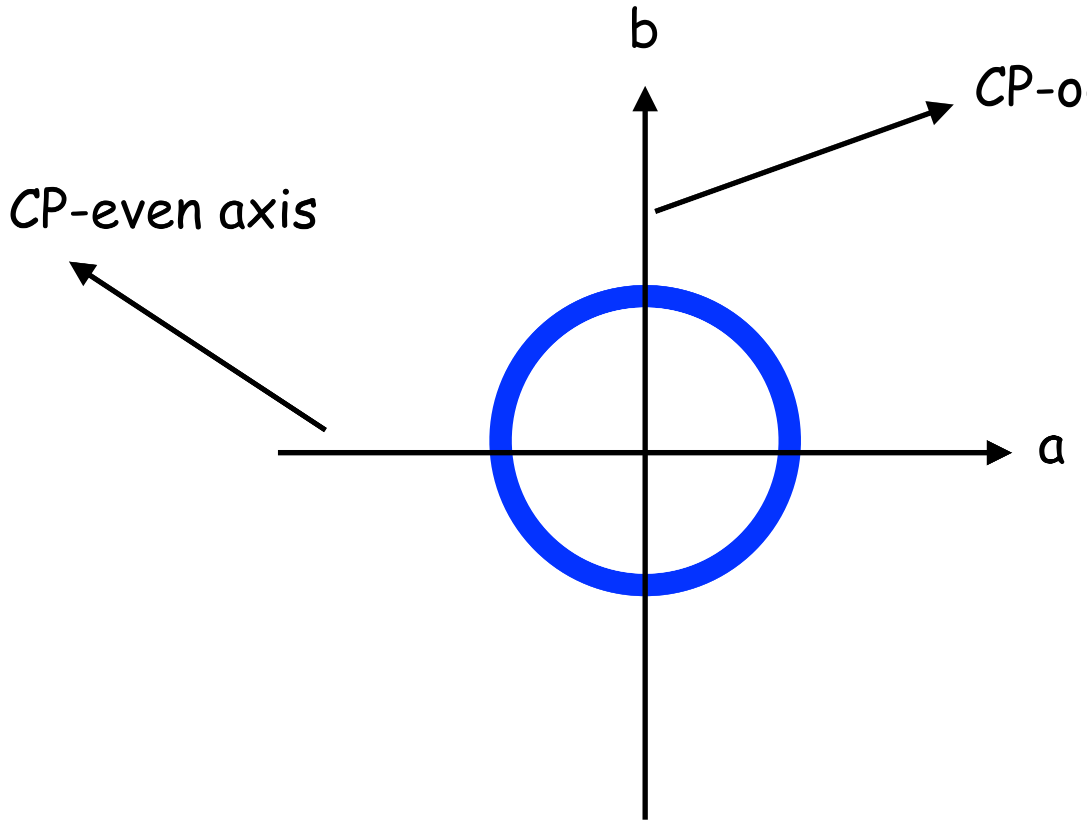
To unambiguously identify CP-violation combine as many CP-sensitive measurements as possible

CP-Violation in the Higgs Yukawa Coupling

- Directly accessible in Higgs coupling to fermions: $\bar{\psi}(a + ib\gamma_5)\psi\phi$
- Allowed region based on rates:

CP-conserving Yukawa $\sim a \quad \Rightarrow \quad |a|^2 <$ meas. rate

CP-violating Yukawa $\sim (a + ib\gamma_5) \quad \Rightarrow \quad |a|^2 + |b|^2 <$ meas. rate



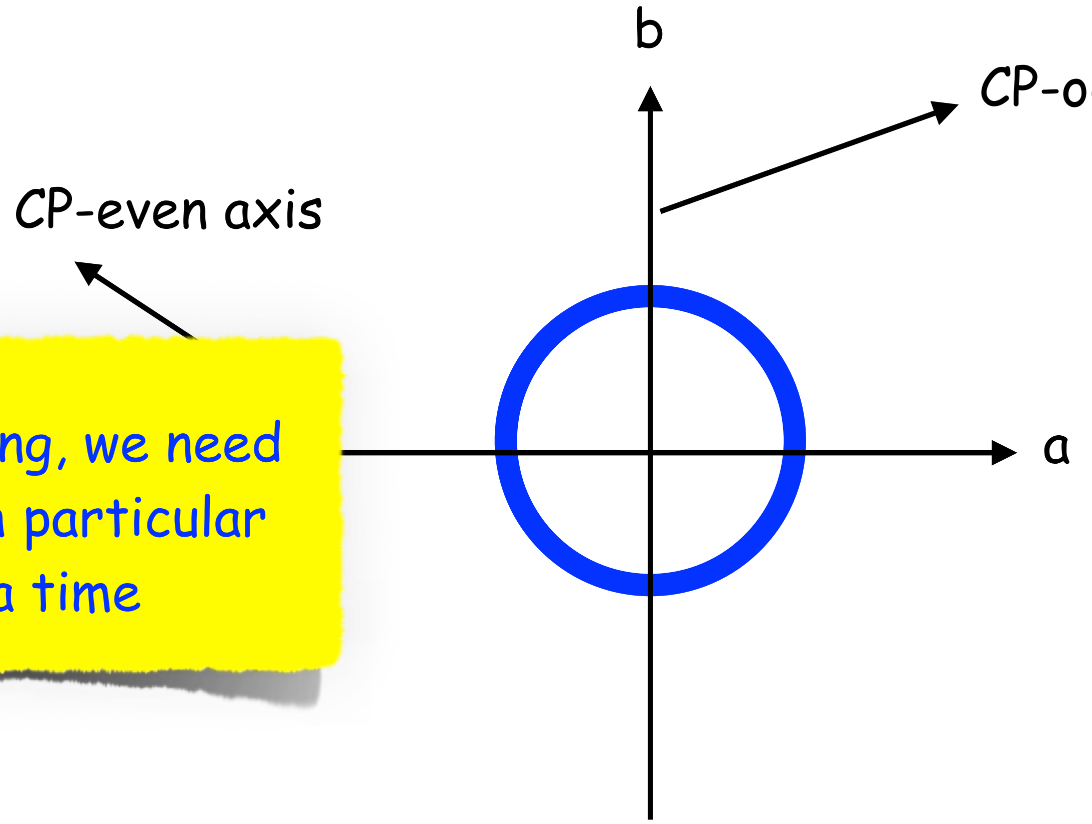
The allowed region is a ring
In the CP-odd/CP-even plane.
This is based only on rates.

CP-Violation in the Higgs Yukawa Coupling

- Directly accessible in Higgs coupling to fermions: $\bar{\psi}(a + ib\gamma_5)\psi\phi$
- Allowed region based on rates:

CP-conserving Yukawa $\sim a \quad \Rightarrow \; |a|^2 <$ meas. rate

CP-violating Yukawa $\sim (a + ib\gamma_5) \quad \Rightarrow \; |a|^2 + |b|^2 <$ meas. rate

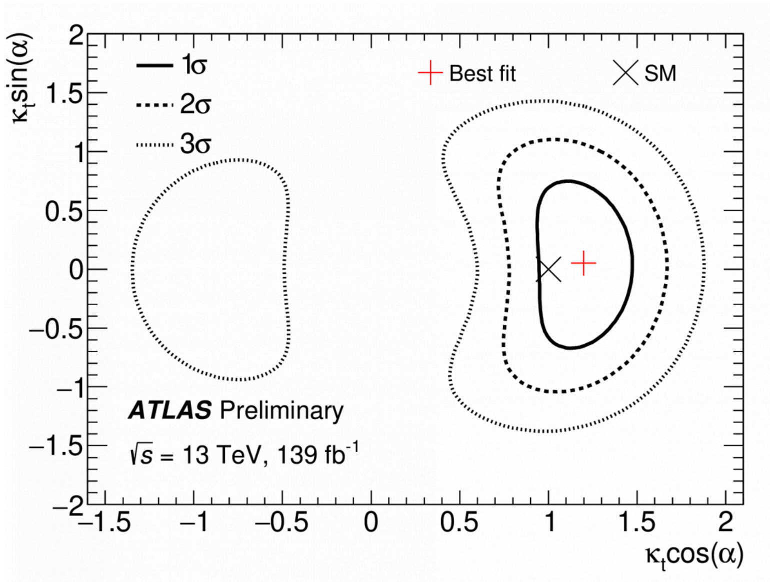


To resolve the ring, we need to look into each particular Yukawa at a time

The allowed region is a ring In the CP-odd/CP-even plane. This is based only on rates.

Experimental Constraints

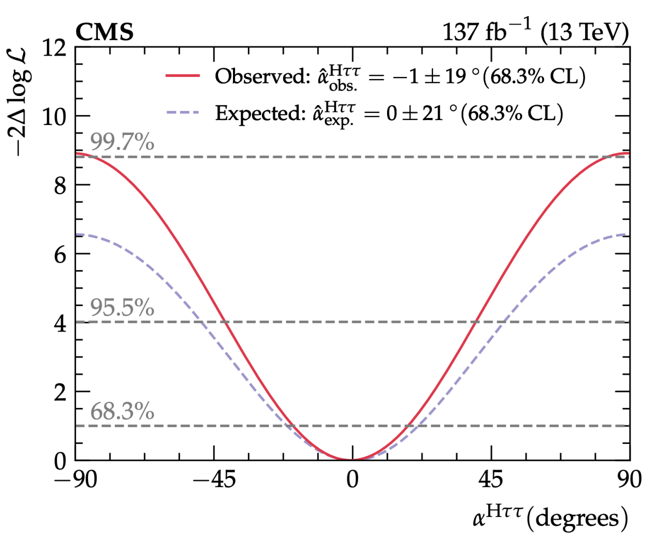
✦ Top Yukawa Coupling: Probe vertex in production $pp \to (h \to \gamma\gamma)\bar{t}t$

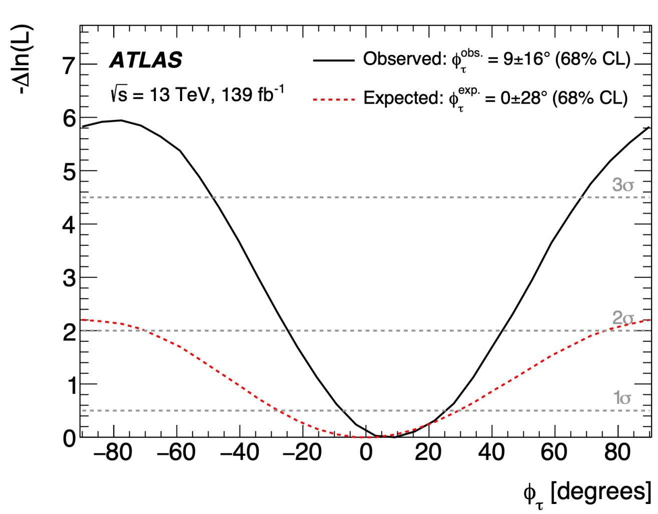


Consistent with the SM. Pure CP-odd coupling excluded at 3.9σ, and $|\alpha| > 43°$ excluded at 95% CL.

$$\mathcal{L}_{t\bar{t}h}^{CPV} = -\frac{y_t}{\sqrt{2}}\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)th \qquad \kappa_t = \kappa\cos\alpha \qquad \tilde{\kappa}_t = \kappa\sin\alpha$$

✦ Tau Yukawa Coupling: Probe vertex in Higgs decay $pp \to h \to \tau^+\tau^-$





Measurement of the CP-violating mixing angle $\Phi_{\tau\tau}$

CMS: -1±19° (0±21°) obs(exp) at 68% C.L.
±41° (±49)° obs(exp) at 99.7% C.L.

ATLAS: 9±16° (0±28°) obs(exp) at 68% C.L.
±34° ($^{+75}_{-70}$°) obs(exp) at 95% C.L.

[CMS JHEP06(2022)012] [ATLAS,Eur.Phys.J.C83(2023)563]

2-Guise Yukawa Couplings in CP-Violating Models

- Same Higgs boson couples once scalar-like, once pseudoscalar-like:

$$\bar{u}\,(a_u + i b_u \gamma_5)\, u h \qquad b_u \approx 0 \quad \rightsquigarrow \quad a_u\, \bar{u} u h \qquad \textbf{scalar}$$

$$\bar{d}\,(a_d + i b_d \gamma_5)\, a_d h \qquad a_d \approx 0 \quad \rightsquigarrow \quad i b_d\, \bar{d} \gamma_5 d h \qquad \textbf{pseudoscalar}$$

- Possible in C2HDM: couplings of h ($h \hat{=} H_{SM}$) for $\alpha_1 = \pi/2$

$$g^{hVV}_{C2HDM} = \cos\alpha_2\, \cos(\beta - \alpha_1) g^{hVV}_{SM} \qquad g^{hVV}_{C2HDM} = \cos\alpha_2\, \sin\beta\, g^{hVV}_{SM}$$

close to 1

$$g^{huu}_{C2HDM} = \left(\cos\alpha_2 \frac{\sin\alpha_1}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta}\gamma_5 \right) g^{hff}_{SM} \qquad g^{huu}_{C2HDM} = \left(\frac{\cos\alpha_2}{\sin\beta} - i \frac{\sin\alpha_2}{\tan\beta}\gamma_5 \right) g^{hff}_{SM}$$

small

$$g^{hbb}_{C2HDM} = \left(\cos\alpha_2 \frac{\cos\alpha_1}{\cos\beta} - i \sin\alpha_2\, \tan\beta\, \gamma_5 \right) g^{hff}_{SM} \qquad g^{hbb}_{C2HDM} = \left(-i \sin\alpha_2\, \tan\beta\, \gamma_5 \right) g^{hff}_{SM}$$

can be large

- Experiment tells us:

$$\frac{\sin\alpha_2}{\tan\beta} \ll 1 \qquad \textbf{but} \qquad \sin\alpha_2\, \tan\beta = \mathcal{O}(1)$$

Impact of New Experimental Data on the C2HDM

✦ C2HDM Analysis 2017: [Fontes,MM,Romao,Santos,Silva,Wittbrodt, JHEP 02 (2018) 073]

- ✏ 125 GeV Higgs signal strengths from the combination of ATLAS and CMS collected at 7 and 8 TeV
- ✏ HiggsBounds 4.3.1 for constraints from searches for additional scalars
- ✏ Electron EDM (eEDM) limit of 8.7×10^{-29} e.cm
- ✏ Lower bound of 580 GeV on the charged Higgs mass from B-meson decays in type II & Flipped models

✦ C2HDM Analysis 2024: [Biekötter,Fontes,MM,Romao,Santos,Silva, JHEP 05 (2024) 127]

- ✏ 125 GeV Higgs signal strengths from ATLAS and CMS w/ all run 2 data collected at 13 TeV
- ✏ HiggsBounds 5.7.1 for constraints from searches for additional scalars w/ all available LHC data
- ✏ Electron EDM (eEDM) limit of 1.1×10^{-29} e.cm (ACME) and 4.1×10^{-30} e.cm (JILA)
- ✏ Updated bounds on the charged Higgs mass from B-meson decays
- ✏ Impact of direct searches, in particular the one using angular correlations in decay planes of the tau-lepton in $h_{125} \to \tau^+\tau^-$ setting an upper limit on the pseudoscalar component of the tau Yukawa
  ⇝ strong impact on the analysis

* For C2HDM facing future EDM and collider tests, cf. talk by Y. Mao Tuesday afternoon.

2-Guise Yukawa-Couplings: hhb Coupling

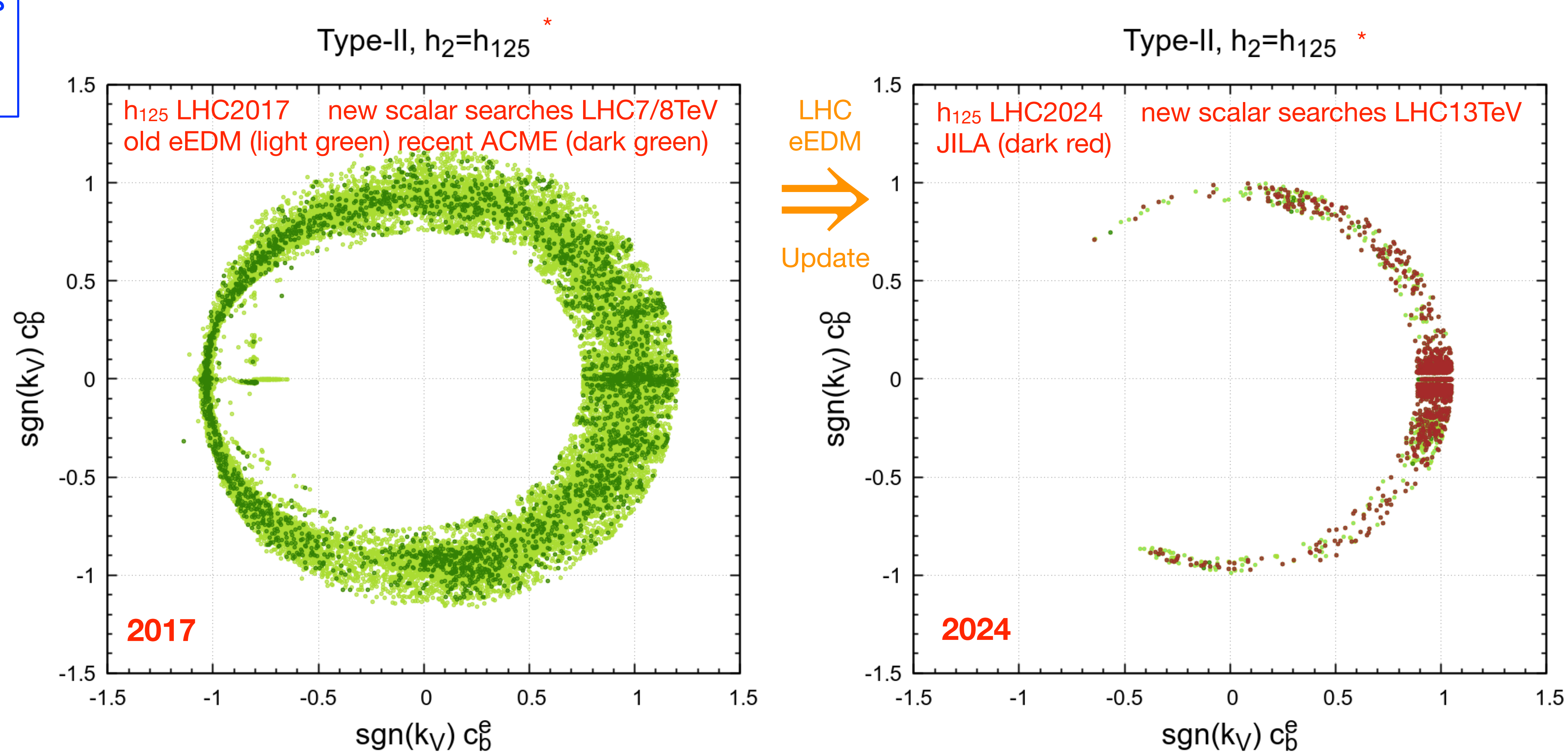
❖ Most 2-guise scenarios already excluded 2017: [Fontes,MM,Romao,Santos,Silva,Wittbrodt, JHEP 02 (2018) 073]

Type	I	II	LS	Flipped
$h_1 = h_{125}$	$\times$	$\times$	✓	✓
$h_2 = h_{125}$	$\times$	✓	✓	$\times$
$h_3 = h_{125}$	$\times$	$\times$	✓	$\times$

⇝ consider 2HDM type II with h_2 being SM-like Higgs

[Biekötter,Fontes,MM,Romao,Santos,Silva, JHEP 05 (2024) 127]

No constraints included from $h_{125} \to \tau^+\tau^-$

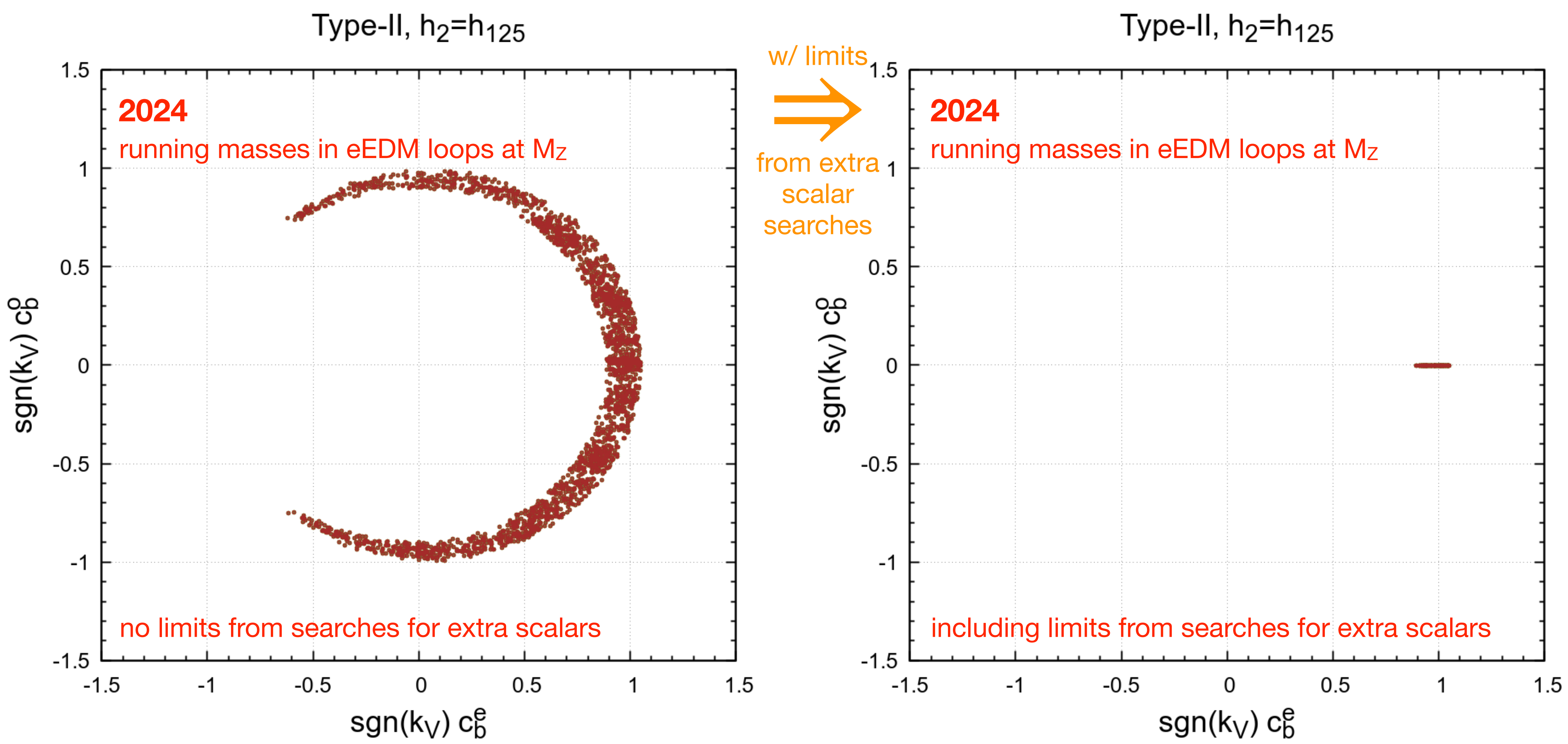


*OS top/tau masses and $\overline{m}_b(\overline{m}_b)$ in eEDM loops

Impact eEDM Scale Choice & Extra Scalar Searches

❖ Impact of the eEDMs: [Biekötter,Fontes,MM,Romao,Santos,Silva, JHEP 05 (2024) 127]

- Results crucially depend on significant fine-tuning of model parameters to achieve compatibility with stringent eEDM bounds
- Limits can be evaded only as a result of a cancellation between different contributions to the eEDM at 2-loop level in the perturbative expansion

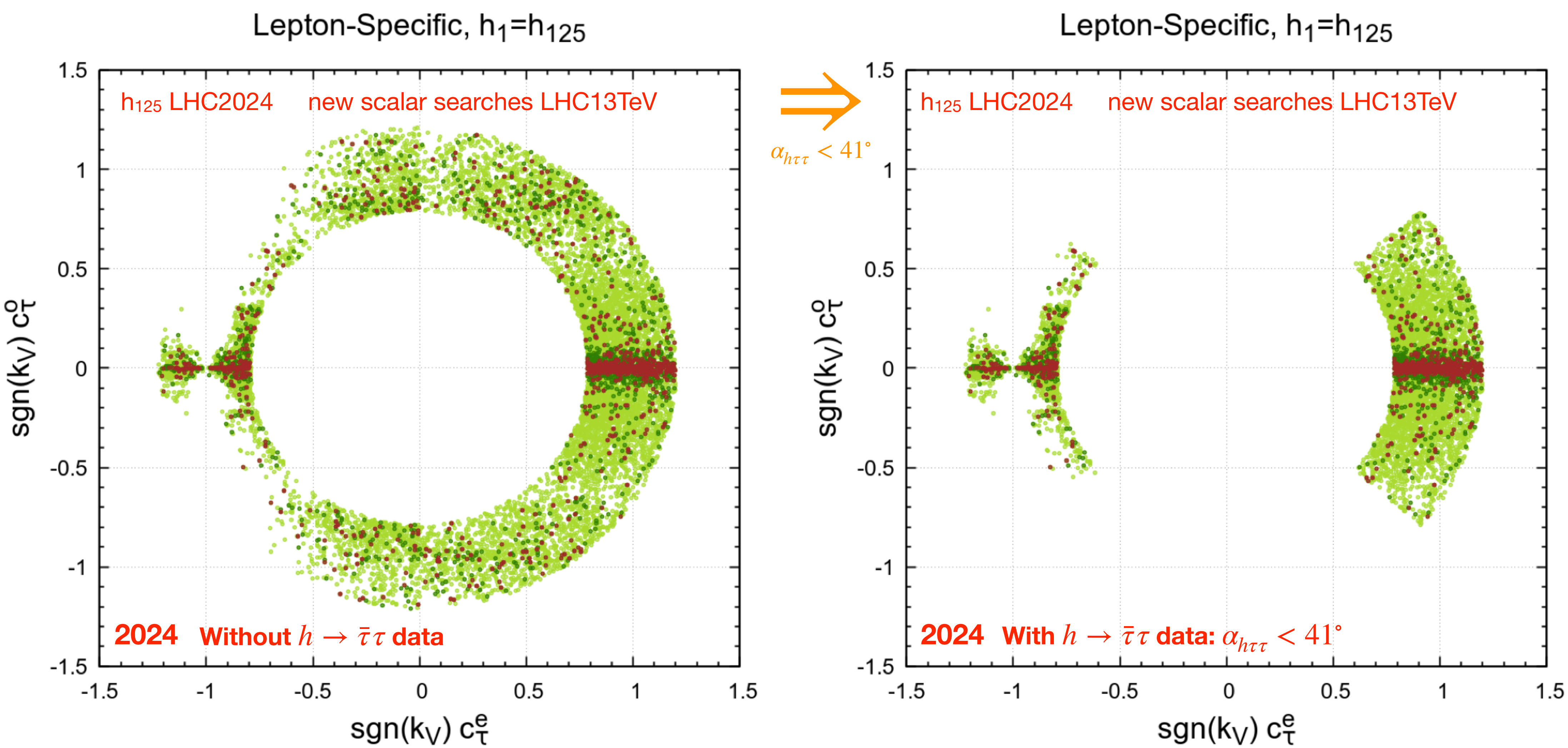


- Cancellation ⇝ strong dependence of predicted eEDM on model parameters, including mass values of virtual fermions in the loops of the Barr-Zee type diagrams

2-Guise Yukawa Couplings: LS - $h\bar{\tau}\tau$ Coupling

[Biekötter,Fontes,MM,Romao,Santos,Silva, JHEP 05 (2024) 127]

❖ 2HDM type LS with h_1 being SM-like Higgs



LHC (direct) experiments give us information beyond EDMs!

$|c^o_\tau| \gg |c^e_\tau|$ not allowed any more, but $|c^o_\tau| \approx |c^e_\tau|$ still possible

Conclusions on 2-Guise Yukawa Coupling-Scenario in 2024

❖ Situation 2017: [Fontes,MM,Romao,Santos,Silva,Wittbrodt, JHEP 02 (2018) 073]

Type	I	II	LS	Flipped
$h_1 = h_{125}$	×	×	✓	✓
$h_2 = h_{125}$	×	✓	✓	×
$h_3 = h_{125}$	×	×	✓	×

✓ large CP-odd component possible

× large CP-odd component not possible

❖ Situation 2024: Can we still find large CP-odd Yukawa couplings?

Type	I	II	LS	Flipped
$h_1 = h_{125}$	×	×	τ	<u>×</u>
$h_2 = h_{125}$	×	<u>×</u>	τ	×
$h_3 = h_{125}$	×	×	τ	×

Crosses ×: not possible to have a large CP-odd component;

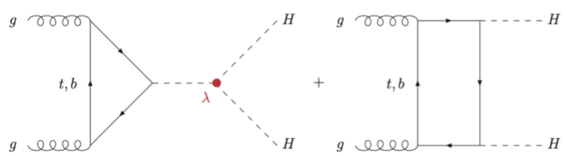
Notation τ: exclusion comes from the direct searches for CP-violation in $h \to \tau^+\tau^-$;

Underlined crosses <u>×</u>: refer to scenarios that were previously allowed.

CP-Violating Effects on Higgs Pair Production

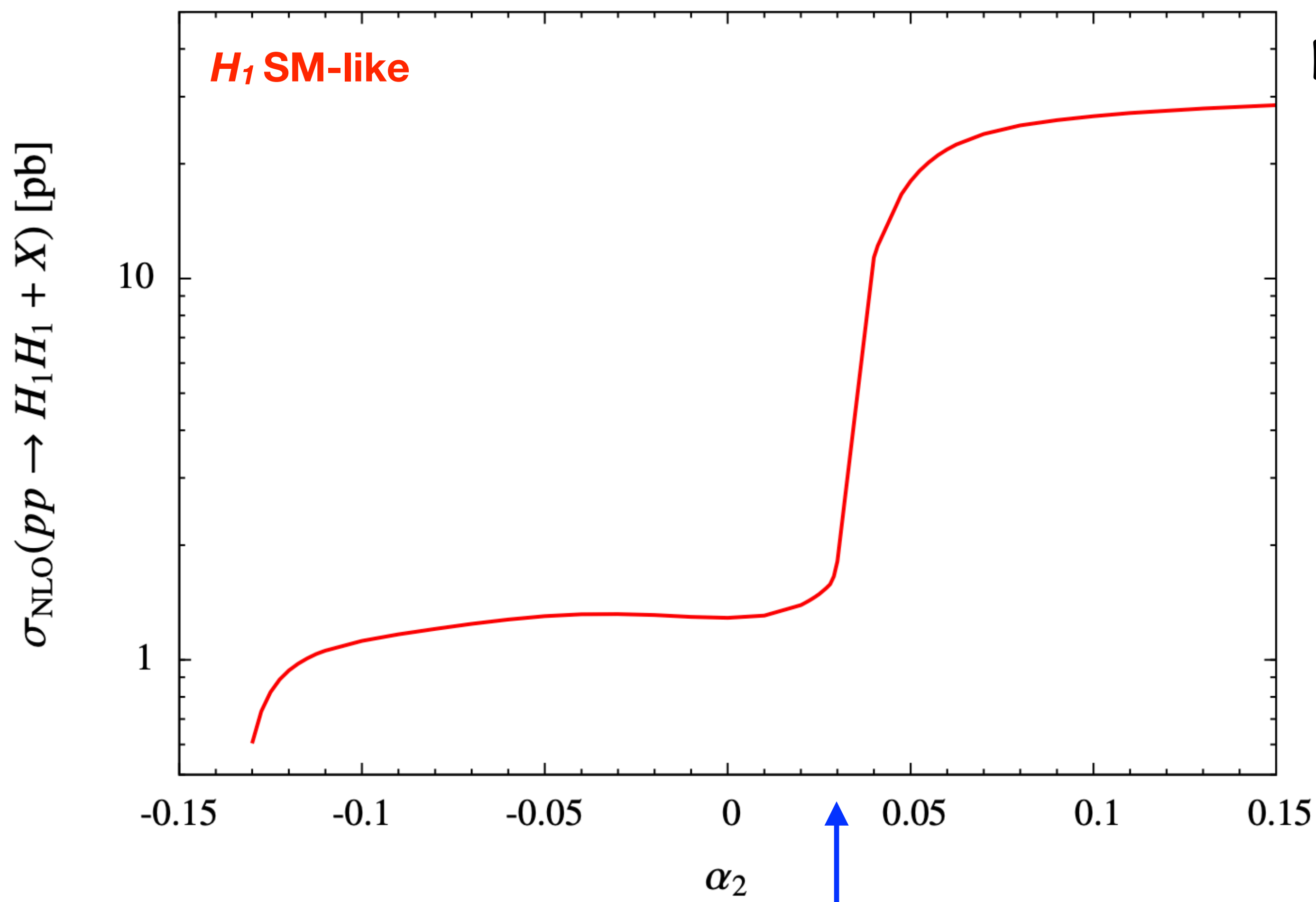
- C2HDM with H_1 SM-like: (eEDM@2017 included)

$$\alpha_1 = 0.853\,,\ \alpha_2 = -0.103\,,\ \alpha_3 = 0.0072\,,\ \tan\beta = 0.969\,,\ \mathrm{Re}(m_{12}^2) = 70957\ \mathrm{GeV}^2$$
$$m_{H_1} = 125\ \mathrm{GeV}\,,\ m_{H_2} = 377.6\ \mathrm{GeV}\,,\ m_{H^\pm} = 709.7\ \mathrm{GeV}\,,$$



[Gröber,MM,Spira,'17]

NLO QCD corrections in heavy top-limit included



SM reference value (NLO QCD heavy top-limit): 38.2 fb

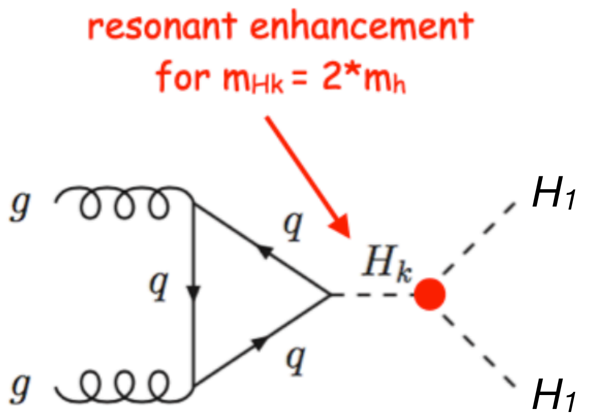
m_{H2} as function of α_2 drops below $t\bar{t}$ threshold

⇝ main decay channel into H_1H_1 ⇝ large resonant enhancement

CP-Violating Effects on Higgs Pair Production

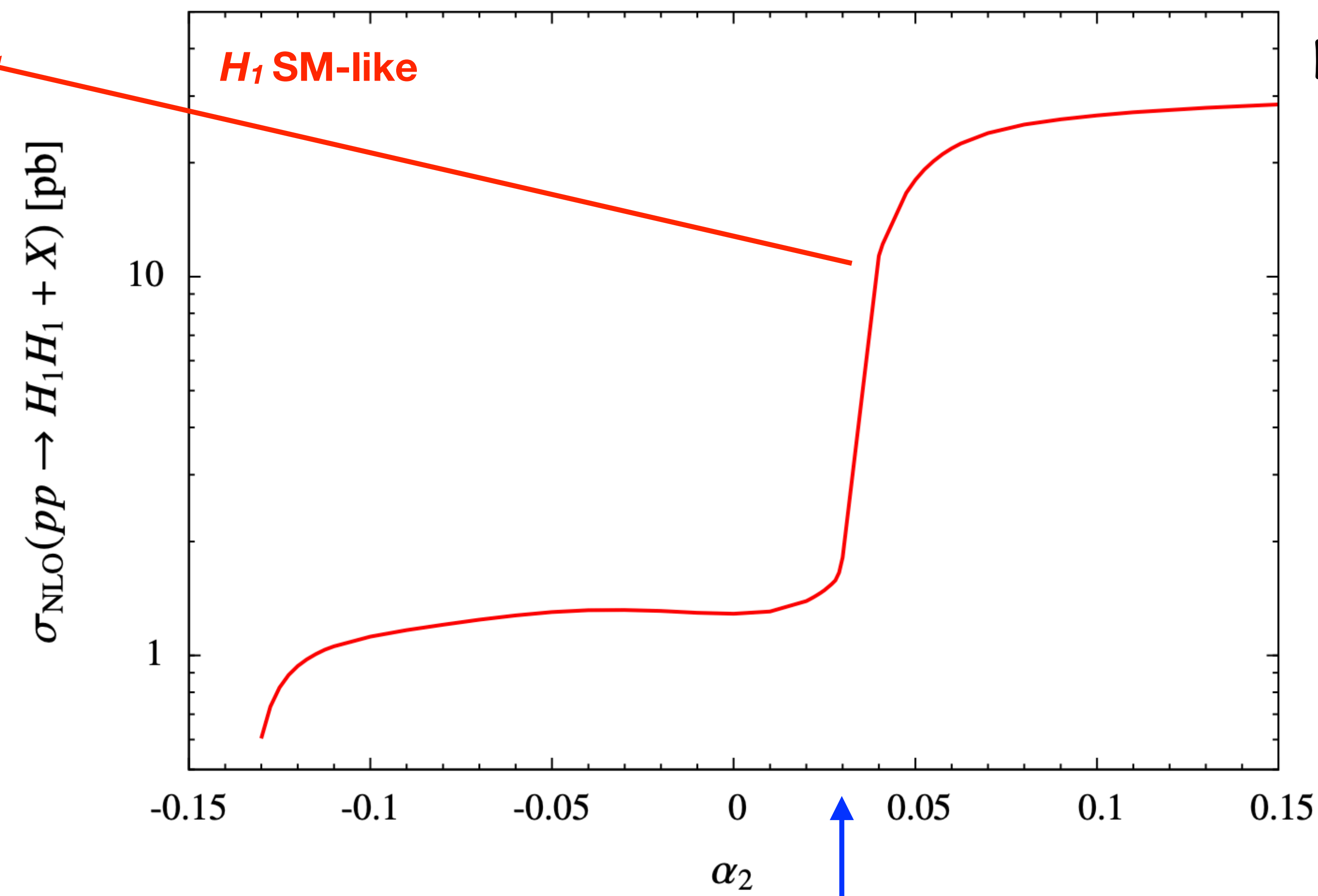
- C2HDM with H_1 SM-like: (eEDM@2017 included)

$$\alpha_1 = 0.853\,,\ \alpha_2 = -0.103\,,\ \alpha_3 = 0.0072\,,\ \tan\beta = 0.969\,,\ \mathrm{Re}(m_{12}^2) = 70957\ \mathrm{GeV}^2$$
$$m_{H_1} = 125\ \mathrm{GeV}\,,\ m_{H_2} = 377.6\ \mathrm{GeV}\,,\ m_{H^\pm} = 709.7\ \mathrm{GeV}\,,$$



SM reference value (NLO QCD heavy top-limit): 38.2 fb

[Gröber,MM,Spira,'17]



NLO QCD corrections in heavy top-limit included

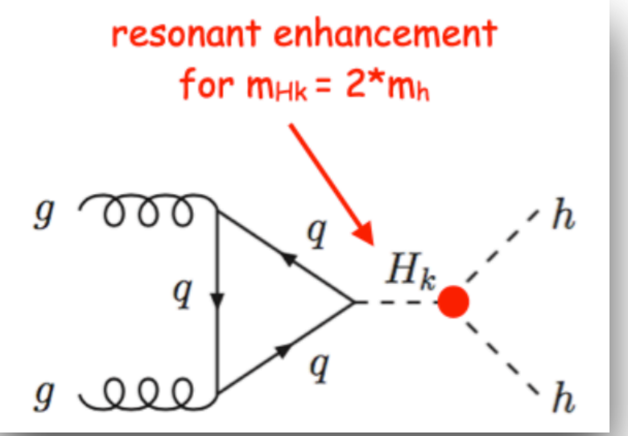
m_{H2} as function of α_2 drops below $t\bar{t}$ threshold

⇝ main decay channel into H_1H_1 ⇝ large resonant enhancement

Maximum Resonant Di-Higgs Production 2021

❖ Maximum SM-like Higgs pair production from **resonant** heavy Higgs production: after applying all relevant theoretical and experimental constraints (including di-Higgs constraints)

[Abouabid,Arhrib,Azevedo,El Falaki,Ferreira,MM,Santos,´21]



in fb	H_1	H_2
R2HDM-I	444	n.a.
R2HDM-II	81	n.a.
C2HDM-I	387	47
C2HDM-II	130	–
N2HDM-I	376	344
N2HDM-II	188	63
NMSSM	183	65

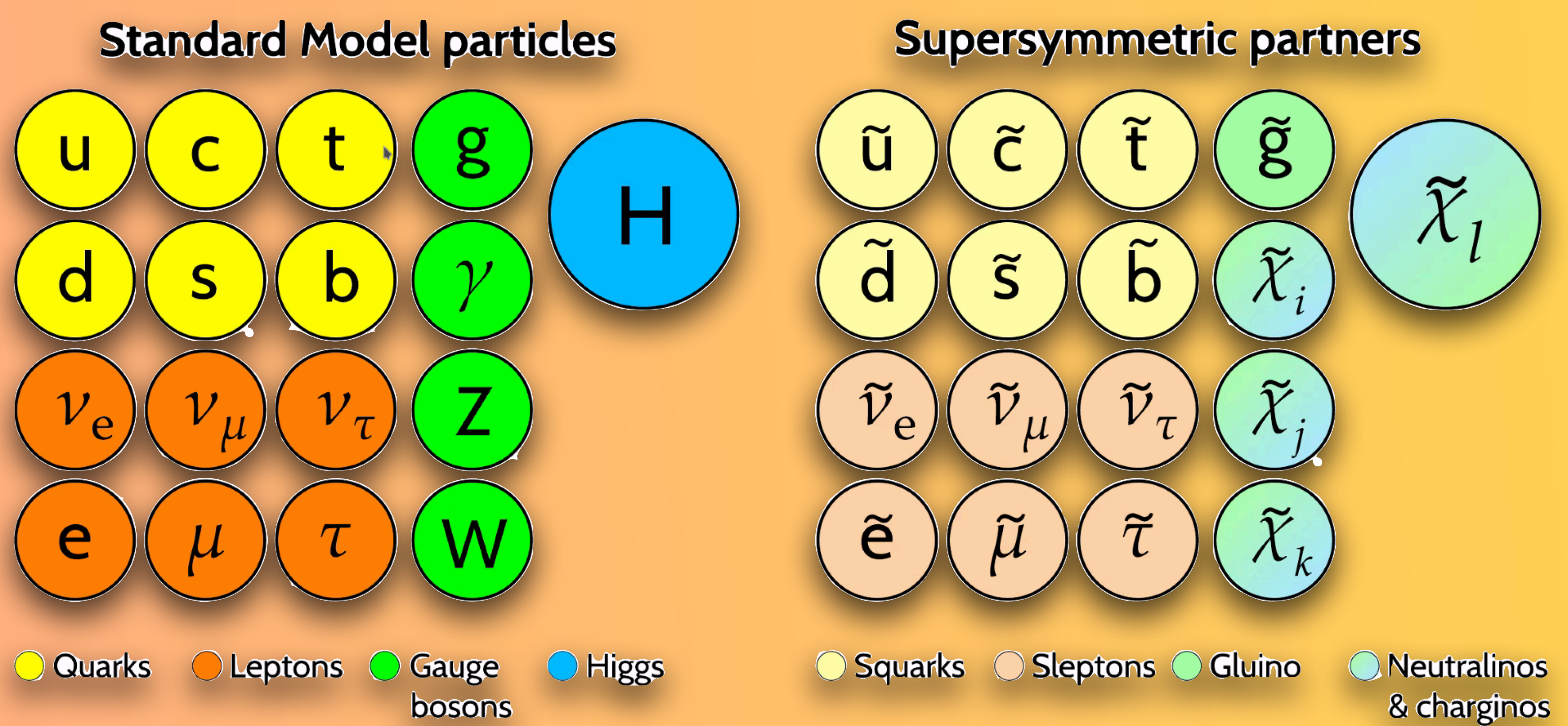
<- SM-like Higgs

SM Cross Section (NLO QCD, heavy top limit): 38 fb

max. enhancement (R2HDM-I): non-resonant: 1.2, resonant: 10.2

* For NLO QCD corrections w/ full mtop, cf. talk by M. Spira Wednesday afternoon.

CP-Violation in Supersymmetric NP Extension



Tree-Level CP-Violation in the Higgs Sector

❖ Minimal Supersymmetric Extension (MSSM): two complex Higgs doublets (type II 2HDM)
Minimum condition precludes CP-violating phase in the tree-level Higgs sector*

$$\mathcal{M}_{\phi^0\zeta^0} = \begin{pmatrix} 0 & m_{12}^2 \sin(\xi) \\ -m_{12}^2 \sin(\xi) & 0 \end{pmatrix} \qquad t_{\zeta_1^0} = -\frac{v_1}{v_2} t_{\zeta_2^0} = \sqrt{2} m_{12}^2 v_2 \sin(\xi) \overset{!}{=} 0$$

❖ Next-to-Minimal Supersymmetric Extension (NMSSM): two complex Higgs doublets + complex singlet
Tree-level CP-violation in Higgs sector possible

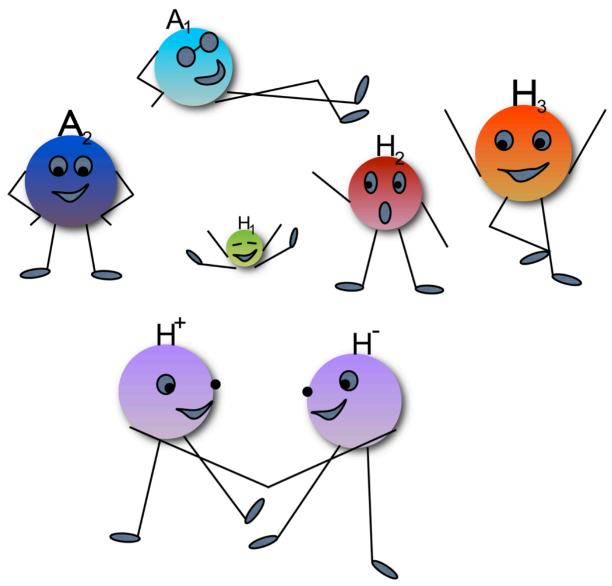
*While tree-level CP-violation in the Higgs sector is not possible, there is radiatively induced CP-violation which impacts the Higgs (and other) observables.

The CP-Violating NMSSM Higgs Sector

- The Higgs spectrum: two doublets H_u,H_d plus complex singlet S ⇝ after EWSB

CP-conserving (CPC): 3 CP-even Higgs bosons H_i (i=1,2,3),
2 CP-odd Higgs boson A_j (j=1,2),
2 charged H^+,H^-

CP-violating (CPV): 5 CP-mixing Higgs bosons H_k (k=1,…,5),
2 charged Higgs bosons H^+, H^-



- Tree-Level CP-Violating Phase:

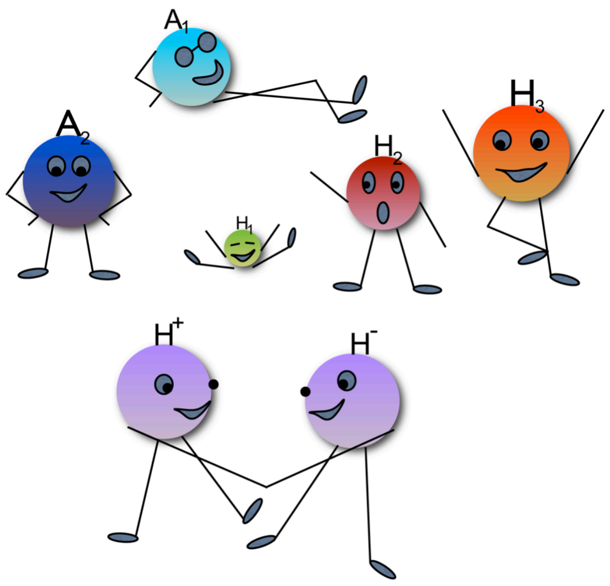
$$\varphi_y = \varphi_\kappa - \varphi_\lambda + 2\varphi_s - \varphi_u$$

CP-violating mixing in the Higgs mass matrix is proportional to $\sin\varphi_y$

- Higher-Order Corrections to Higgs Masses: required to shift SM-like mass to 125 GeV

CP-violating phases independent of each other, CP-violating phases from all other sectors (electroweakino, sfermion) enter

Spectrum Calculator NMSSMCALC



NMSSMCALC

Calculator of One-Loop and
$O(\alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2)$ Two-Loop
Higgs Mass Corrections
and of Higgs Decay Widths
in the CP-conserving and the CP-violating NMSSM

Higgs masses in the CP-violating high-scale NMSSM
based on EFT pole-mass and quartic-coupling matching
at one-loop order and MSSM-limit 2-loop order

Computation of the Loop-Corrected Effective Higgs Self-Couplings
and the Loop-Corrected Higgs-to-Higgs Decays
up to $O(\alpha_t \alpha_s + \alpha_t^2)$

Computation of the muon anomalous magnetic moment and the electric dipole moment

Computation of the ϱ parameter up to $O(\alpha + \alpha_t \alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\varkappa)^2)$;
W-mass prediction in the SM, at 1-loop NMSSM, 2-loop QCD NMSSM, 2-loop EW NMSSM

New: Higgs masses in the CP-violating high-scale NMSSM
based on EFT pole-mass and quartic-coupling matching
at one-loop order and MSSM-limit 2-loop order

Authors: Julien Baglio, Christoph Borschensky, Thi Nhung Dao, Martin Gabelmann, Ramona Gröber, Marcel Krause, Duc Ninh Le, Margarete Mühlleitner, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz

Program: NMSSMCALC version 5.3 NEW! Higgs mass predictions in the CP-violating NMSSM based on EFT pole-mass and quartic-coupling matching - 26 June 2024.

Program Extension: NMSSMCALCEW which includes the SUSY-EW and SUSY-QCD corrections to the decay widths and branching ratios. Information and download at: webpage of NMSSMCALCEW.

Web page: https://www.itp.kit.edu/~maggie/NMSSMCALC/

CP-Violating Effects on Masses/Couplings/Decays

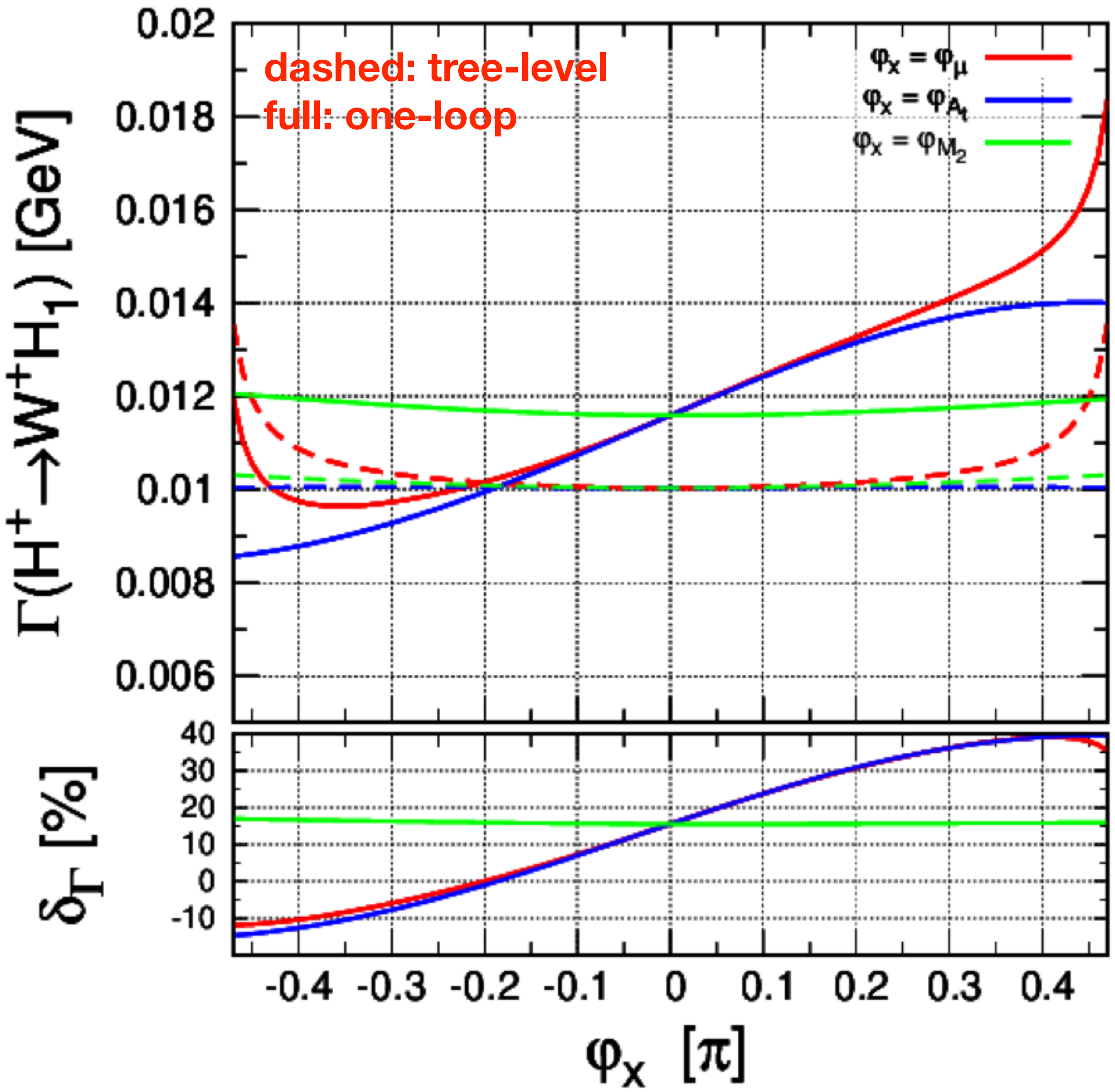
Note: no constraints from EDMs included here

tree-level dependence on φ_x ($x=\mu, A_t, M_2$):

φ_x-dependent HO corrections to m_{H_1}

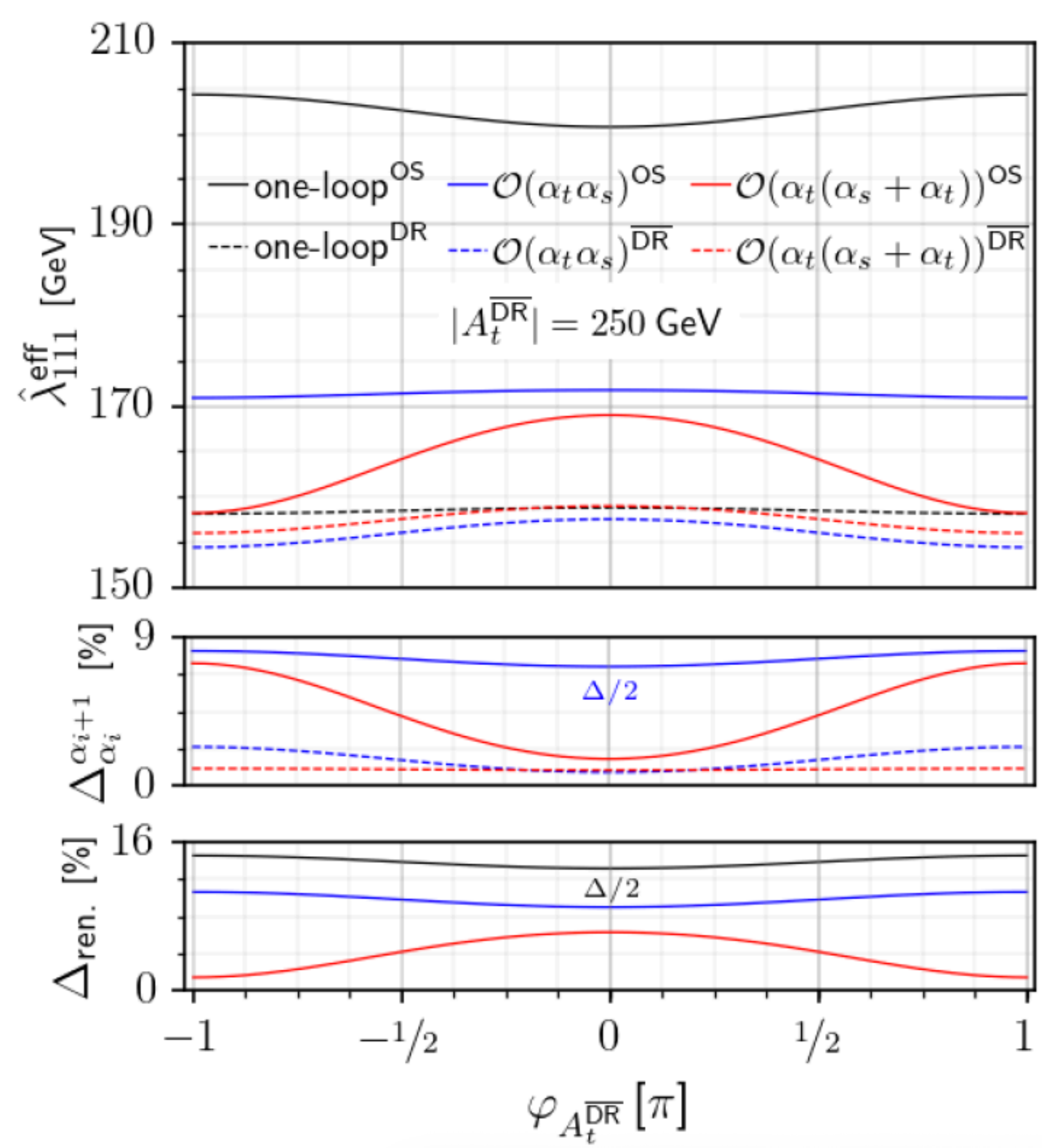
δ_Γ: size of relative 1-loop correction

[Dao,MM,Patel,Sakurai,'20]



H_1 SM-like Higgs; loop-corrected Higgs self-coupling as a function of φ_{A_t} of $A_t = |A_t| \exp(i\, \varphi_{A_t})$

[Borschenschky,Dao,Gabelmann,MM,Rzehak,'22]



* For precision predictions of λ_{3H}, cf. talk by M. Gabelmann Friday afternoon.

CP-Violation and Baryon Asymmetry

Electroweak Baryogenesis

- **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

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

* For viable model for ν, DM & EWBG, cf. talk by S.Kanemura Tuesday afternoon.

The Model „CP in the Dark“

- Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,Wittbrodt,'18]

  one exact $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$

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

CP-violating portal term

CP-conserving portal terms

- General vacuum structure at T=0: no VEVs for Φ_2, Φ_S ⇝ 3 particles in the dark sector

$$\langle\Phi_1\rangle|_{T=0} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}\,,\ \langle\Phi_2\rangle|_{T=0} = \begin{pmatrix}0\\0\end{pmatrix}\,,\ \langle\Phi_S\rangle|_{T=0} = 0$$

$\omega_1|_{T=0\text{ GeV}} = v1 \equiv v = 246.22$ GeV

- General vacuum structure at T≠0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_1 + i\eta_1\\ \zeta_1 + \omega_1 + i\Psi_1\end{pmatrix}\,,\ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_2 + \omega_{CB} + i\eta_2\\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{CP})\end{pmatrix}\,,\ \Phi_S = \zeta_S + \omega_S$$

electroweak VEVs: ω_1, ω_2 , CP-violating VEV: ω_{CP}

charge-breaking VEV: ω_{CB} (unphysical; found to be zero for all of our scan points)

Z_2-symmetry breaking VEV: ω_S

The Model „CP in the Dark“

- Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,Wittbrodt,'18]
  one exact $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$

$$V^{(0)} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + \text{ h.c.}\right)$$

CP-violating portal term

$$+ \frac{\lambda_1}{2}|\Phi_1| \ldots + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

$$+ \frac{\lambda_6}{4}\Phi_S^4 + \ldots$$

CP violation purely in the dark sector
⇝ not constrained
by electric dipole moment

- General vacuum structure at T=0: no VEVs for Φ_2, Φ_3 ⇝ 3 DM candidates

$$\langle\Phi_1\rangle|_{T=0} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \ \langle\Phi_2\rangle|_{T=0} = \begin{pmatrix}0\\ 0\end{pmatrix}, \ \langle\Phi_S\rangle|_{T=0} = 0$$

$\omega_1|_{T=0\,\text{GeV}} = v1 \equiv v = 246.22$ GeV

- General vacuum structure at T≠0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_1 + i\eta_1\\ \zeta_1 + \omega_1 + i\Psi_1\end{pmatrix}, \ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\rho_2 + \omega_{CB} + i\eta_2\\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{CP})\end{pmatrix}, \ \Phi_S = \zeta_S + \omega_S$$

electroweak VEVs: ω_1, ω_2 , CP-violating VEV: ω_{CP}

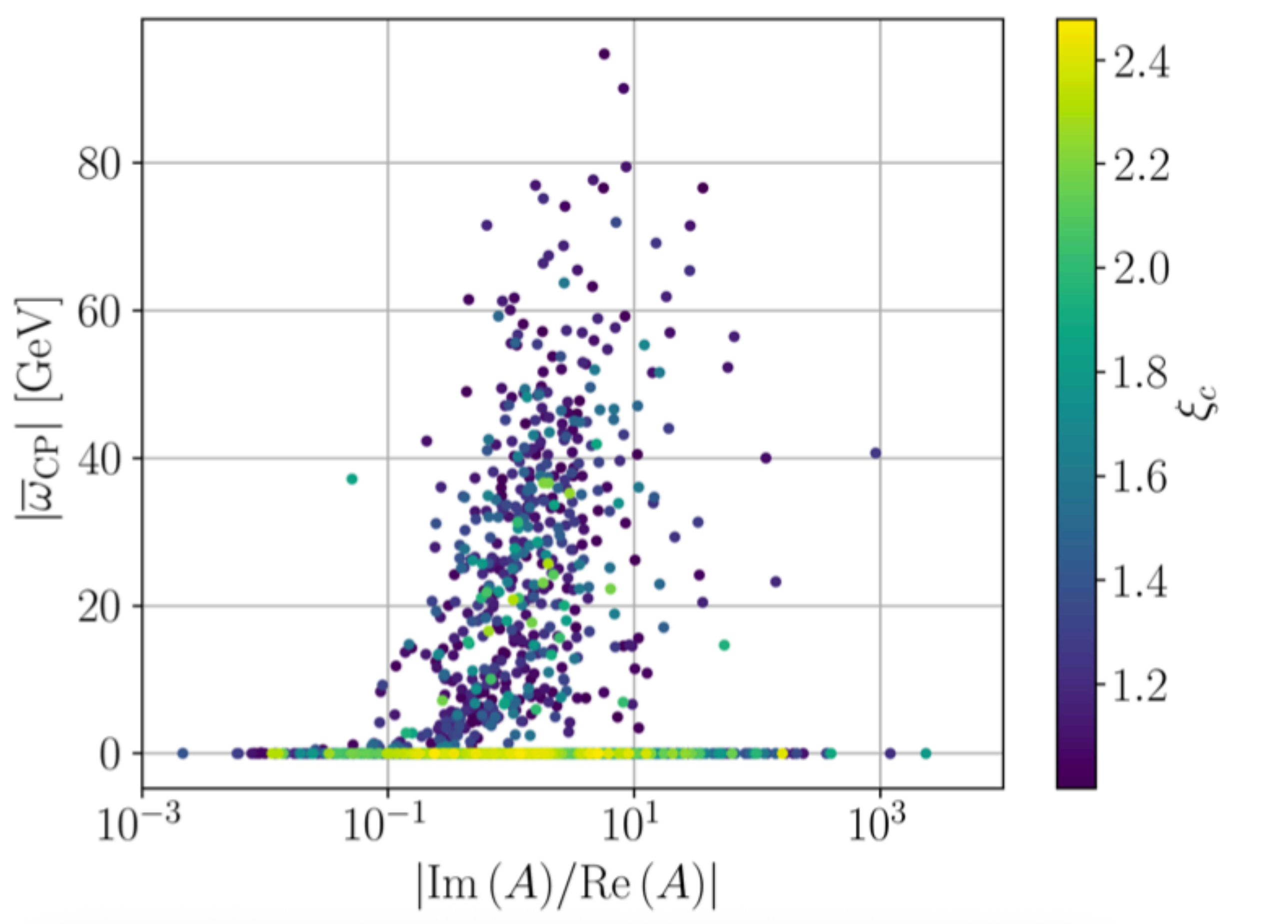
charge-breaking VEV: ω_{CB} (unphysical; found to be zero for all of our scan points)

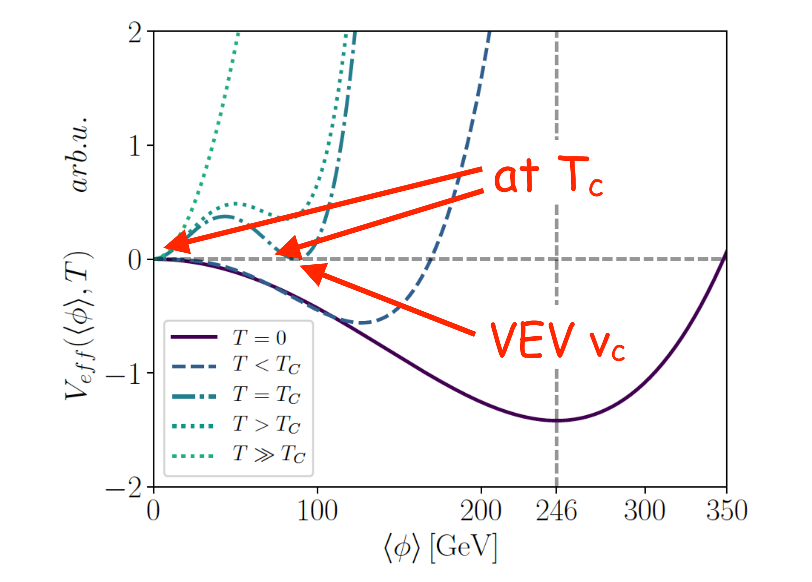
Z2-symmetry breaking VEV: ω_S

Spontaneous CP Violation

[Biermann,MM,Müller,'22] [Biermann,MM,Santos,Viana,'24]

CP-Violation in Dark Sector: at T=0 unconstrained by EDMs!





$$\xi_c \equiv \frac{v_c}{T_c} \geq 1$$

- possibility of SFOEWPT & spontaneous CP violation (CPV)
- spontaneous $\mathbb{Z}_2$ violation also possible
  => non-standard CPV transferred to visible sector
- interesting for EWBG!

* For spontaneous CPV by a scalar singlet, cf. talk by F. Joaquim Tuesday afternoon.

Conclusions

- Sizable CP-Violation:
  - clear sign of BSM physics; required for EWBG
- Measuring CP-Violation in the Higgs sector:
  - Combination of Higgs-to-Scalar Decays
  - Angular distributions, CP-sensitive observables in Higgs production/decay
  - Measurement of CP-violating Yukawa couplings
  - Caveat: Combination of measurements required to unambiguously identify CP-violation (2-guise Yukawa couplings, misidentification of CPV/CPC)
- CP-Violation in supersymmetry:
  - Large number of CP-violating phases
  - NMSSM allows for tree-level CP-violation in the Higgs sectors
  - Masses/trilinear couplings affected by CP-violation (tree-level, radiatively induced)
- CP-Violation and EWBG
  - Sizable CP-violation required, conflict w/ EDMs
  - Nice way out: CP-violation in Dark Sector

CP-Violation appears in many different guises
⇝ Creativity required both on Exp and Th side to identify unambiguously CP-violation


Thank you for your attention!

Test of CP-Violation in „CP in the Dark“

CP-Violation in Loops

❖ Another possibility to detect P-even CP-violating signals: through loops

❖ Remember detection through combination of decays:

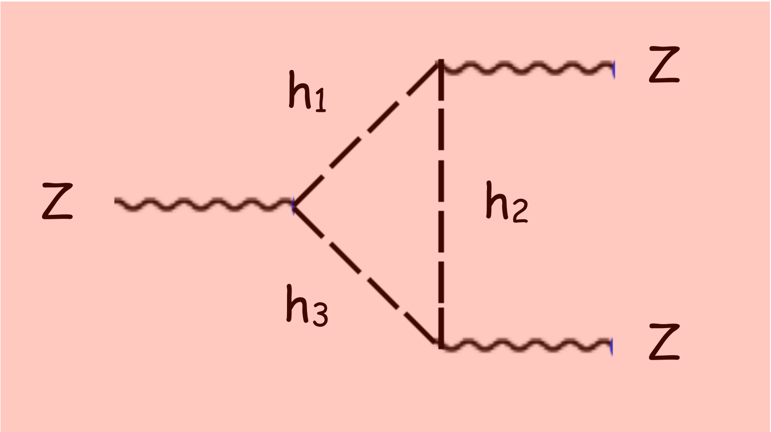
$$h_2 \to h_1 Z \quad CP(h_2) = -\,CP(h_1)$$

$$h_3 \to h_1 Z \quad CP(h_3) = -\,CP(h_1)$$

$$h_3 \to h_2 Z \quad CP(h_3) = -\,CP(h_2)$$

In case of no access to decays: build Feynman diagram with the same vertices:

And see if it is possible to extract information from the measurement of the triple ZZZ anomalous coupling:



Can we build such a model?

Test of CP Violation in „CP in the Dark“

- How can we test CP violation? Look at the vertex ZZZ <- CP-violation from C-violation inside loops

$$i\Gamma_{\mu\alpha\beta} = -\, e\frac{p_1^2 - m_Z^2}{m_Z^2}\, f_4^Z\,(g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

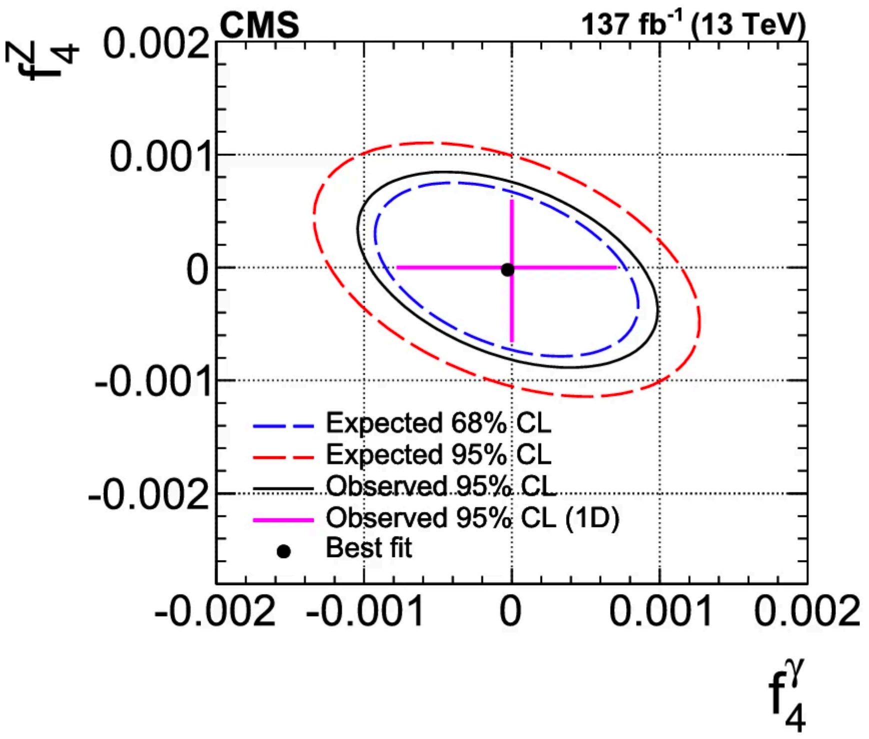
[Gaemers,Gounaris,'79;Hagiwara,Peccei, Zeppenfeld,Hikasa,'87;Grzadkowski, Ogreid,Osland,'16]

[CMS Collaboration, EPJC78 (2018) 165]

$$-1.2\times 10^{-3} < f_4^Z < 1.0\times 10^{-3}$$

[ATLAS Collaboration, PRD97 (2018) 032005]

$$-1.5\times 10^{-3} < f_4^Z < 1.5\times 10^{-3}$$



[CMS Collaboration, EPJC81 (2021) 200]

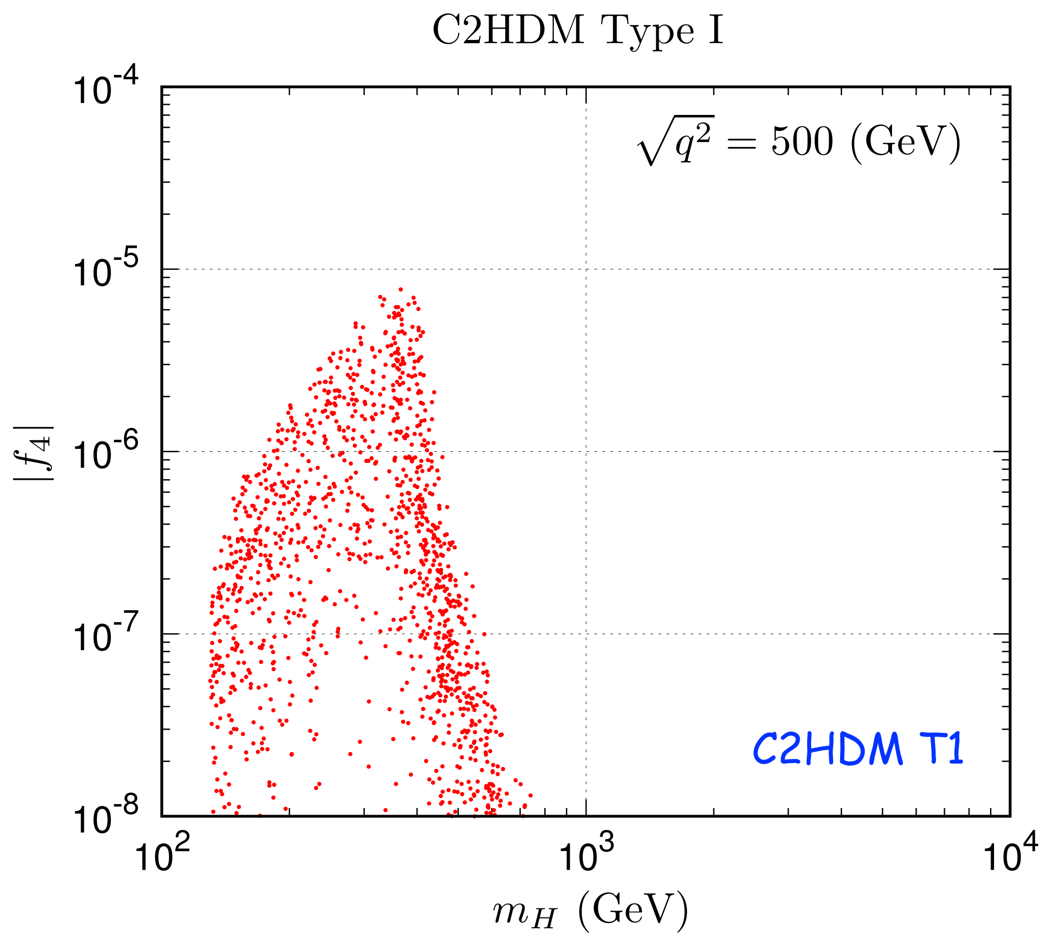
Test of CP Violation in „CP in the Dark"

- How can we test CP violation? Look at the vertex ZZZ <- CP-violation from C-violation inside loops

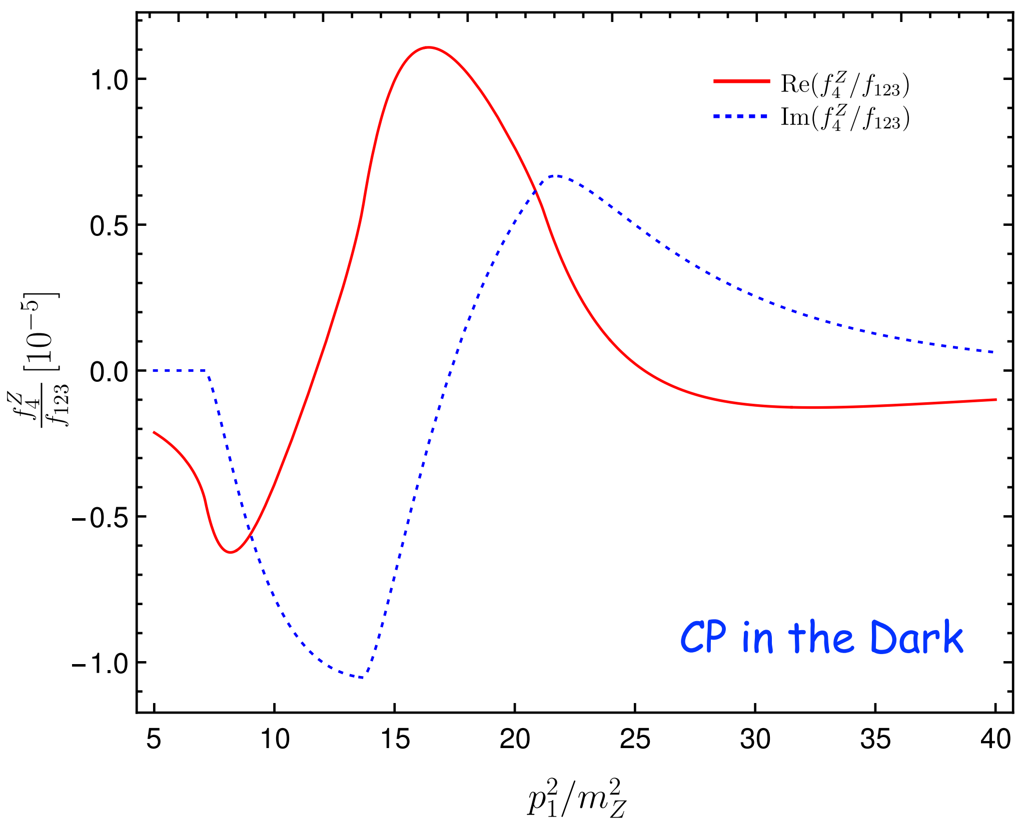
$$i\Gamma_{\mu\alpha\beta} = -\,e\frac{p_1^2 - m_Z^2}{m_Z^2}\, f_4^Z\,(g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

[Gaemers,Gounaris,'79;Hagiwara,Peccei, Zeppenfeld,Hikasa,'87;Grzadkowski, Ogreid,Osland,'16]

[Belusca-Maito,Falkowski,Fontes,Romao,Silva, JHEP04 (2018) 002]



[Azevedo,Ferreira,MM,Patel,Santos, Wittbrodt,JHEP11(2018)091]



Test of CP Violation in „CP in the Dark“

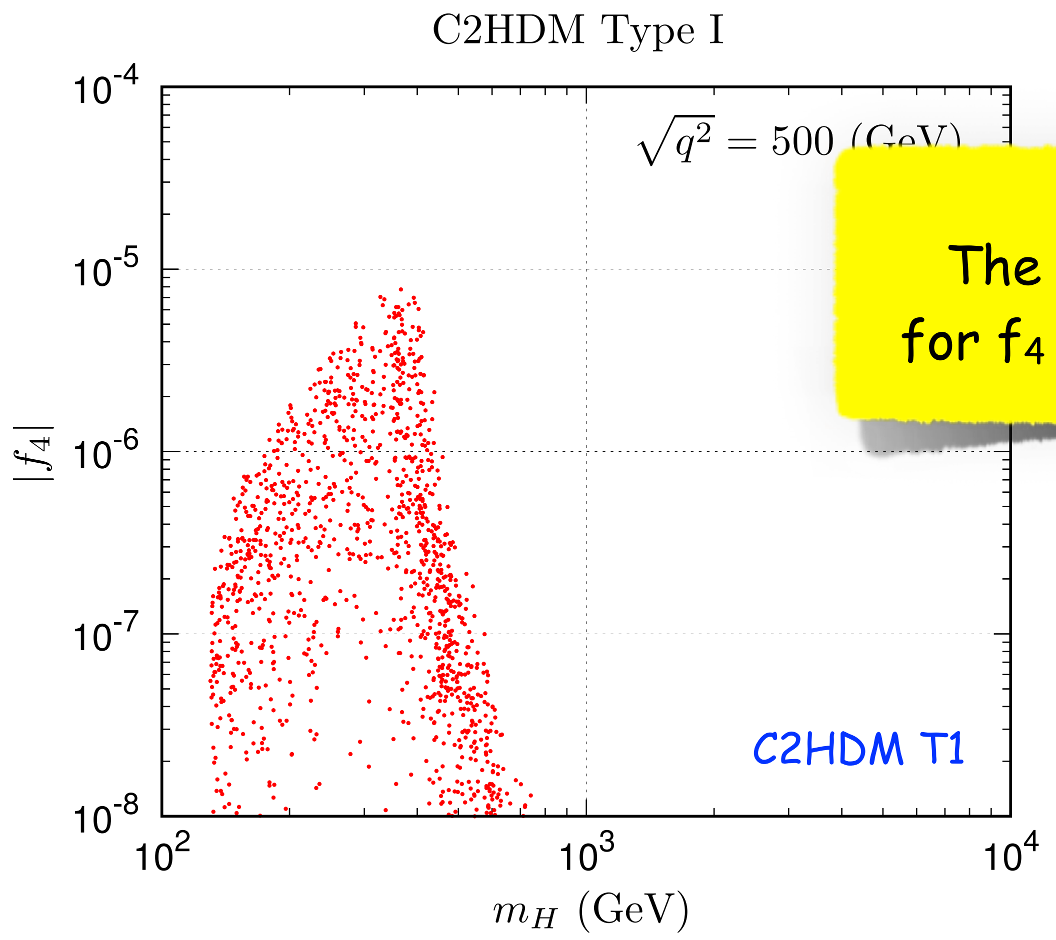
- How can we test CP violation? Look at the vertex ZZZ <- CP-violation from C-violation inside loops

$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

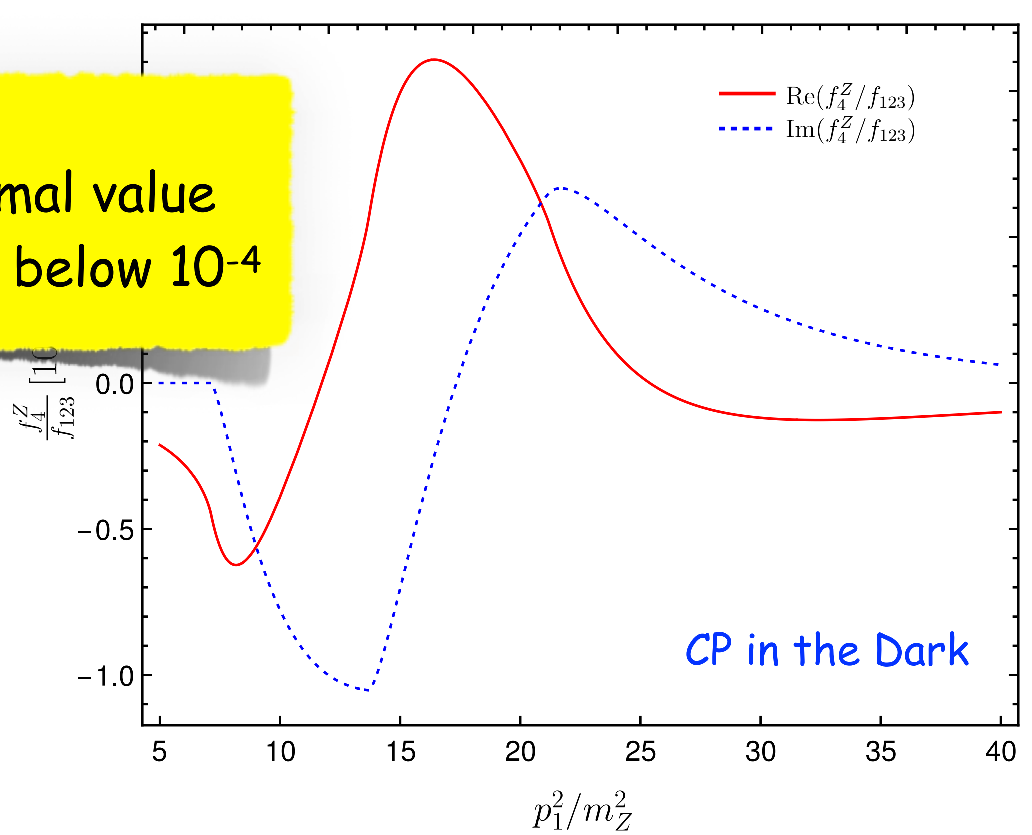
[Gaemers,Gounaris,'79;Hagiwara,Peccei, Zeppenfeld,Hikasa,'87;Grzadkowski, Ogreid,Osland,'16]

[Belusca-Maito,Falkowski,Fontes,Romao,Silva, JHEP04 (2018) 002]

[Azevedo,Ferreira,MM,Patel,Santos, Wittbrodt,JHEP11(2018)091]



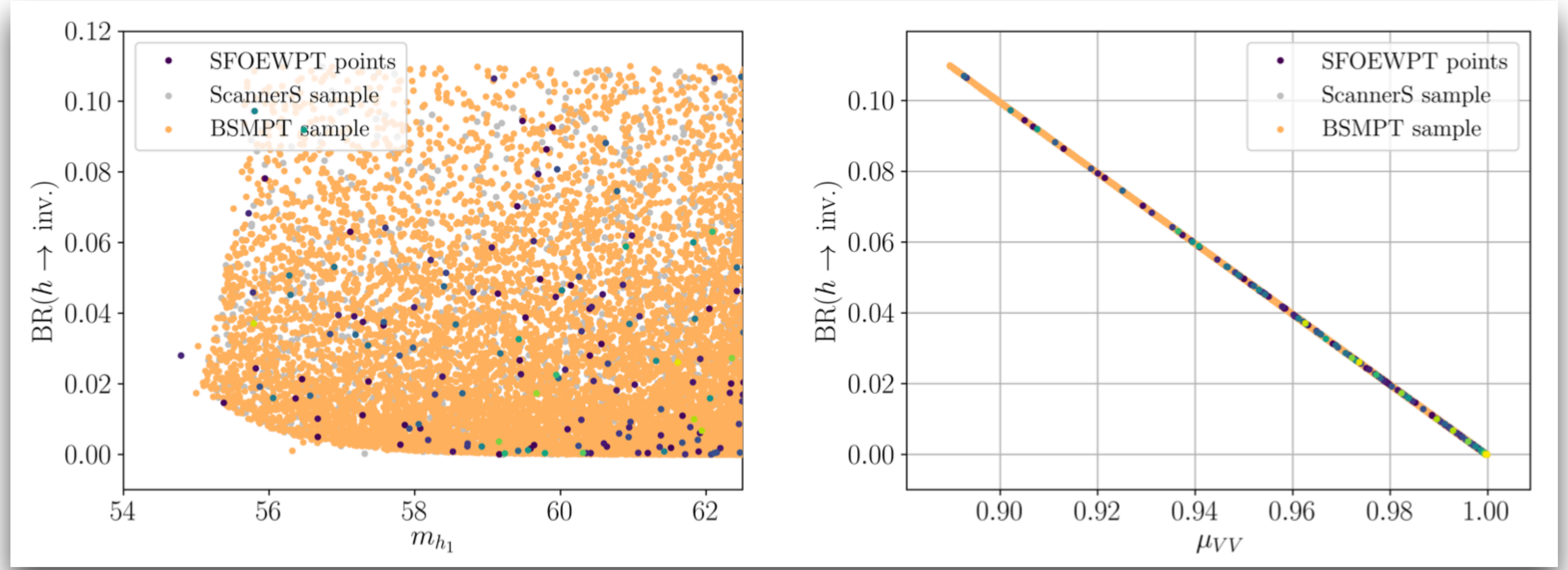
The typical maximal value for f_4 seems to be below 10^{-4}



DM Observables and LHC Observables in „CP in the Dark“

Higgs-to-Invisible Decay

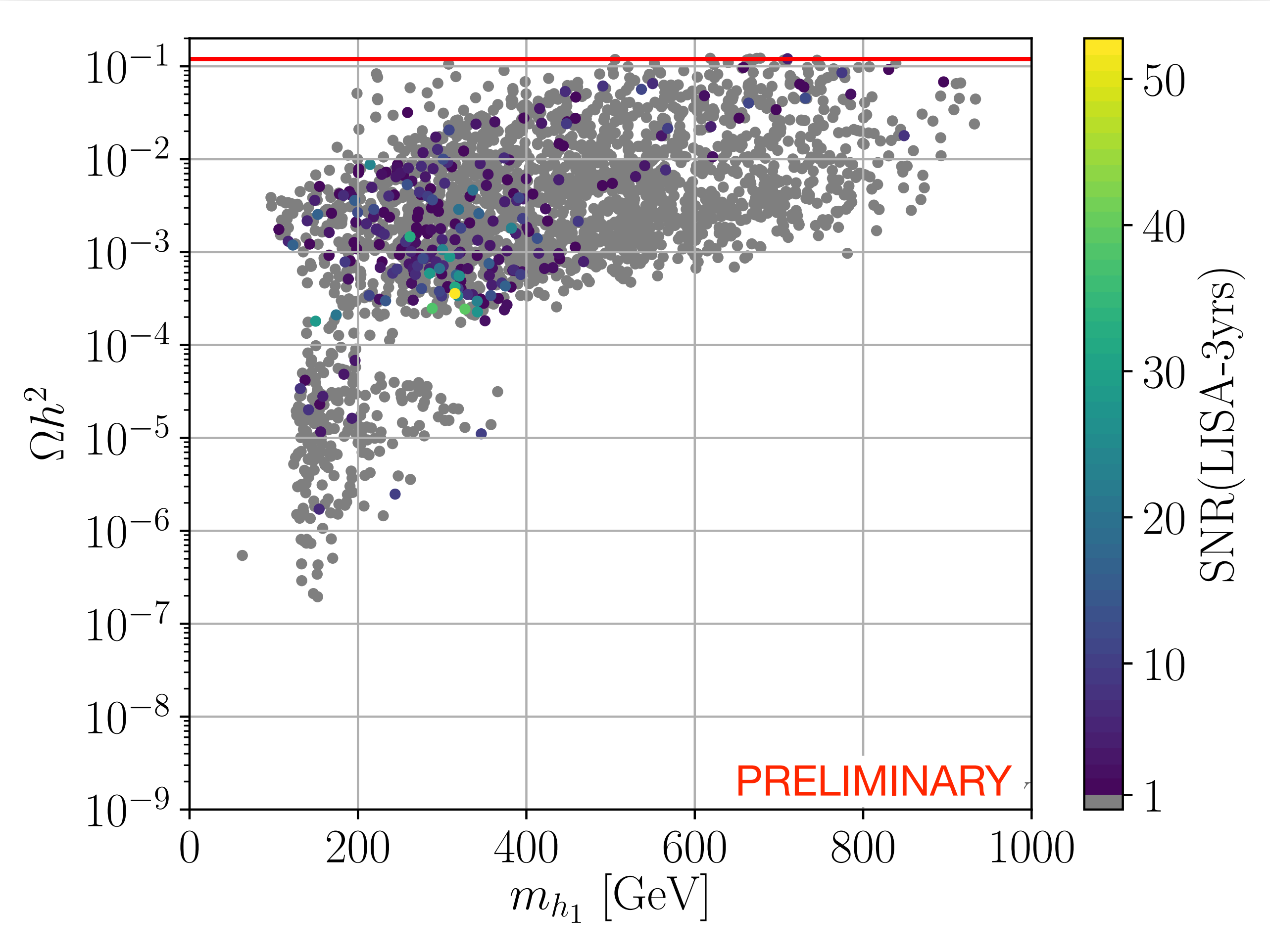
[Biermann,MM,Müller,'22]

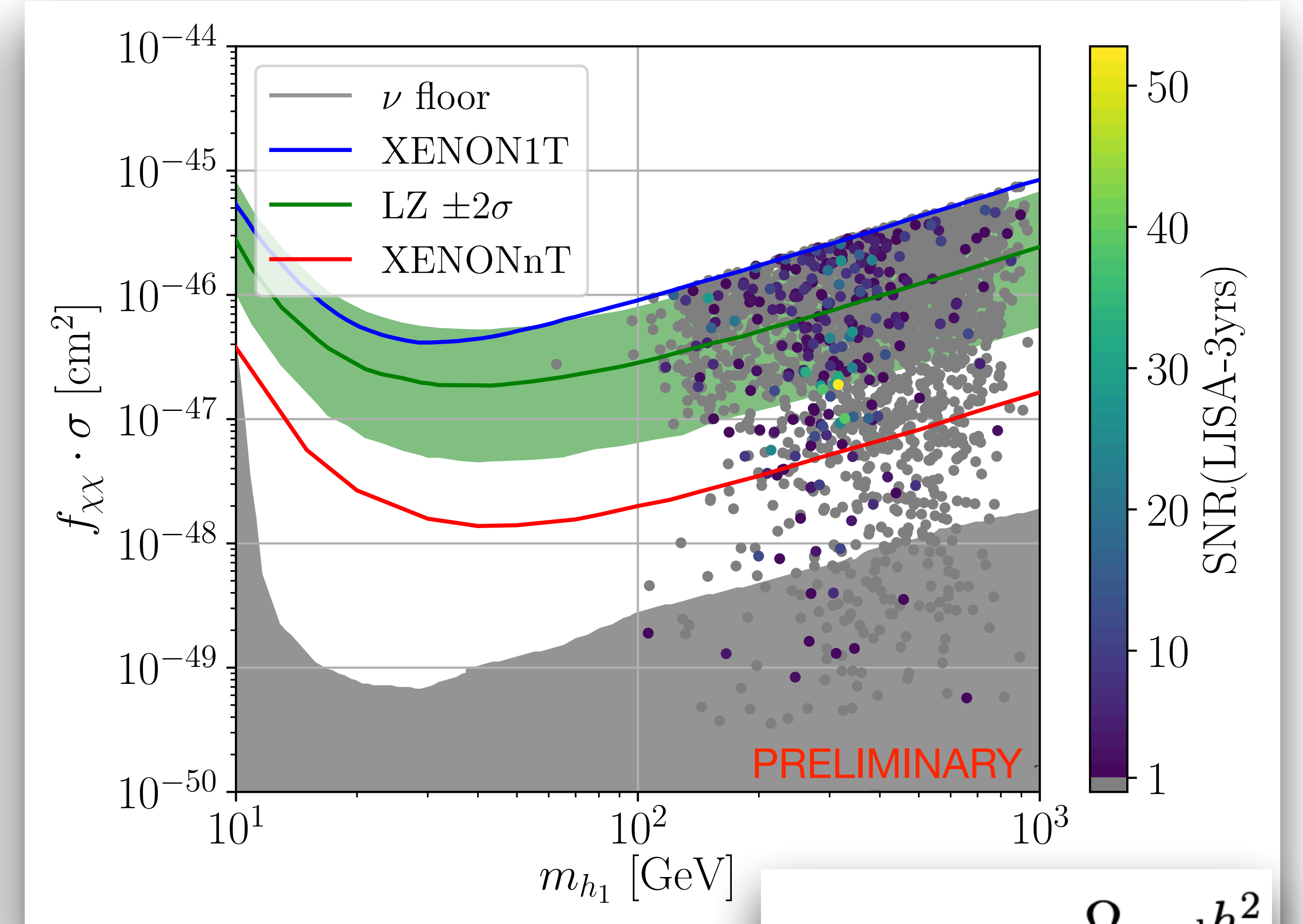


- SFOEWPT points scattered across allowed ScannerS parameter space
- BR(h->inv) strongly correlated w/ μ_{VV} ($V=W^\pm,Z$): for μ_{VV}->1 SM-like Higgs BRs converge to SM values ⇝ BR(h->inv) forbidden =>
- future increased precision in BR(h->inv) and μ_{VV} constrain parameter space, however, no further insights in strength of EWPT gained

DM Observables and GW

[Biermann,MM,Santos,Viana]

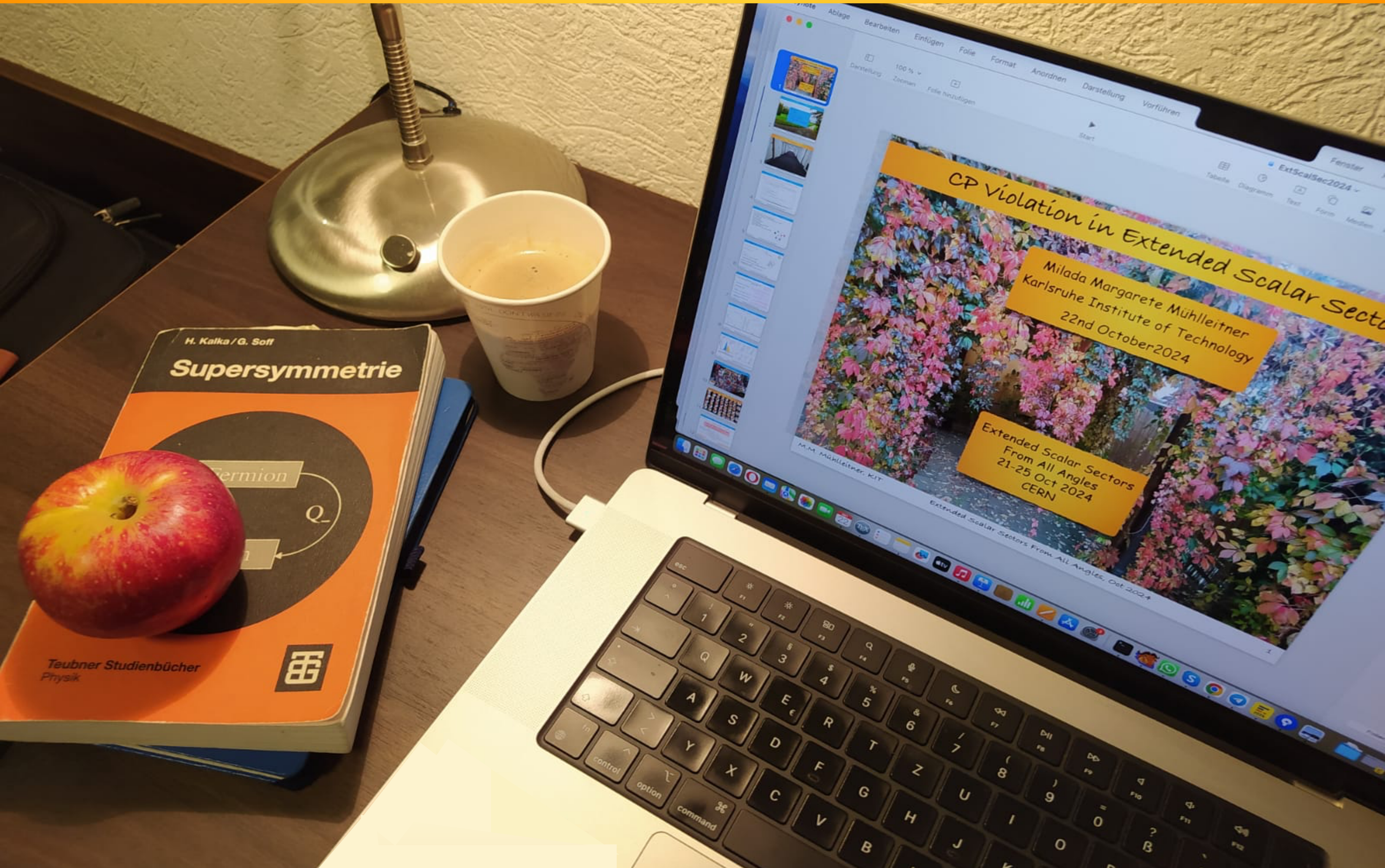




$$\sigma \cdot f_{\chi\chi} \equiv \sigma \cdot \frac{\Omega_{\rm prod} h^2}{\Omega_{\rm obs} h^2}$$

- Viable GW points (SNR(LISA-3yrs)>1 - colored points):
  compatible w/ relic density (<Ωh^2)
  above neutrino floor
  testable at future direct detection experiments

Further Backup Slides



C2HDM Higgs Pair Production - Cascade Decays

❖ C2HDM contains three neutral CP-mixing Higgs bosons H_i (I=1,2,3), $m_{H_3} \geq m_{H_2} \geq m_{H_1}$:

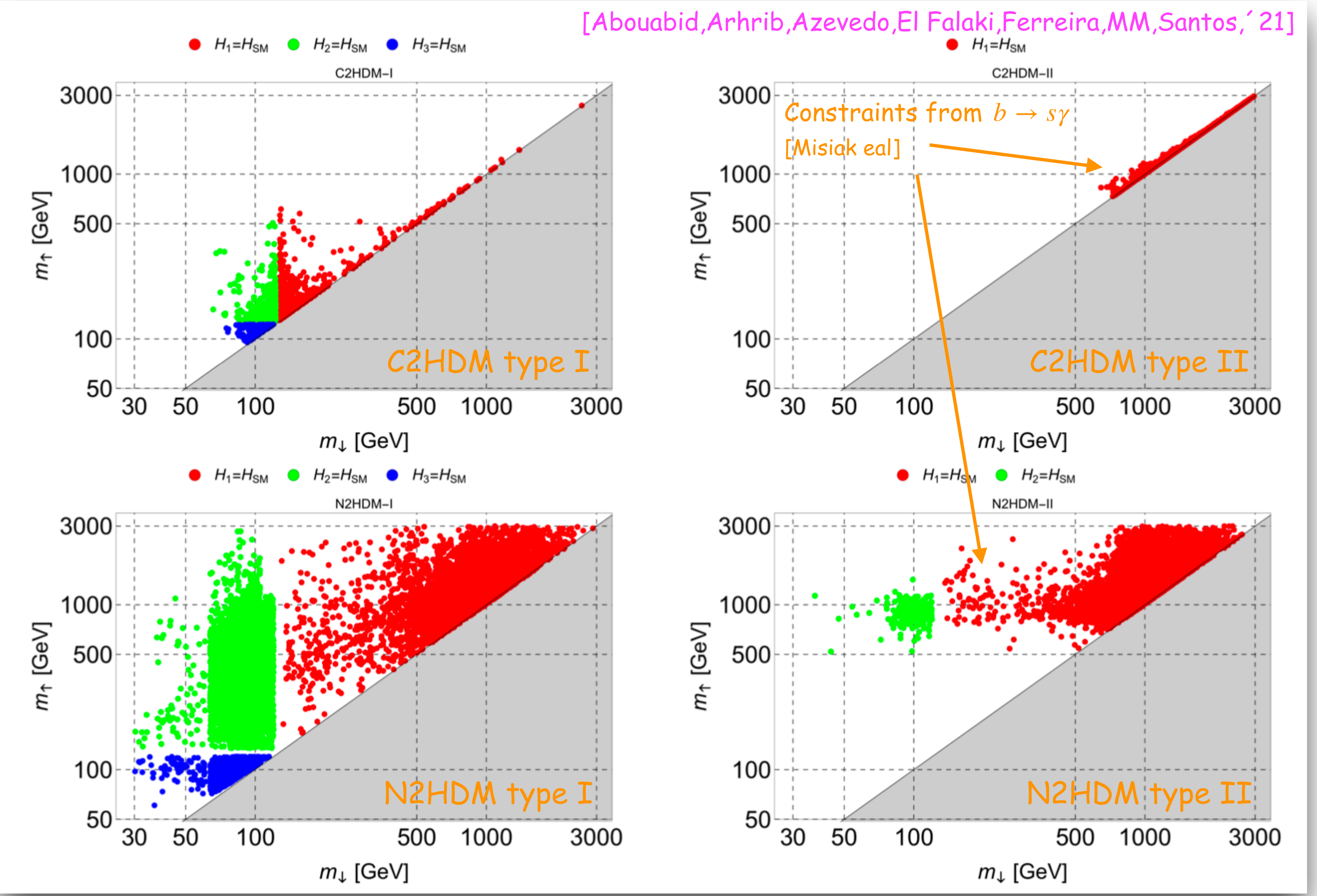
⇝ Interesting possibility of Higgs-to-Higgs cascade decays

$$H_3 \to H_2 H_2 \to (H_1 H_1)(H_1 H_1)$$

⇝ Spectacular production of four Higgs bosons!

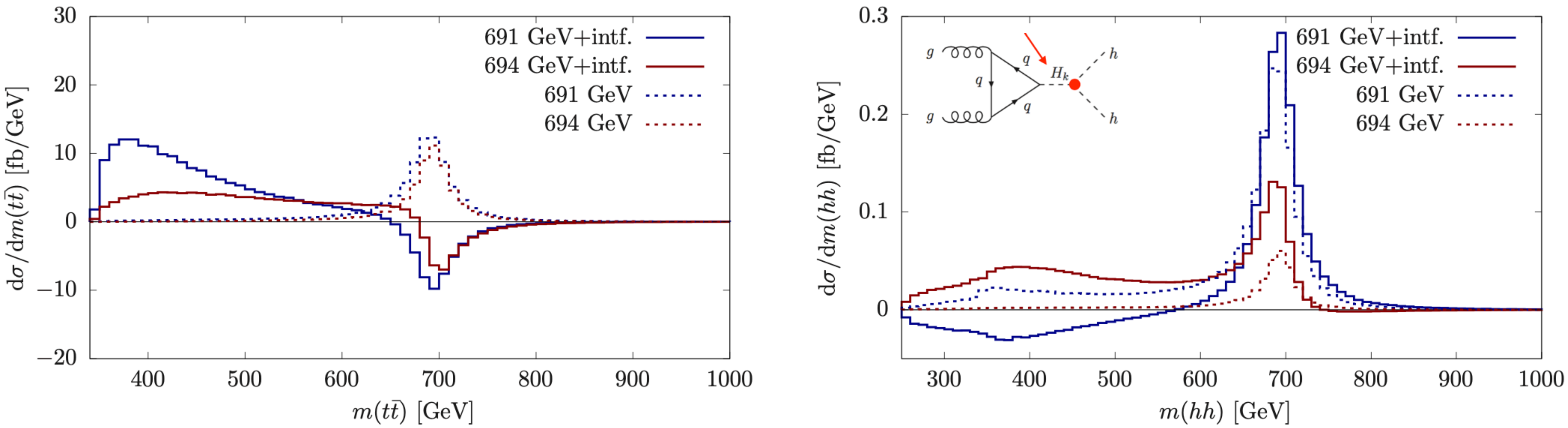
C2HDM Higgs Pair Production - Mass Distribution

❖ Heavy Higgs mass spectrum for H₁ SM-like (red points): rather compressed for $m_\downarrow \geq 250$ GeV ⇝ **no Higgs-to-Higgs cascade decays** $H_\uparrow \to H_\downarrow H_\downarrow \to (H_1 H_1)(H_1 H_1)$ in contrast to e.g. N2HDM, NMSSM



Di-Higgs Peaks and Top Valleys

- C2HDM type II: degenerate mass spectrum! $|m_{H_2} - m_{H_3}| < 0.1\, m_{H_3}$ [Basler,Dawson,Englert,MM,'21]



heavy Higgs production
w/ subsequent decay into tt
destructive interference effects
between signal and SM background

heavy Higgs production
w/ subsequent decay into SM-like hh
constructive signal-signal (H_2-H_3)
interference effects

* For interference effects in simplified model, cf. talk by R. Kumar Thursday afternoon.

[Basler,Dawson,Englert,MM'21]

	BP1	BP2	BP3	BP4
m_{H_1} [GeV]	125.090	125.090	125.090	125.090
m_{H_2} [GeV]	764.044	691.319	608.588	442.903
m_{H_3} [GeV]	814.578	694.637	609.393	626.371
$m_{H^\pm}$ [GeV]	853.064	654.204	679.601	651.550
α_1	0.746	0.766	0.818	0.736
α_2	-0.132	0.042	0.053	0.045
α_3	-0.086	1.144	0.913	1.567
$\tan(\beta)$	0.921	0.870	0.892	0.928
R_{13}^2	0.017	0.002	0.003	0.002
R_{23}^2	0.007	0.827	0.624	0.998
R_{33}^2	0.975	0.171	0.373	0.000
$\sigma(gg \to H_1)$ [pb]	45.908	49.699	53.640	43.233
$\sigma(gg \to H_2)$ [pb]	0.651	1.700	2.903	19.042
$\sigma(gg \to H_3)$ [pb]	0.637	1.284	2.670	1.899
$\lambda_{H_1 H_1 H_1}$ GeV]	-30.633	150.815	115.626	-184.173
$\lambda_{H_1 H_1 H_2}$ [GeV]	-49.478	253.524	305.386	-55.652
$\lambda_{H_1 H_1 H_3}$ [GeV]	-448.381	120.882	-121.714	6.123
$\Gamma(H_1)$ [GeV]	0.004	0.004	0.004	0.004
$\Gamma(H_2)$ [GeV]	36.623	41.150	31.551	21.580
$\Gamma(H_3)$ [GeV]	51.865	34.787	29.057	32.449
$BR(H_2 \to H_1 H_1)$	0.001	0.021	0.044	0.003
$BR(H_2 \to t\bar{t})$	0.936	0.962	0.922	0.990
$BR(H_3 \to H_1 H_1)$	0.045	0.006	0.008	0.000
$BR(H_3 \to t\bar{t})$	0.871	0.979	0.965	0.793

The CP-Violating NMSSM Higgs Sector

- Tree-level Higgs potential: (neglecting D-term contributions)

$$V_H = (|\lambda S|^2 + m_{H_d}^2) H_d^\dagger H_d + (|\lambda S|^2 + m_{H_u}^2) H_u^\dagger H_u + m_S^2 |S|^2 + \left|\kappa S^2 - \lambda H_d \cdot H_u\right|^2 + \left(\frac{1}{3}\kappa A_\kappa S^3 - \lambda A_\lambda S H_d \cdot H_u + \text{h.c.}\right)$$

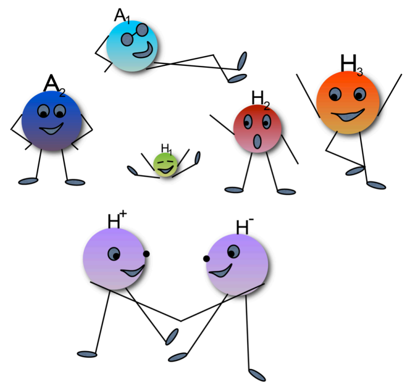
- CP violation in the Higgs sector: λ, κ, A_λ, A_κ can be complex

- Higgs fields after electroweak symmetry breaking (EWSB):

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + i a_d) \\ h_d^- \end{pmatrix}, \quad H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + i a_u) \end{pmatrix}, \quad S = \frac{e^{i\varphi_s}}{\sqrt{2}}(v_s + h_s + i a_s)$$

effective μ parameter: $\mu = \frac{\lambda v_s}{\sqrt{2}}$

What about EDM Constraints?



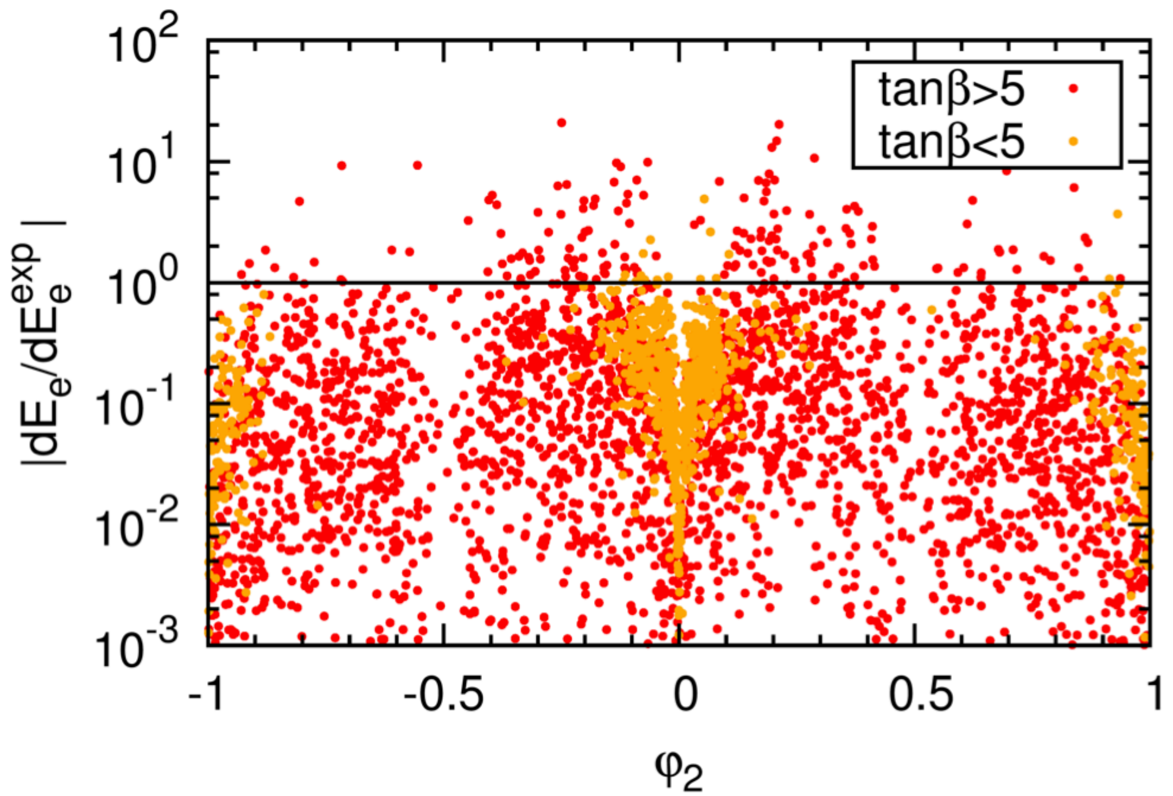
- Computation of EDMs: included in NMSSMCALC
- Tree-level CP-violation in the Higgs sector:

$$\varphi_y = \varphi_2 - \varphi_1 \qquad \varphi_1 = \varphi_\lambda + \varphi_s + \varphi_u \quad \text{MSSM-like}$$

$$\varphi_2 = \varphi_\kappa + 3\varphi_s \quad \text{NMSSM-like}$$

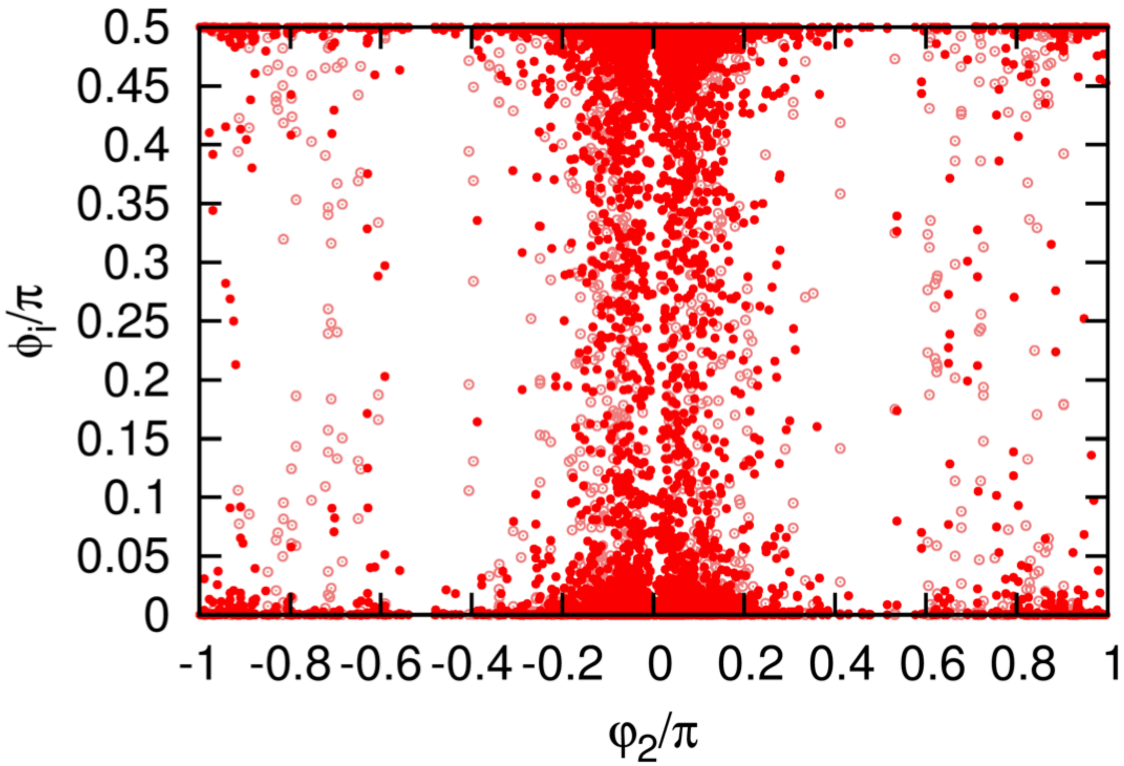
Due to cancellation of diagrams contributing to EDM: rather larger CP-violating NMSSM-like φ_2 phase still possible

[King,MM,Nevzorov,Walz,Nucl.Phys.B 901 (2015) 526]



Note: these are EDM constraints of 2015

$$\mathcal{L}_{H_i\tau\tau} = -g_\tau\, \tau^+ \left(c^S_\tau + i c^P_\tau \gamma_5\right) \tau^- H_i \qquad \tan\phi_i = \frac{c^P_\tau}{c^S_\tau}$$

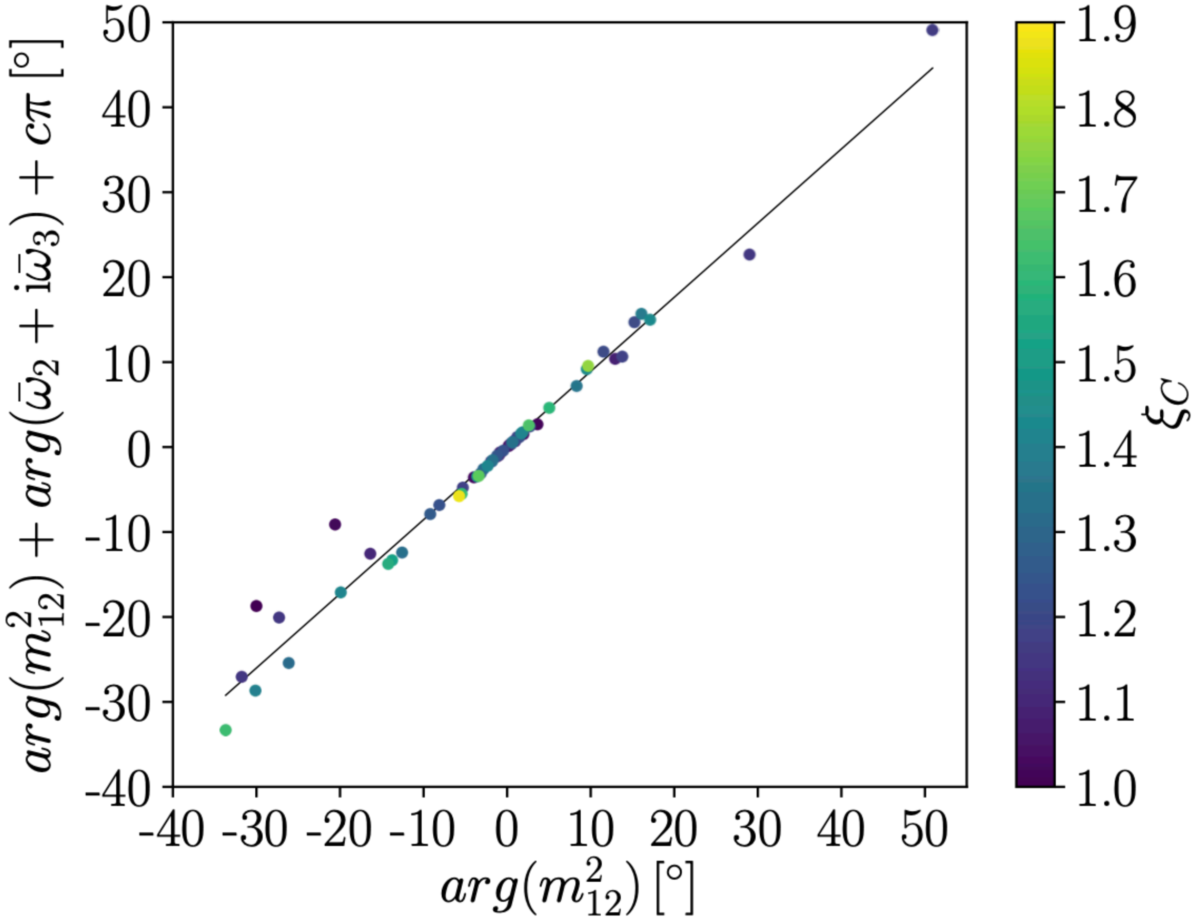


Full (empty) circles: allowed (forbidden) by EDMs

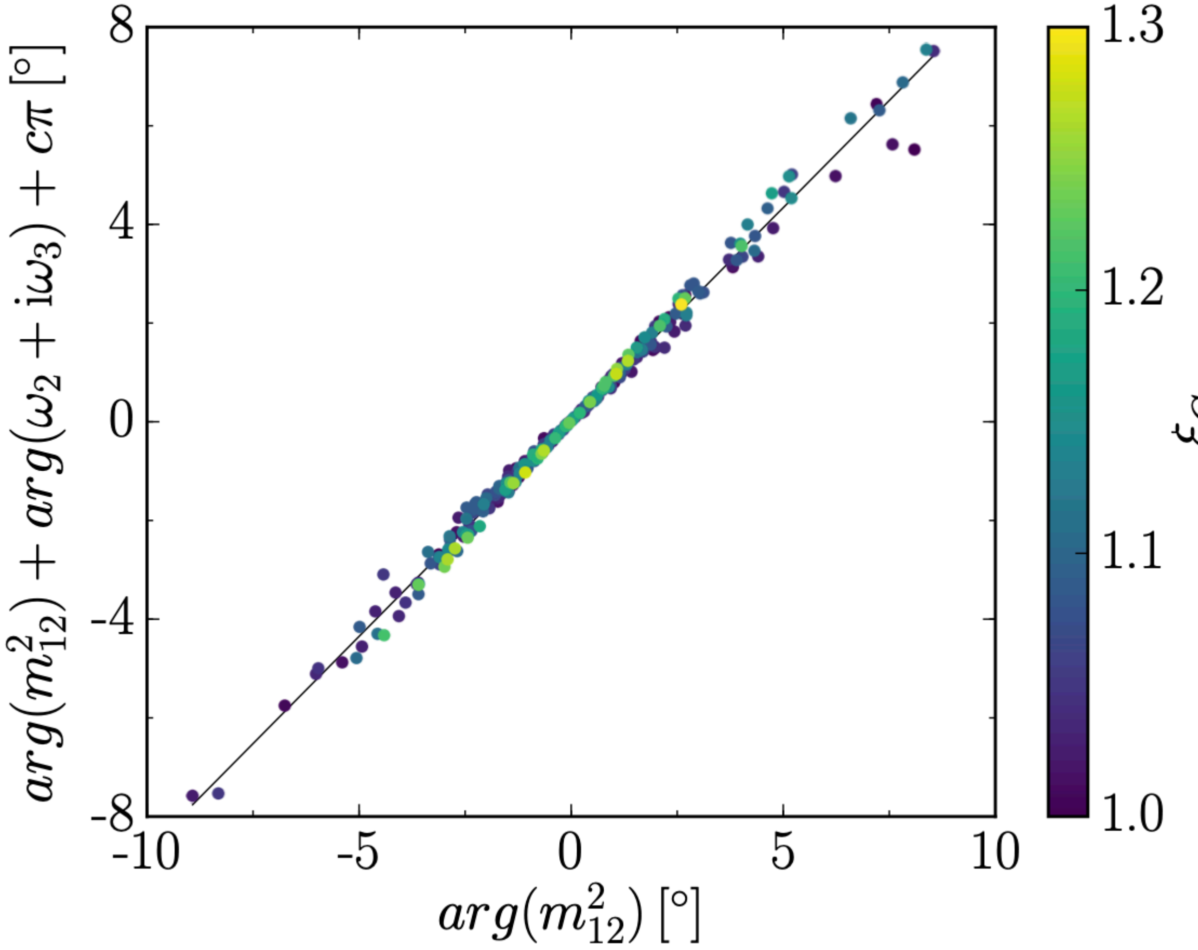
[Basler,MM,Wittbrodt,'17]

Total CP-violating angle at the phase transition

- C2HDM type 1



- C2HDM type 2



Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves

SFOEWPT
(for EWBG)

↓ can source

Gravitational Waves
(GW)

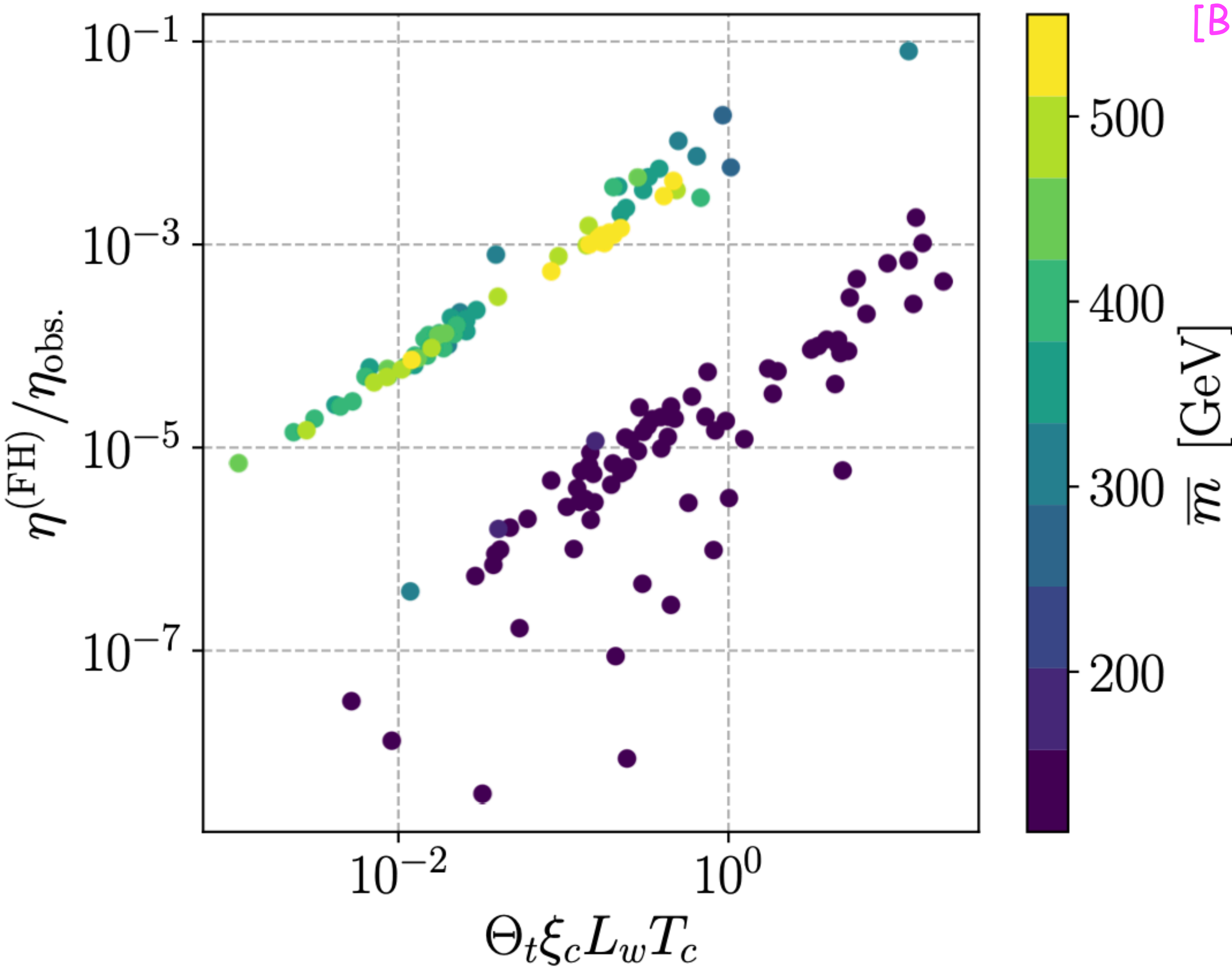
↑ sensitive to

Pulsar timing arrays, LISA
(space bound interferometer)

Generated Baryon Asymmetry in the C2HDM

- C2HDM Type I+II baryon asymmetry calculated in FH approach normalized to observed value: bubble wall velocity fixed to v_W=0.1, L_W: bubble wall length, T_c: critical temperature at degenerate vacua $V(v_c \neq 0)=V(v=0)$, $\xi_c=v_c/T_c$ phase transition strength, Θ_t CP-violating phase of m_t ($m_i \equiv |m_i(z)| \exp(\mathrm{i}\,\theta^{(i)}(z))$)

[Basler,Biermann,Müller,'21]



$\overline{m}$ average non-SM-like Higgs mass scale

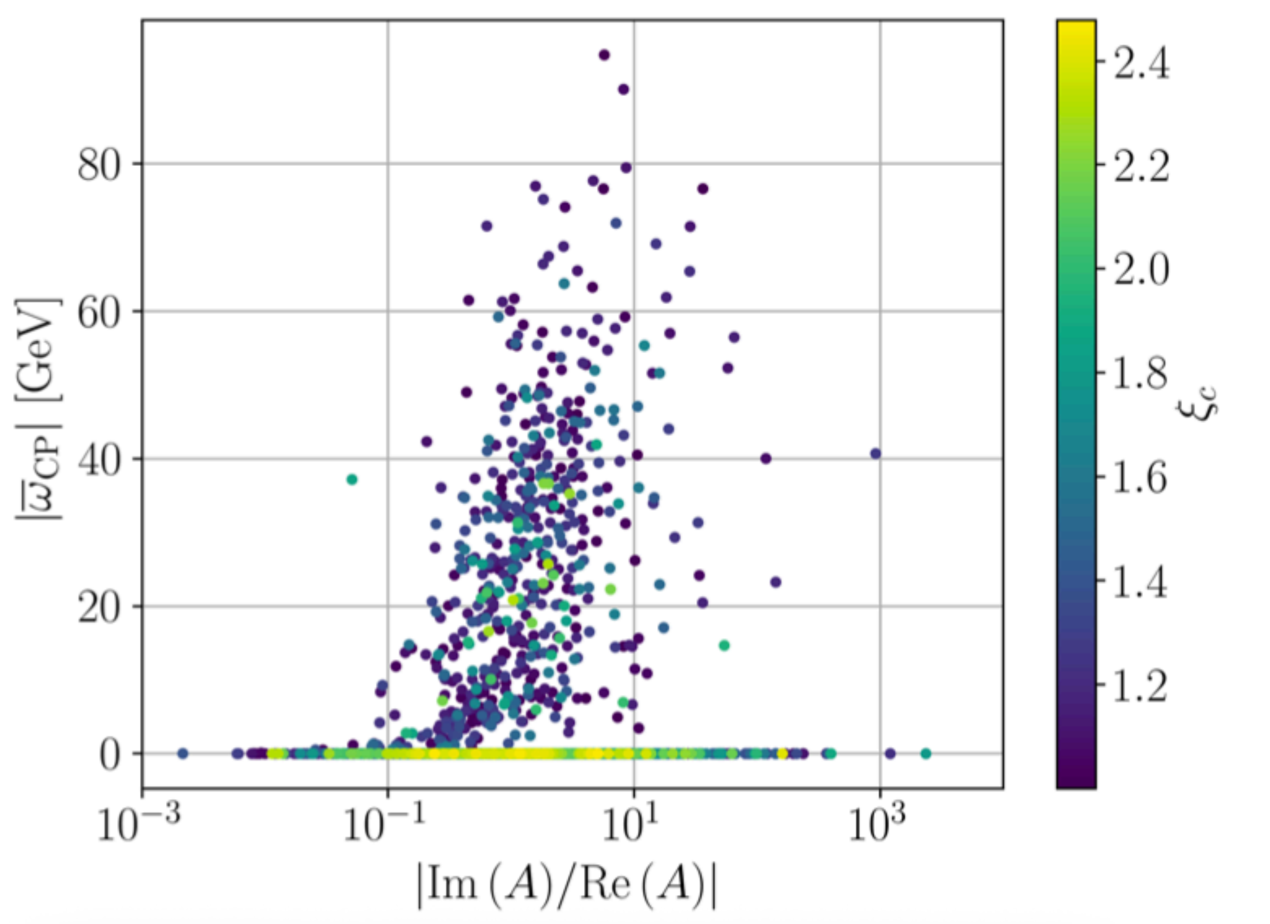
See also [Bahl,Fuchs,Heinemeyer,Katzy,Menen,Peters,Saimpert,Weiglein,'22] for impact of tau-lepton CP-violating phase in „VIA" approach; caveat, however: VIA approach overestimated [Postma,van de Vis,White,'22]

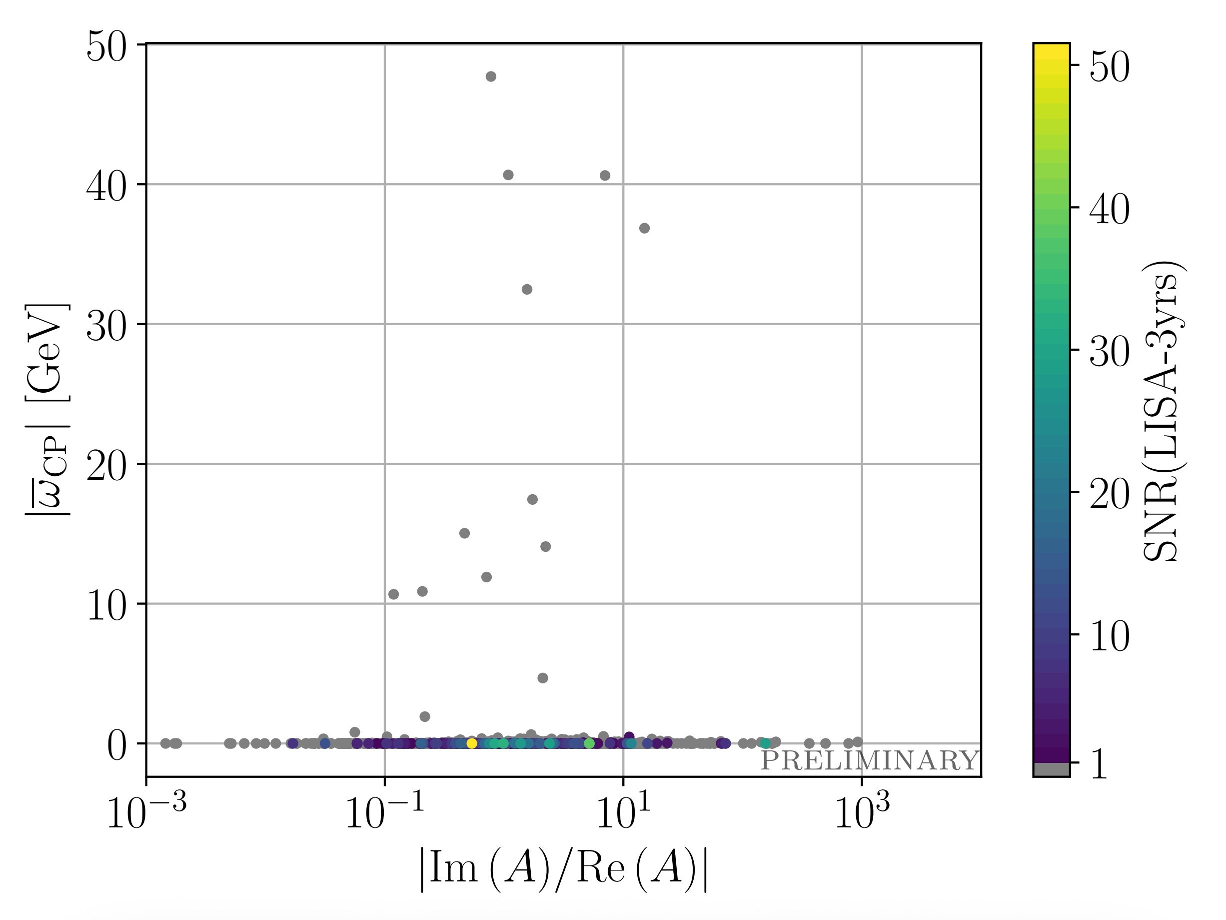
Spontaneous CP Violation

[Biermann,MM,Müller,'22]

[Biermann,MM,Santos,Viana,'24]

CP-Violation in Dark Sector: at T=0 unconstrained by EDMs!





- possibility of SFOEWPT & spontaneous CP violation (CPV)
- spontaneous $\mathbb{Z}_2$ violation also possible => non-standard CPV transferred to visible sector
- interesting for EWBG!

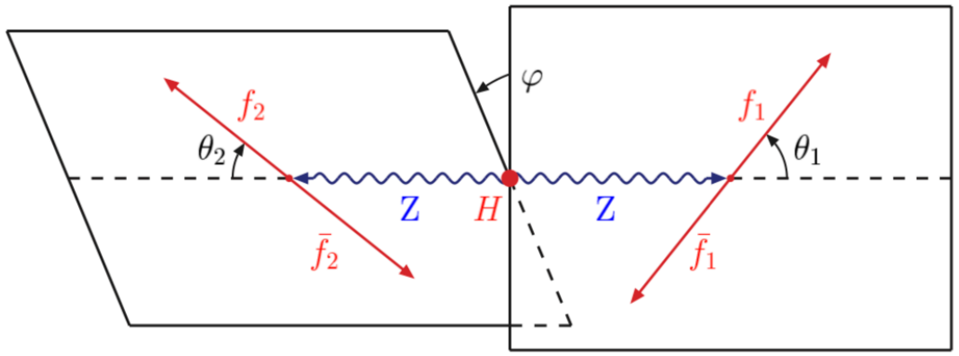
- SNR(LISA-3yrs)>1 (colored) for max. $|\omega_{CP}|=O(10^{-1})$
- spontaneous $\mathbb{Z}_2$ violation leads to plasma friction w/ (former) DM direction =>
- spontaneous CPV may escape run-away

Example for Spin and CP Determination

❖ Higgs Decay into Z boson pair: $H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$

SM Double polar angle distribution

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{16}\frac{1}{\gamma^4+2}\left[\gamma^4\sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\right]$$



SM Azimuthal angular distribution

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\phi} = \frac{1}{2\pi}\left[1+\frac{1}{2}\frac{1}{\gamma^4+2}\cos 2\phi\right]$$

❖ Angular distributions for particle w/ arbitrary spin and parity:
helicity analyses & operator expansion

✏ Azimuthal angular distribution differs for scalar and pseudoscalar particle:

$$0^+ \;:\; d\Gamma/d\phi \sim 1 + 1/(2\gamma^4+4)\cos 2\phi$$
$$0^- \;:\; d\Gamma/d\phi \sim 1 - 1/4\cos 2\phi$$

✏ Threshold behavior allows to determine the spin of the particle:

spin 0: linear rise w/ β
spin 1 (2) particle ~ β^3 (~ β^5)

$$\frac{d\Gamma[H\to Z^*Z]}{dM_*^2} \sim \beta = \sqrt{(M_H-M_Z)^2 - M_*^2}/M_H$$

Other Spectrum Calculators

- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: DR, FO & hybrid, through FlexibleEFTHiggs
- NMSSMCALC [Baglio,Dao,Gröber,MM,Rzehak,Spira,Streicher,Walz]: FO, real & complex NMSSM, DR and mixed OS-DR
- NMSSMTools [Ellwanger,Gunion,Hugonie]: FO, DR scheme
- SOFTSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: FO, DR scheme
- SPheno [Porod,Staub]: FO, DR scheme

Remarks:

- comparison of codes in DR scheme: [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15] FlexibleSUSY, NMSSMCALC, NMSSMTools, SOFTSUSY, SPheno
- comparison of codes in mixed OS-DR scheme: [Drechsel,Gröber,Heinemeyer,MM,Rzehak,Weiglein,'16] FeynHiggs, NMSSMCALC
- solution of Goldstone boson catastrophe [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15]
- advances in FeynHiggs: [Drechsel,Galeta,Heinemeyer,Hollik,Liebler,Moortgat-Pick,Paßehr,Weiglein]
- OS masses CP-violating NMSSM, consistent description production/decay [Domingo,Drechsel,Paßehr]
- Review on Higgs mass predictions in the MSSM and beyond [Slavich eal,´20]
- Higgs mass predictions w/ heavy BSM particles [Bagnaschi,Goodsell,Slavich,'22]

Recap Standard Model

❖ Recap SM Higgs Sector:

$$\mathscr{L} = (D_\mu\Phi)(D^\mu\Phi)^\dagger - (\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2) \qquad \mu^2 < 0, \lambda > 0$$

Parametrization of the complex Higgs doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \rho + i\eta \end{pmatrix}$$

Minimum of the potential is at:

$$v = \sqrt{\frac{|\mu|^2}{\lambda}} = 246 \text{ GeV}$$

Mass and trilinear couplings (uniquely determined in terms of m_h!):

$$m_h^2 = 2\lambda v^2\,, \quad \lambda_{hhh} = \frac{3m_h^2}{v}\,, \quad \lambda_{hhhh} = \frac{3m_h^2}{v^2}$$

Spectrum: Physical Higgs boson + 3 Goldstone bosons; potential does not allow for C or P violation (neither explicit nor spontaneous)