Karlsruher Institut für Technologie

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Institute for Theoretical Physics (ITP)

A3a: Extended Higgs Sectors at the LHC

Siegen, Oct 6-8, 2020

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Overview

- PIs: Margarete Mühlleitner, Tilman Plehn

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  Marcel Krause (PhD/KIT), Tanmoy Modak (Postdoc/HD),
  Jonas Müller (PhD/KIT), Nguyen Than Tien Dat (PhD/KIT),
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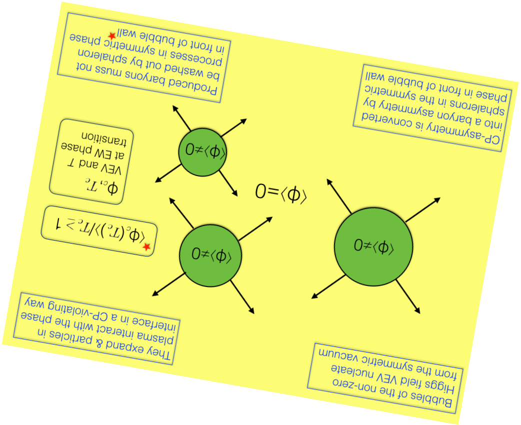
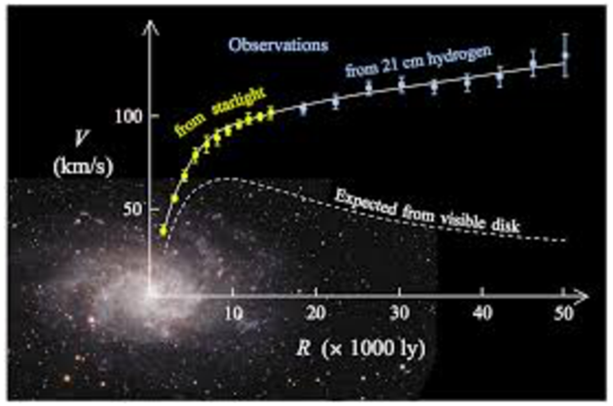
- Topics: - Vacua of extended Higgs sectors
  - Extended Higgs Sectors and Dark Matter
  - Higher-order corrections to Higgs boson decays
  - Higher-order corrections to gluon fusion into pseudoscalar MSSM Higgs boson

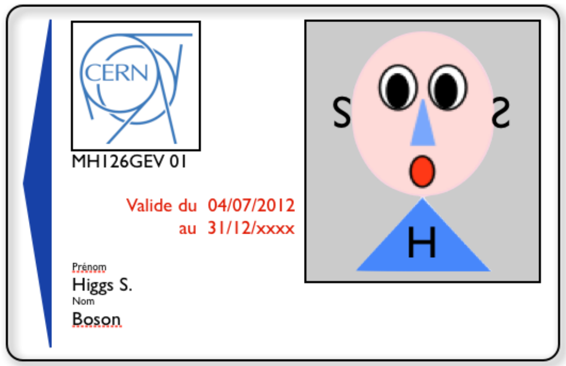
Extended Higgs Sectors - Precision





✦ Why extended Higgs sectors?
Unsolved puzzles in the SM call
for Higgs sector extensions

✦ Extended Higgs sectors: provide Dark Matter (DM) candidates,
additional sources of CP violation, enable successful baryogenesis, alleviate metastability

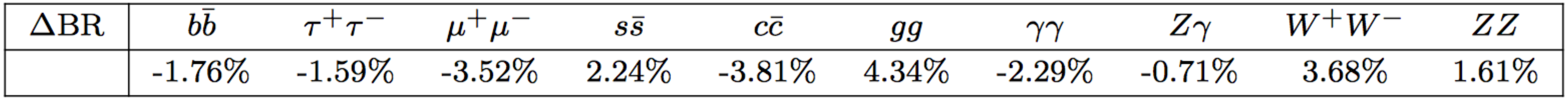


✦ Why precision calculations?
- No direct sign of new physics yet, but we have the Higgs boson
  -> indirect search for new physics in the Higgs sector
- Higgs boson behaves very SM-like -> new physics effects are small
- different new physics models lead to similar effects
- We have to check if our models are still valid <- theoretical and experimental constraints
  How are they affected by higher-order corrections?

✦ How select our models?
- effective field theory (EFT) valid for new physics scales much larger than electroweak scale
- investigate specific UV complete models to be sensitive to light resonances

Extended Higgs Sectors - Precision

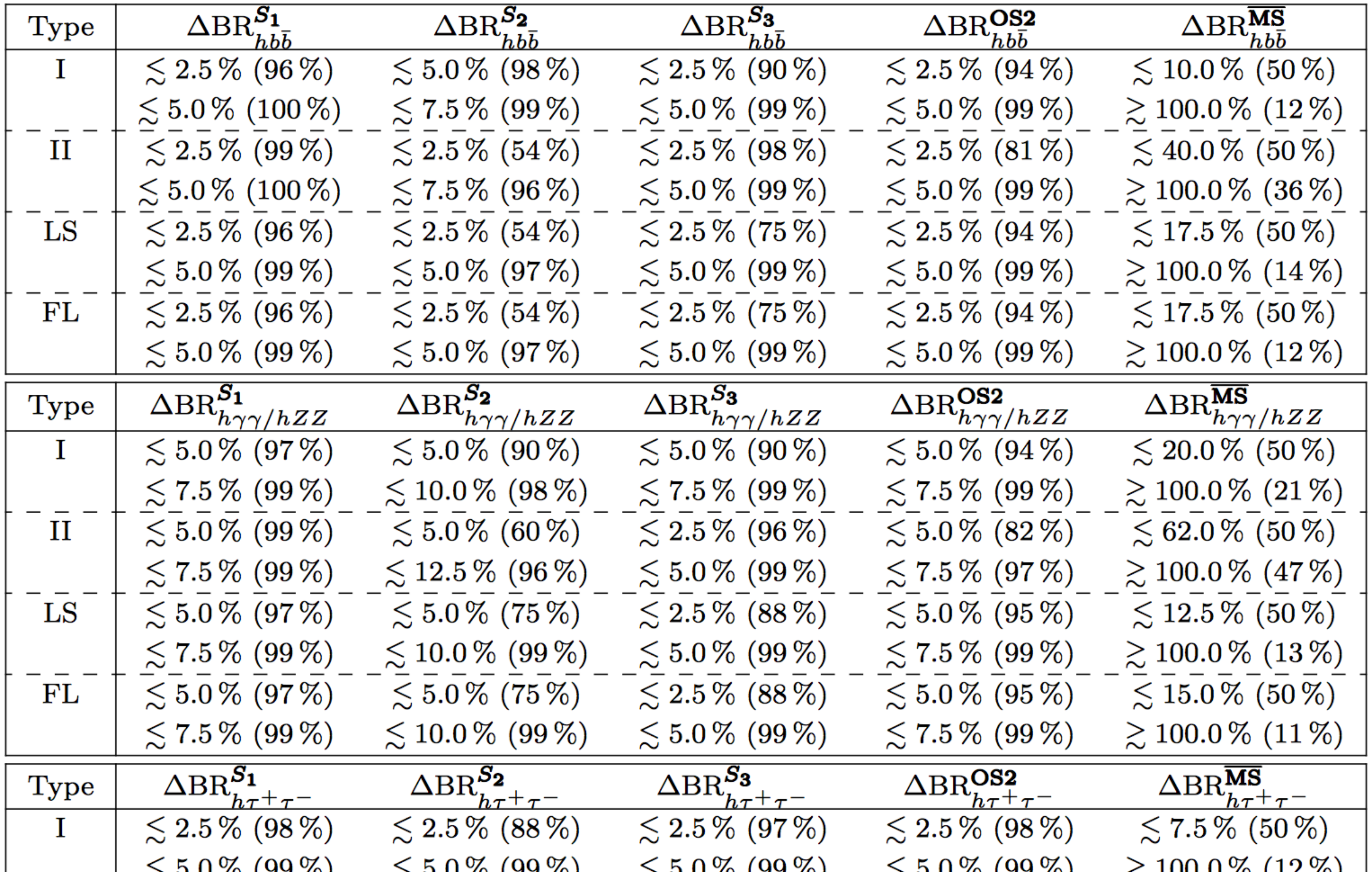
Impact of EW corrections on SM Higgs branching ratios $\Delta\mathrm{BR} = \dfrac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]



$\Delta\mathrm{BR}$	$b\bar b$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar s$	$c\bar c$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Impact of EW corrections on branching ratios of SM-like 2HDM Higgs boson

[Krause,MMM,JHEP04(2020)083]



Type	$\Delta\mathrm{BR}^{S_1}_{hb\bar b}$	$\Delta\mathrm{BR}^{S_2}_{hb\bar b}$	$\Delta\mathrm{BR}^{S_3}_{hb\bar b}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{hb\bar b}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{hb\bar b}$
I	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (98 %)	$\lesssim 2.5\,\%$ (90 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 10.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)
II	$\lesssim 2.5\,\%$ (99 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (81 %)	$\lesssim 40.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (36 %)
LS	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (14 %)
FL	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_2}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_3}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\gamma\gamma/hZZ}$
I	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (94 %)	$\lesssim 20.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (98 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (21 %)
II	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (60 %)	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (82 %)	$\lesssim 62.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 12.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (97 %)	$\gtrsim 100.0\,\%$ (47 %)
LS	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 12.5\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (13 %)
FL	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 15.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (11 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_2}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_3}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\tau^+\tau^-}$
I	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 2.5\,\%$ (97 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 7.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

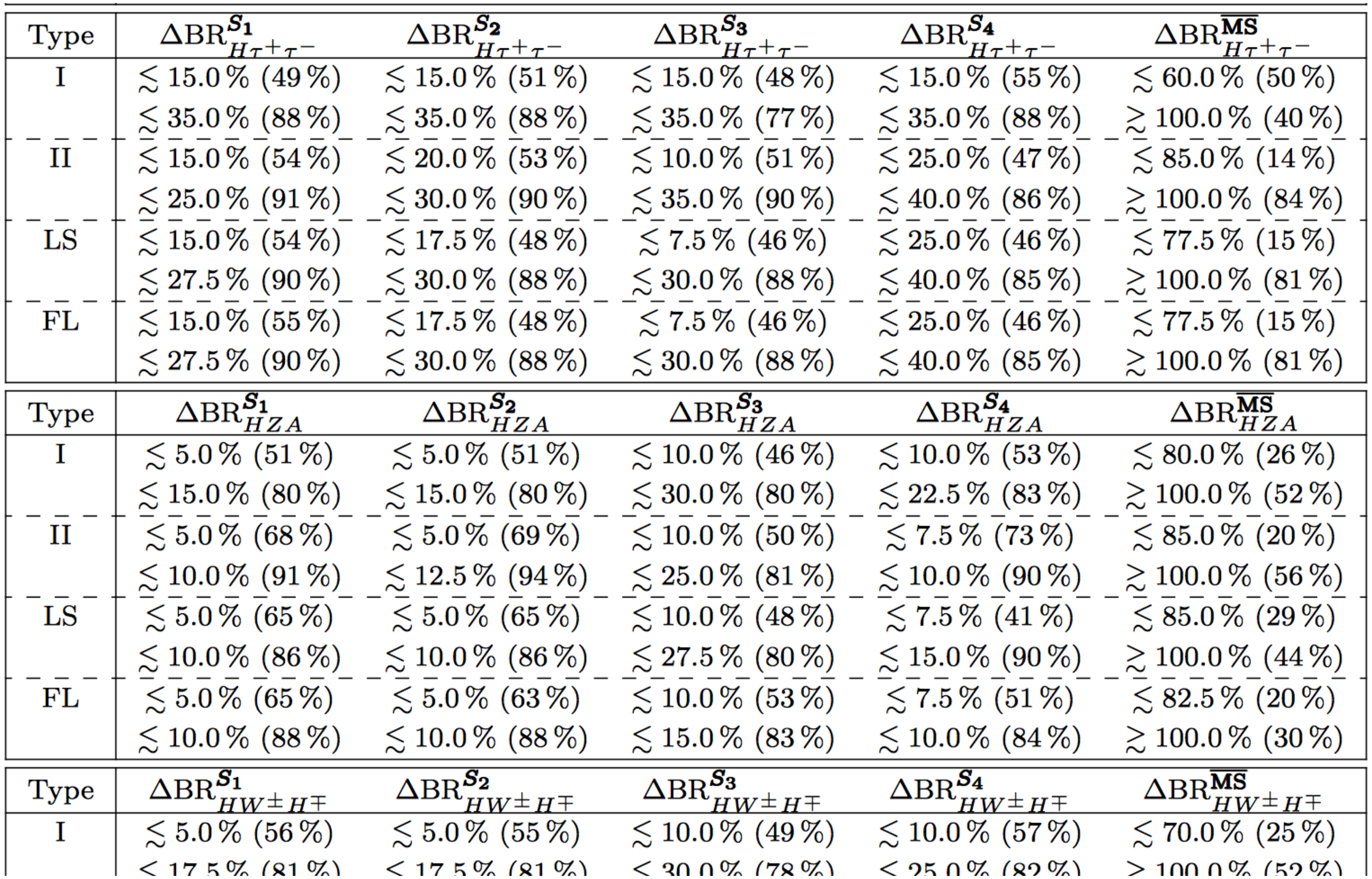
Extended Higgs Sectors - Precision

Impact of EW corrections on SM branching ratios $\Delta\mathrm{BR} = \dfrac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Impact of EW corrections on branching ratios of non-SM-like 2HDM Higgs boson

[Krause,MMM,JHEP04(2020)083]

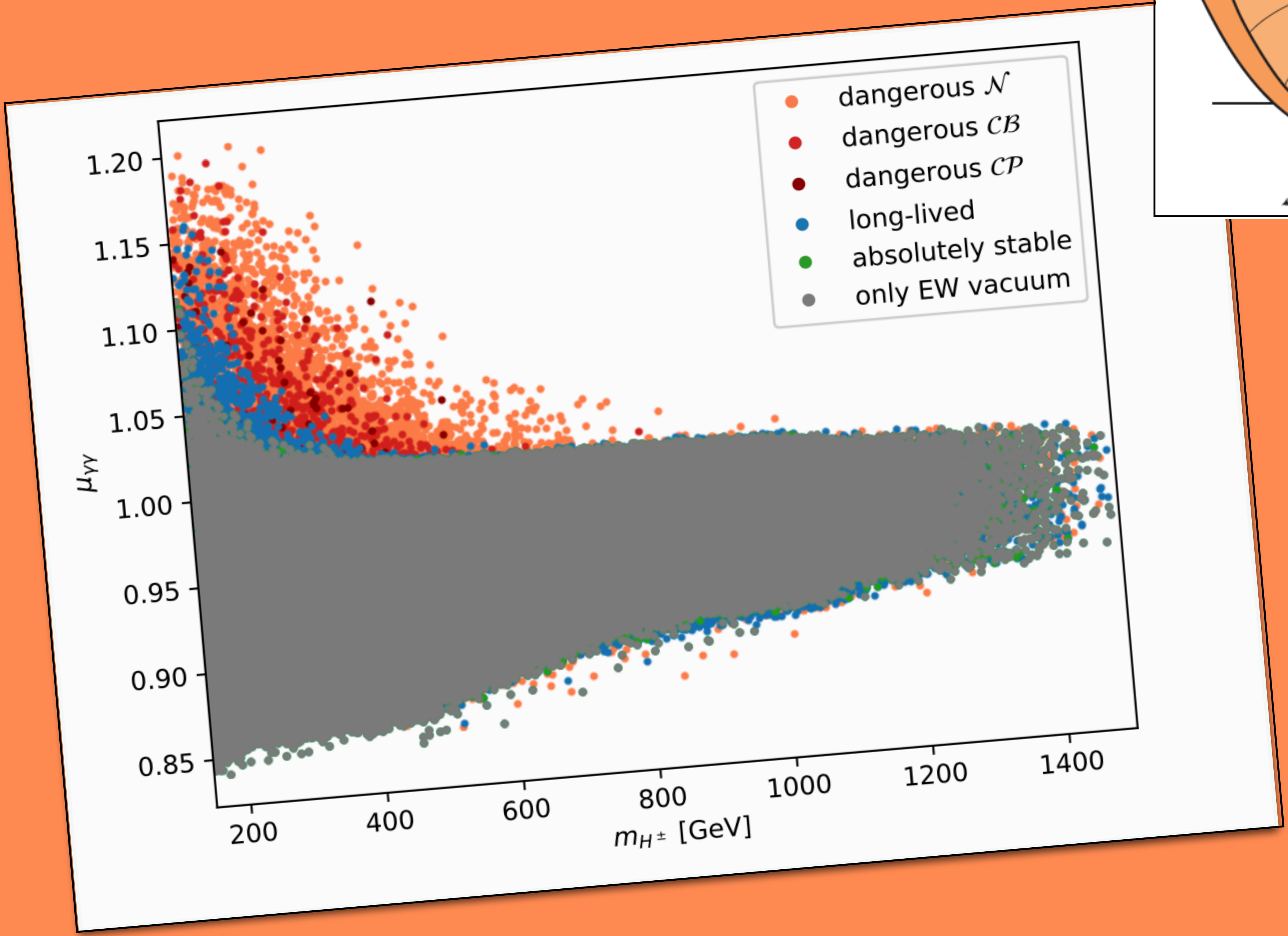


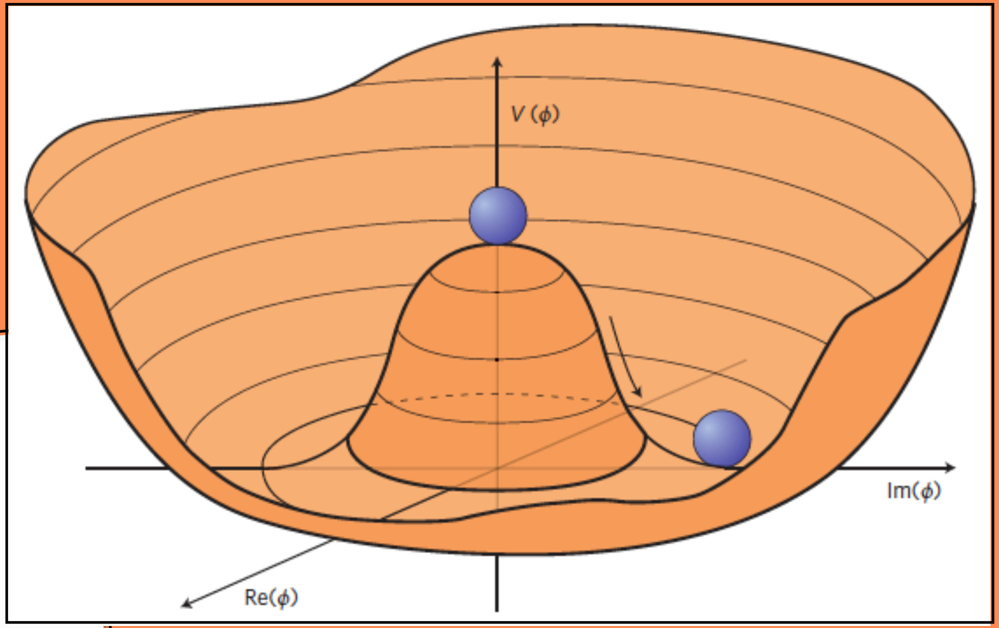
Type	$\Delta\mathrm{BR}^{S_1}_{H\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_2}_{H\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_3}_{H\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_4}_{H\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{H\tau^+\tau^-}$
I	$\lesssim$ 15.0 % (49 %)	$\lesssim$ 15.0 % (51 %)	$\lesssim$ 15.0 % (48 %)	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 60.0 % (50 %)
	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (77 %)	$\lesssim$ 35.0 % (88 %)	$\gtrsim$ 100.0 % (40 %)
II	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 20.0 % (53 %)	$\lesssim$ 10.0 % (51 %)	$\lesssim$ 25.0 % (47 %)	$\lesssim$ 85.0 % (14 %)
	$\lesssim$ 25.0 % (91 %)	$\lesssim$ 30.0 % (90 %)	$\lesssim$ 35.0 % (90 %)	$\lesssim$ 40.0 % (86 %)	$\gtrsim$ 100.0 % (84 %)
LS	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)
FL	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)

Type	$\Delta\mathrm{BR}^{S_1}_{HZA}$	$\Delta\mathrm{BR}^{S_2}_{HZA}$	$\Delta\mathrm{BR}^{S_3}_{HZA}$	$\Delta\mathrm{BR}^{S_4}_{HZA}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{HZA}$
I	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 10.0 % (46 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 80.0 % (26 %)
	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 30.0 % (80 %)	$\lesssim$ 22.5 % (83 %)	$\gtrsim$ 100.0 % (52 %)
II	$\lesssim$ 5.0 % (68 %)	$\lesssim$ 5.0 % (69 %)	$\lesssim$ 10.0 % (50 %)	$\lesssim$ 7.5 % (73 %)	$\lesssim$ 85.0 % (20 %)
	$\lesssim$ 10.0 % (91 %)	$\lesssim$ 12.5 % (94 %)	$\lesssim$ 25.0 % (81 %)	$\lesssim$ 10.0 % (90 %)	$\gtrsim$ 100.0 % (56 %)
LS	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 10.0 % (48 %)	$\lesssim$ 7.5 % (41 %)	$\lesssim$ 85.0 % (29 %)
	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 27.5 % (80 %)	$\lesssim$ 15.0 % (90 %)	$\gtrsim$ 100.0 % (44 %)
FL	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (63 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 7.5 % (51 %)	$\lesssim$ 82.5 % (20 %)
	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 15.0 % (83 %)	$\lesssim$ 10.0 % (84 %)	$\gtrsim$ 100.0 % (30 %)

Type	$\Delta\mathrm{BR}^{S_1}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_2}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_3}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{S_4}_{HW^\pm H^\mp}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{HW^\pm H^\mp}$
I	$\lesssim$ 5.0 % (56 %)	$\lesssim$ 5.0 % (55 %)	$\lesssim$ 10.0 % (49 %)	$\lesssim$ 10.0 % (57 %)	$\lesssim$ 70.0 % (25 %)
	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 30.0 % (78 %)	$\lesssim$ 25.0 % (82 %)	$\gtrsim$ 100.0 % (52 %)

Extended Higgs Sectors - Vacua, Dark Matter





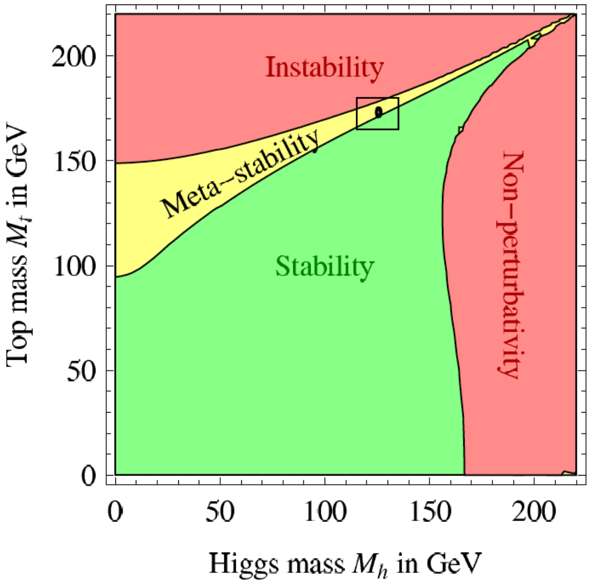
Vacua of Extended Higgs Sectors

- Stability of electroweak (EW) vacuum of the Standard Model (SM) guaranteed at tree level by postulated form of Higgs potential

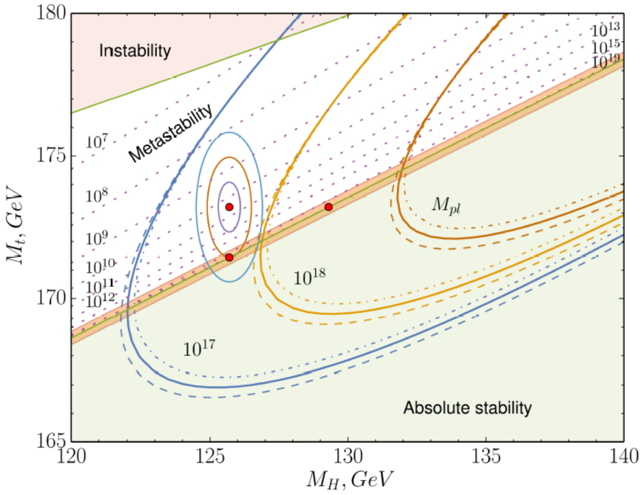
- Higher-order corrections -> stability of EW vacuum related to the other SM parameters (m_t!)

  EW vacuum metastable for Lambda > 10^{10} GeV

  [Degrassi eal,´12;Bednyakov eal,´15]



Degrassi,Di Vita,Elias-Miro,Espinosa '12



Bednyakov,Kniehl,Pikelner,Veretin '15

- SM extensions -> additional scalar degrees of freedom -> structure of Higgs potential modified ->
  - * additional (non-EW) vacua possible, e.g. CP-breaking, charge-breaking (CB), color-breaking vacua
  - * second EW minimum w/ wrong VEV: e.g. panic vacuum in 2HDM [Ivanov,´07,´08;Barroso eal.,´07,´12,´13]

- Fast tunneling (< age of universe) in false vacua [Branchina eal,´18] must be avoided

=> Requirement of stable vacuum at cosmological time scales has immediate consequences for allowed parameter region of BSM models and hence observables and signatures

Status and Computer Tools

- 2HDM vacuum: [Ivanov,´07,´08;Ferreira eal,´04;Barroso eal.,´05]
  - * if normal/EW vacuum exists -> any stationary point that is CP or CB breaking necessarily is a saddle point above normal minimum
  - * existence of panic vacua

- Inert 2HDM (2HDM w/ exact Z_2 symmetry): inert- and inert-like vacua can coexist at tree-level for certain parameter regions; regions at one-loop level changed [Ferreira,Swiezewska,´13]

- Loop-corrected effective potential at non-zero temperature CP-conserving and CP-violating 2HDM: allowed minima at LO do not necessarily lead to allowed minima at NLO and vice versa [Basler,Krause,MM,Wittbrodt,Wlotzka,´16;Basler,MM,Wittbrodt,'17]

- Tools:
  - * BSMPT NLO computation of BSM vacua at zero and non-zero temperature [Basler,MM,´18;Basler,MM,Müller,´20]
  - * Vevacious global minima at NLO of extended Higgs sectors [Camargo-Molina eal,´13,´14]
  - * EVADE: fast and efficient method for vacuum (meta)stability studies at tree level in multi-Higgs models [Hollik,Weiglein,Wittbrodt,´18]

Study of N2HDM Vacuum Structure

[Ferreira,Santos,MMM,Weiglein,Wittbrodt, JHEP09 (2019),006]

✦ Next-to-Minimal 2-Higgs Doublet Model (N2HDM): [Chen eal,´13;Drozd eal,´14;Yiang eal.,´16;MM eal,'16]

Motivation: possibility of DM candidate, additional singlet -> interesting phenomenology, more freedom than in SUSY counterpart models

Higgs sector: 2 Higgs doublets + real singlet field with two discrete symmetries:

$$\mathbb{Z}_2^{(1)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to \Phi_S$$

$$\mathbb{Z}_2^{(2)}: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Phi_S \to -\Phi_S$$

Higgs potential:

$$\begin{aligned} V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] \\ &+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{1}{8}\lambda_6\Phi_S^4 + \frac{1}{2}\lambda_7|\Phi_1|^2\Phi_S^2 + \frac{1}{2}\lambda_8|\Phi_2|^2\Phi_S^2\,, \end{aligned}$$

Remark: N2HDM w/ DM candidate and CP violation under investigation [Basler,Müller,Williamson,Wittbrodt]

Definitions N2HDM Vacuum Structure

- Normal Vacua $\mathcal{N}$:

$$\langle\Phi_1\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}} = 0$$

- Normal Vacua $\mathcal{N}s$:

$$\langle\Phi_1\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{N}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2' \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{N}s} = v_S'$$

- S-type Vacua $\mathcal{S}$: doublets acquire no VEV, only singlet acquires VEV

- Charge-breaking vacua $\mathcal{CB}$ and $\mathcal{CB}s$:

$$\langle\Phi_1\rangle_{\mathcal{CB}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{CB}} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2 \\ c_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{CB}} = 0$$

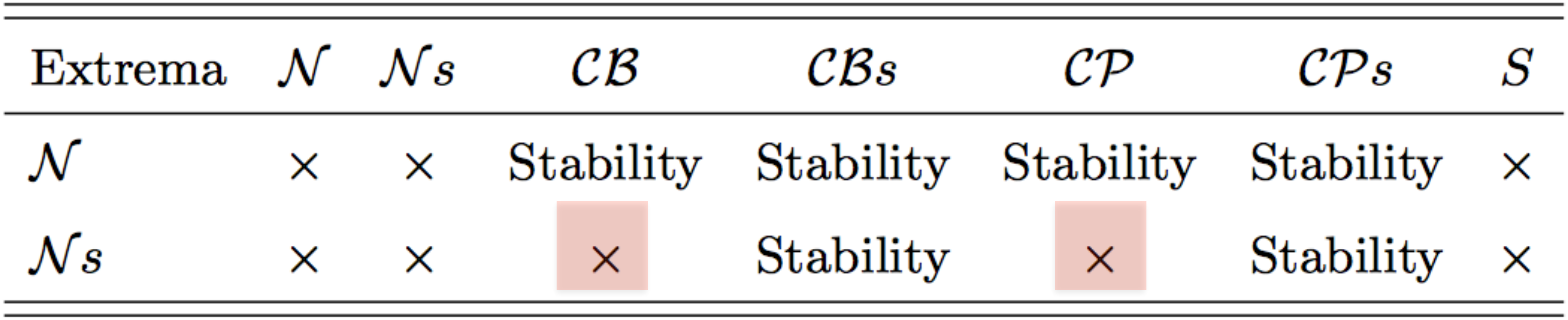
$$\langle\Phi_1\rangle_{\mathcal{CB}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ c_1' \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{CB}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} c_2' \\ c_3' \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{CB}s} = c_4'$$

- CP-breaking vacua $\mathcal{CP}$ and $\mathcal{CP}s$:

$$\langle\Phi_1\rangle_{\mathcal{CP}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \bar{v}_1 \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{CP}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \bar{v}_2 + \mathrm{i}\bar{v}_3 \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{CP}} = 0\,.$$

$$\langle\Phi_1\rangle_{\mathcal{CP}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \bar{v}_1' \end{pmatrix}, \quad \langle\Phi_2\rangle_{\mathcal{CP}s} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \bar{v}_2' + \mathrm{i}\bar{v}_3' \end{pmatrix}, \quad \langle\Phi_S\rangle_{\mathcal{CP}} = \bar{v}_4'$$

Analytical Analysis N2HDM Vacuum Structure



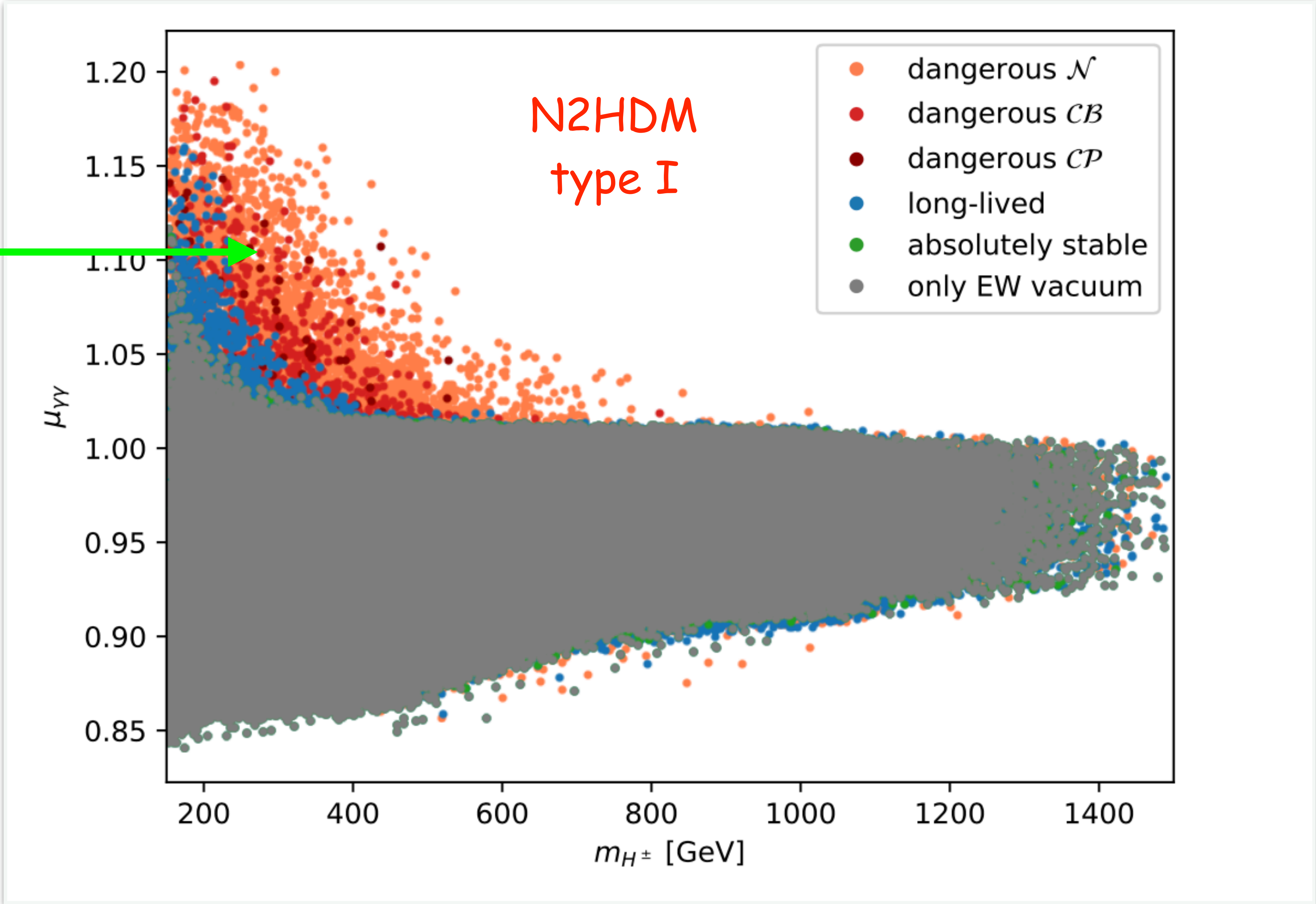
Extrema	$\mathcal{N}$	$\mathcal{N}s$	$\mathcal{CB}$	$\mathcal{CB}s$	$\mathcal{CP}$	$\mathcal{CP}s$	$\mathcal{S}$
$\mathcal{N}$	×	×	Stability	Stability	Stability	Stability	×
$\mathcal{N}s$	×	×	×	Stability	×	Stability	×

Panic vacua of either type $\mathcal{N}$ and $\mathcal{N}s$ can exist

Phenomenological Impact

Not allowed

models can be excluded based on vacuum study



$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to \gamma\gamma)}{\sigma(pp \to h_{\mathrm{SM}})\mathrm{BR}(h_{\mathrm{SM}} \to \gamma\gamma)}$$

Extended Higgs Sector

Dark matter or else? [Bauer, Foldenauer, TP, Reimitz]

- new renormalizable scalar coupled to the Higgs [Higgs portal, Aachen group]
- broad mass range μeV...GeV, λ_{hs} completely free

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu s \partial^\mu s - \frac{1}{2} m_s^2 s^2 - \frac{1}{4!}\lambda_s s^4 - \frac{1}{2}\lambda_{hs}\, s^2\, H^\dagger H$$

1- dark matter constraints
BBN
direct detection

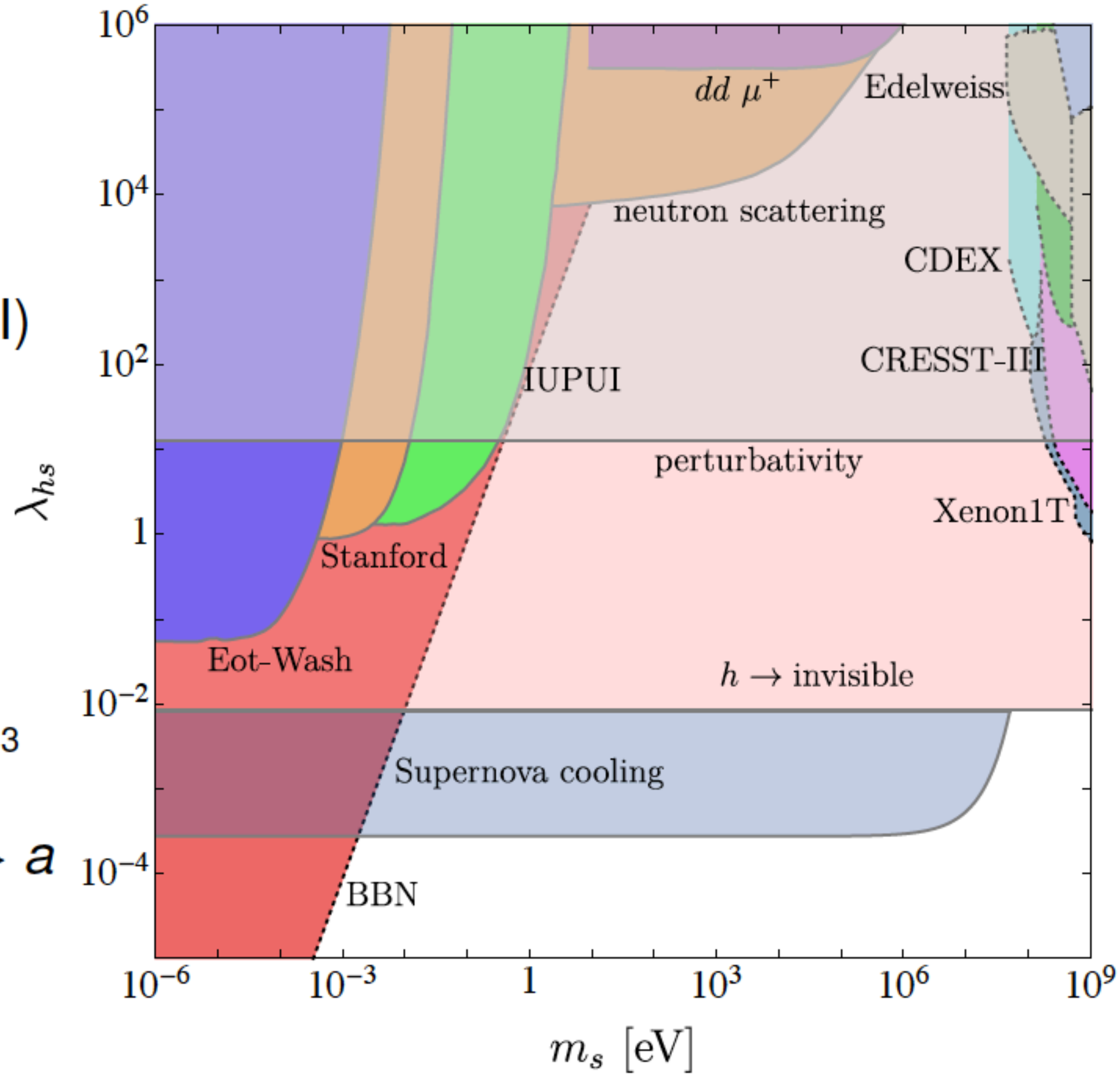
2- particle contraints
fifth force (Eot-Wash,Stanford,UIPUI)
supernova cooling [$\lambda_{hs} < 2.8 \cdot 10^{-4}$]
neutron-nucleon scattering
molecular spectroscopy
invisible Higgs at LHC

- dominated by WBF [by now improved]

$$\text{BR}_\text{inv} < 26\% \quad \Rightarrow \quad \lambda_{hs} \lesssim 8.7 \cdot 10^{-3}$$

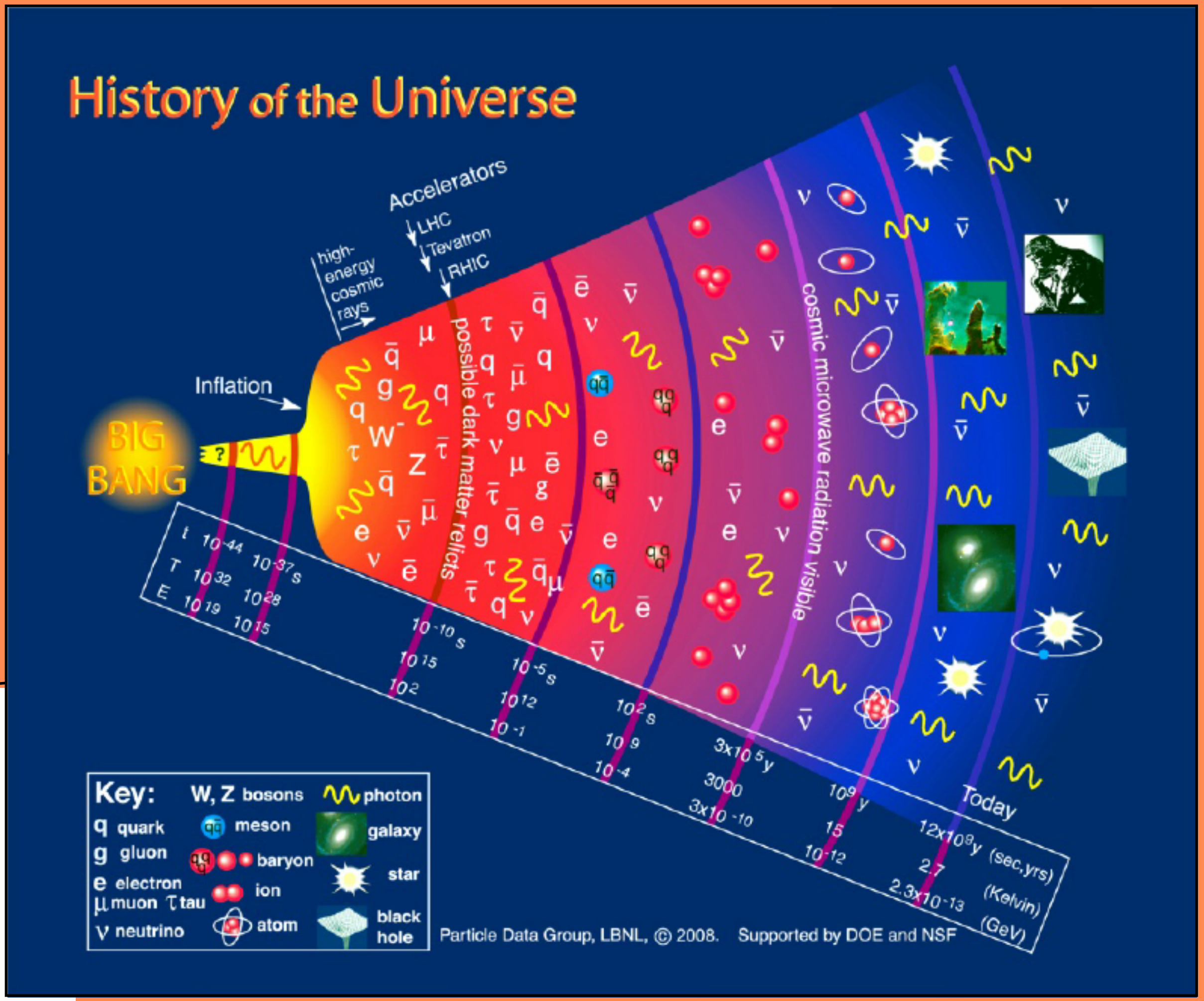
- enhancement for pseudoscalar $h \to a$

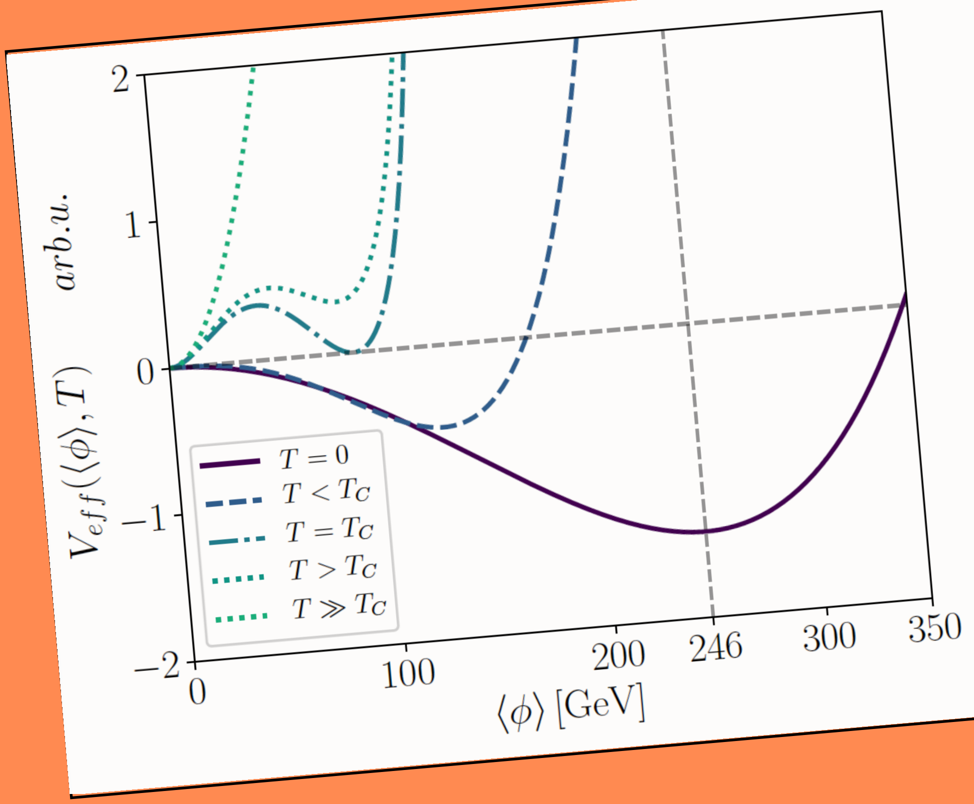
$\Rightarrow$ new LHC measurements, etc...



Electroweak Phase Transition

$$V_{\text{eff}}(\phi_i, T) = V_{\text{tree}}(\phi_i) + V_{\text{CW}}(\phi_i) + V_T(\phi_i, T) + V_{\text{CT}}$$



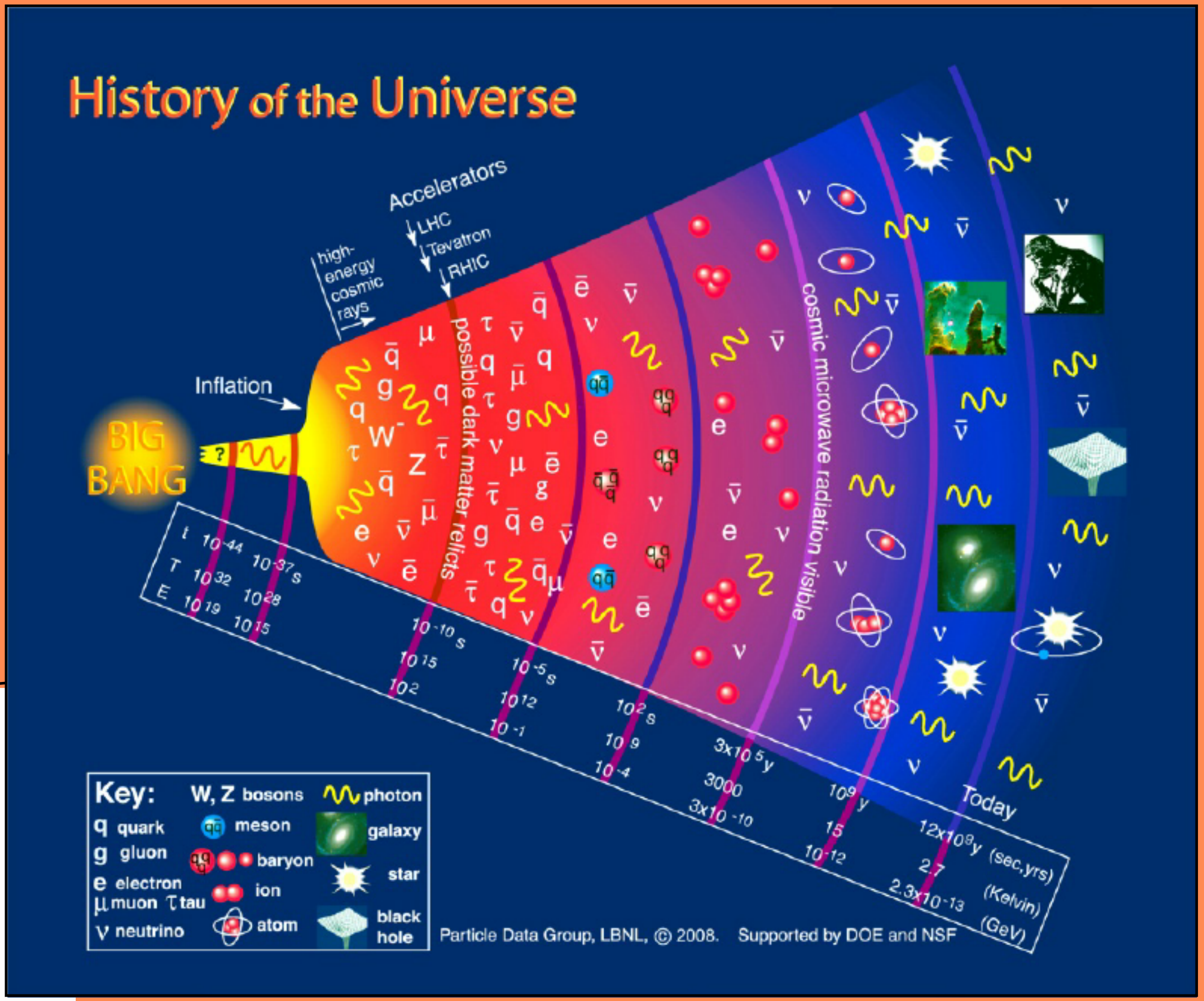


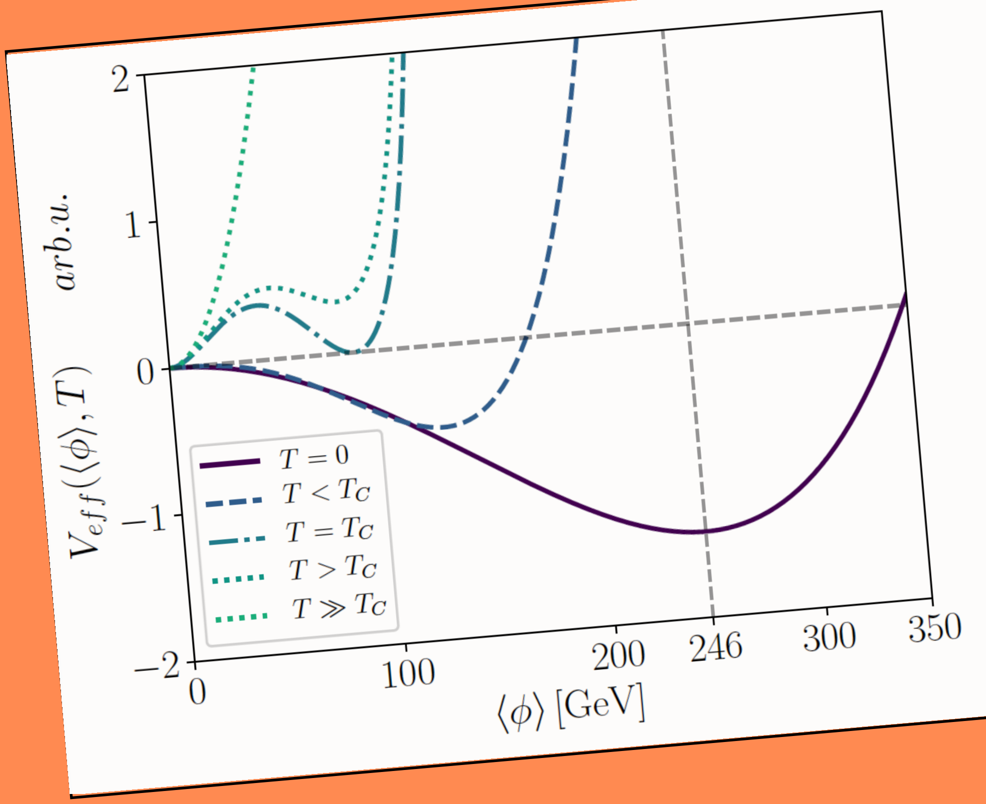
Strong EWPT:

$$\xi_C \equiv \frac{\langle\phi_C\rangle}{T_C} \gtrsim 1$$

Electroweak Phase Transition - Vacuum at non-zero temperature

$$V_{\text{eff}}\left(\phi_i, T\right) = V_{\text{tree}}\left(\phi_i\right) + V_{\text{CW}}\left(\phi_i\right) + V_T\left(\phi_i, T\right) + V_{\text{CT}}$$





Strong EWPT:

$$\boxed{\xi_C \equiv \frac{\langle\phi_C\rangle}{T_C} \gtrsim 1}$$

Vacua at non-zero Temperature - Electroweak Phase Transition

Baryon Asymmetry of the Universe [PhysRevD.98.030001]

$$\frac{n_B - n_{\overline{B}}}{n_B + n_{\overline{B}}} \approx \eta \equiv \frac{n_B}{n_\gamma} = (6.2 \pm 0.4) \cdot 10^{-10}$$

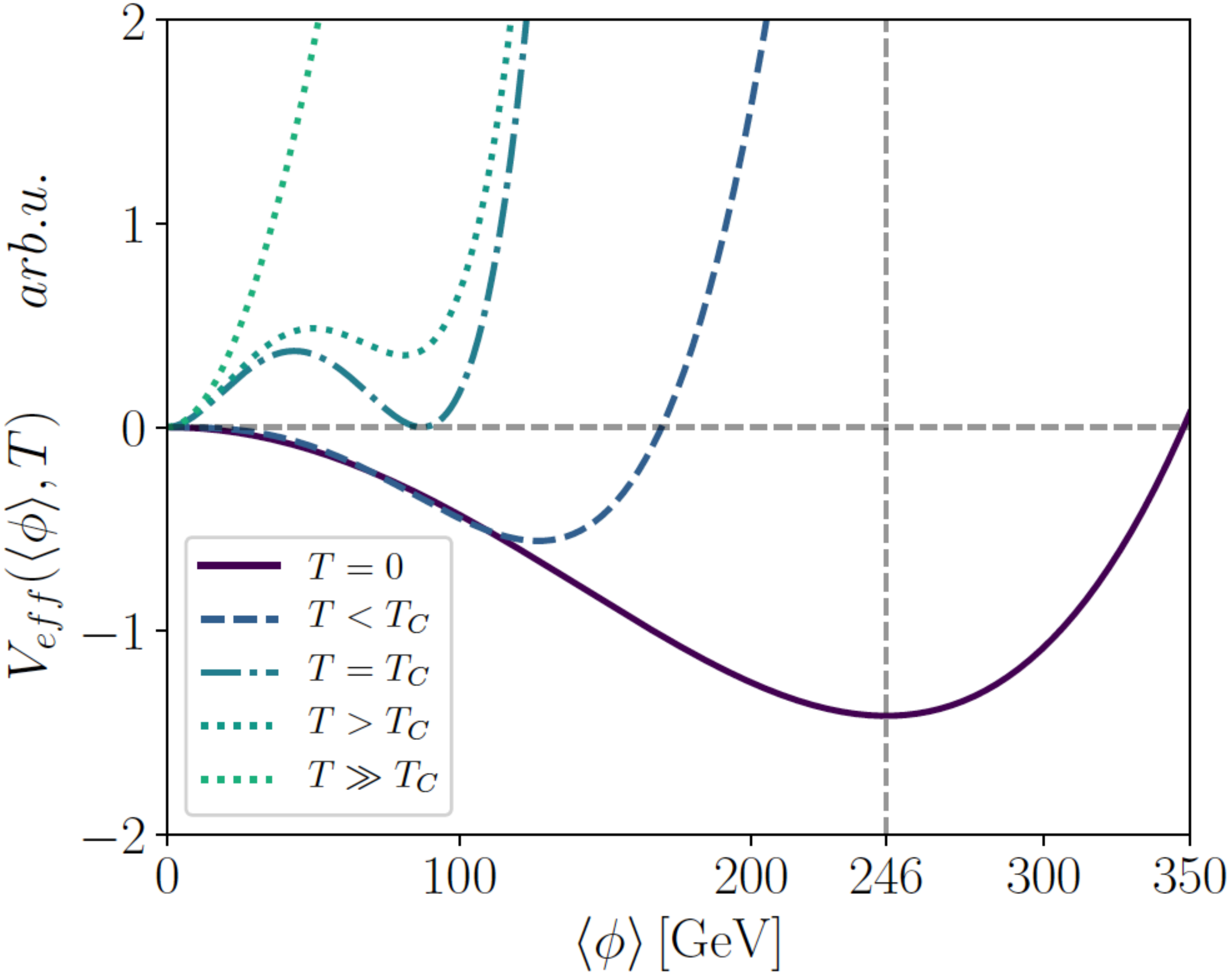
Sakharov Conditions: [Sov. Phys. Usp. 34 no.4 (1991) 392]

* baryon-number violating processes
* C- and CP-violation
* departure from thermal equilibrium

Standard Model: all three conditions are fulfilled - only qualitatively
but smooth cross-over for M_h = 125 GeV

Extended Higgs Sectors: additional scalar degrees of freedom may induce strong first order electroweak phase transition

Electroweak Vacuum - Temperature Evolution



Strong EWPT:

$$\boxed{\xi_C \equiv \frac{\langle\phi_C\rangle}{T_C} \gtrsim 1}$$

[Taken from talk by J. Müller 9/20]

BSMPT

- BSMPT: Beyond the Standard Model Phase Transitions [Basler,MM,18;Basler,MM,Müller,'20]
  * C++ code for the calculation of the strength of the electroweak phase transition in extended Higgs sectors

- One-loop effective potential at finite temperature:

$$\boxed{V_{\mathrm{eff}}\left(\phi_i, T\right) = V_{\mathrm{tree}}\left(\phi_i\right) + V_{\mathrm{CW}}\left(\phi_i\right) + V_T\left(\phi_i, T\right) + V_{\mathrm{CT}}}$$

- Coleman-Weinberg potential:

$$V_{\mathrm{CW}} = \sum_j \frac{n_j}{64\pi^2}(-1)^{2s_j} m_j^4 \left[\ln\left(\frac{m_j^2}{\mu^2}\right) - c_j\right]$$

- Temperature-dependent potential:

$$V_T = \sum_k n_k \frac{T^4}{2\pi^2} J_{\pm}^{(k)}\left(m_k/T\right)$$

- Counterterm potential:

$$V_{\mathrm{CT}} = \sum \frac{\partial V_{\mathrm{tree}}}{\partial p_i}\delta p_i + \sum \delta T_k\left(\phi_k + \omega_k\right)$$

- Renormalization conditions:
  tree-level masses & mixing elements
  = loop-corrected ones

$$0 = \partial_{\phi_i}\left(V_{\mathrm{CW}} + V_{\mathrm{CT}}\right)\big|_{\phi_k = \langle\phi_k\rangle(T=0)},$$

$$0 = \partial_{\phi_i}\partial_{\phi_j}\left(V_{\mathrm{CW}} + V_{\mathrm{CT}}\right)\big|_{\phi_k = \langle\phi_k\rangle(T=0)}$$

Update of BSMPT

[Basler,MM,Müller, submitted to Comput.Phys.Commun]

What is new:

- Computation of the baryon asymmetry of the Universe (BAU) in 2 different approximations

  * FH approximation (based on semiclassical force) [Cline eal,´98;Kainulainen eal,´01;Fromme eal]
  * VIA approximation (based on VEV insertion method) [Riotto,´95,´97]

  1- solution of quantum transport equations to obtain left-handed fermion excess in front of bubble wall
  2- left-handed fermion excess translated into baryon asymmetry through electroweak sphaleron transition

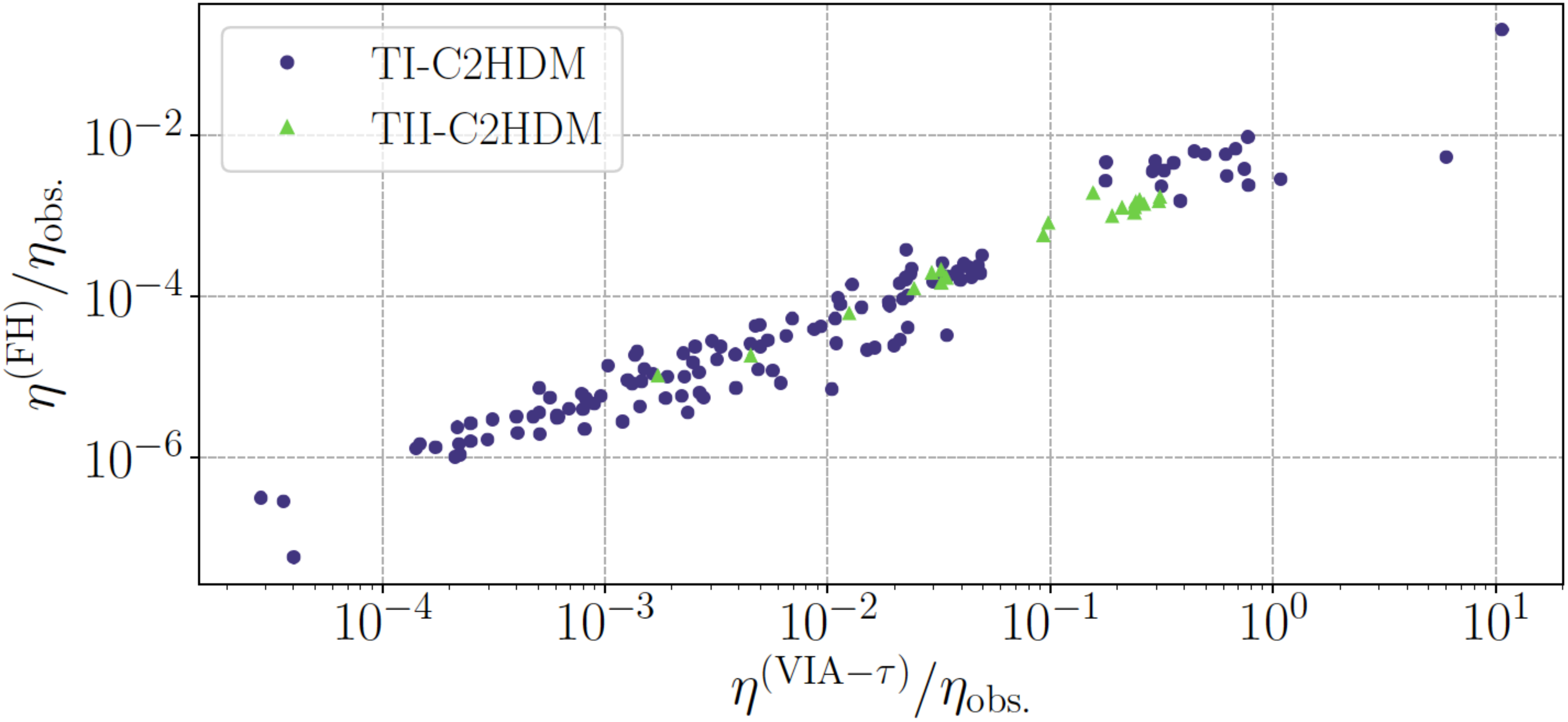
- Possibility to vary renormalisation scale

- Implementation of new model: singlet-extended SM (CxSM) (so far 2HDM, C2HDM, N2HDM)

Results EWBG

Preliminary

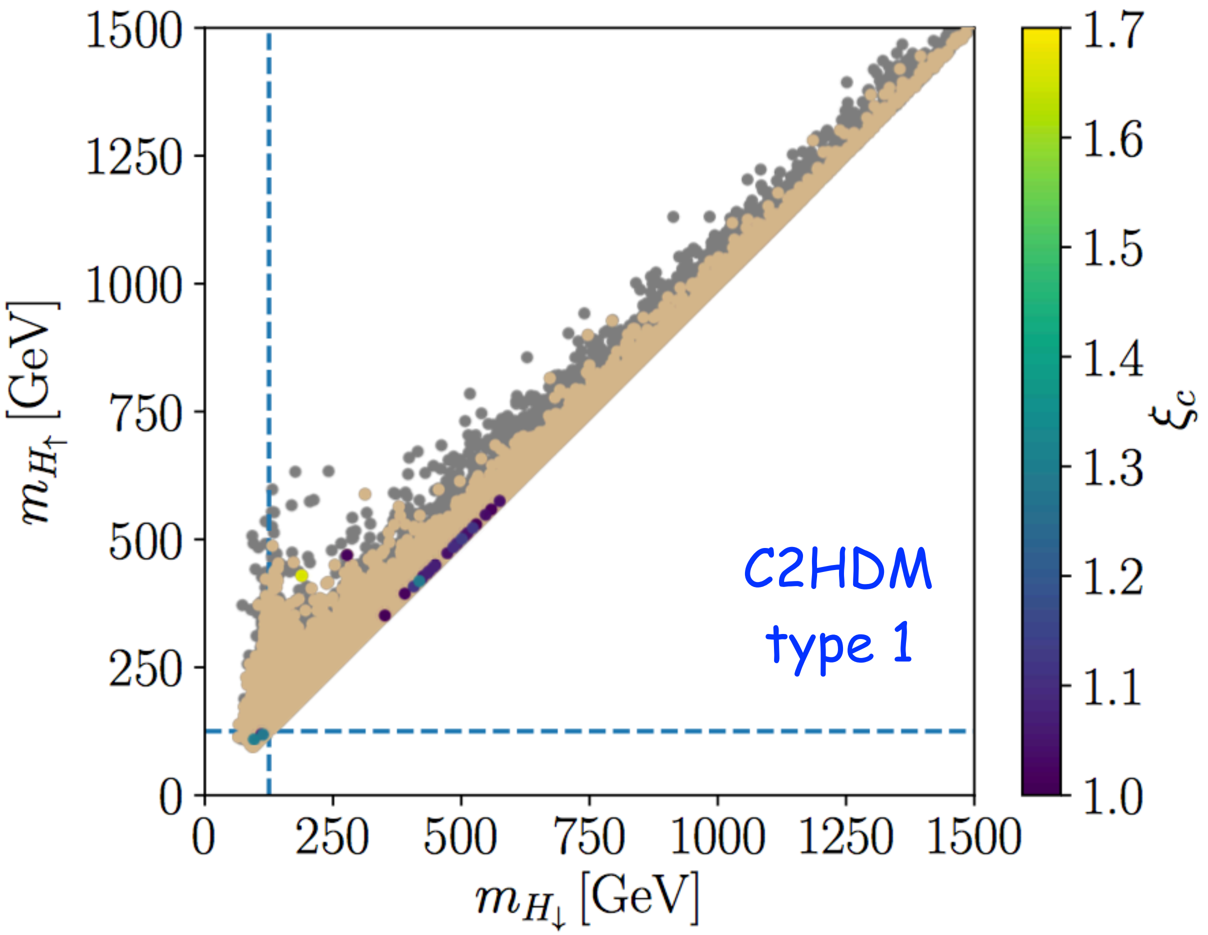
[Basler,MM,Müller]

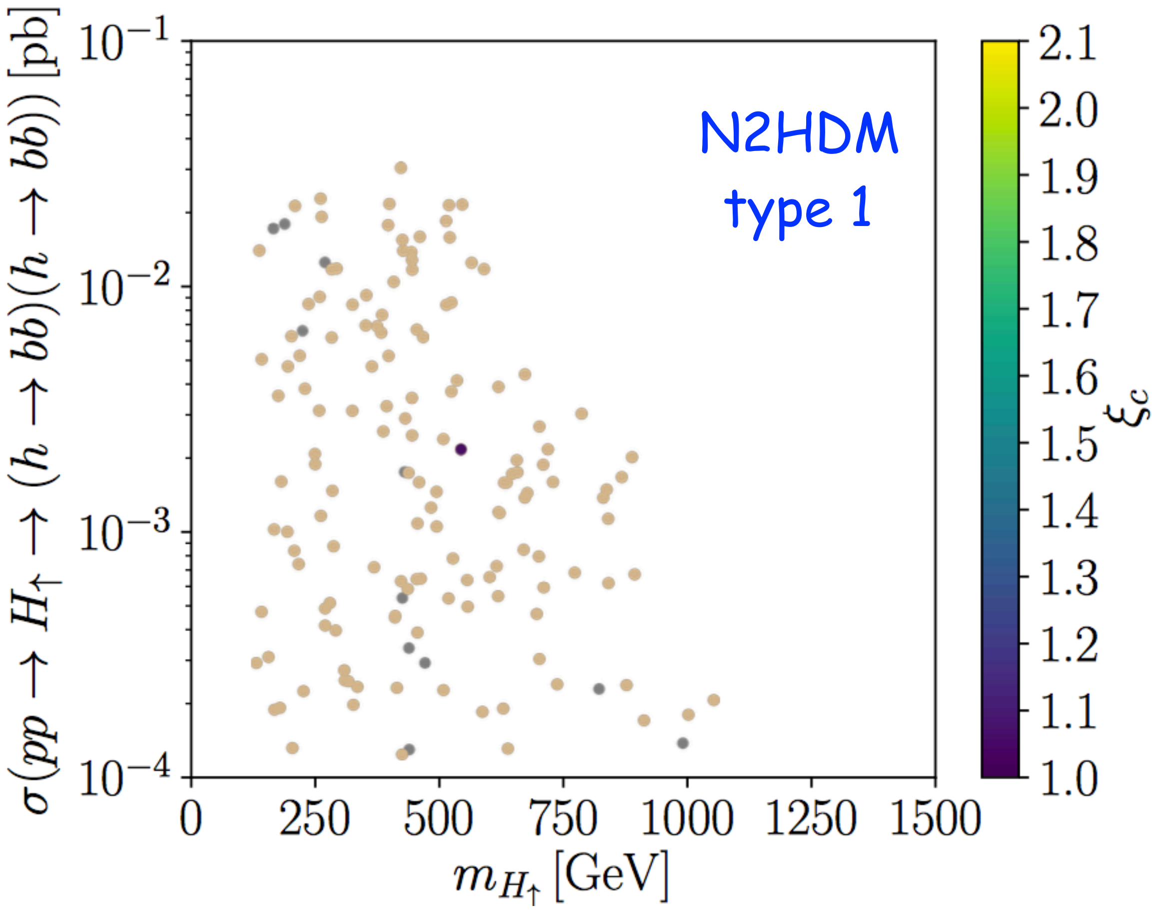


CP-violating 2HDM (C2HDM) type I (TI) and type II (TII)
wall velocity v_W=0.1

Non-minimal Higgs Sectors and Strong First Order EWPT

[Basler,MM,Müller, JHEP05 (2020) 016]





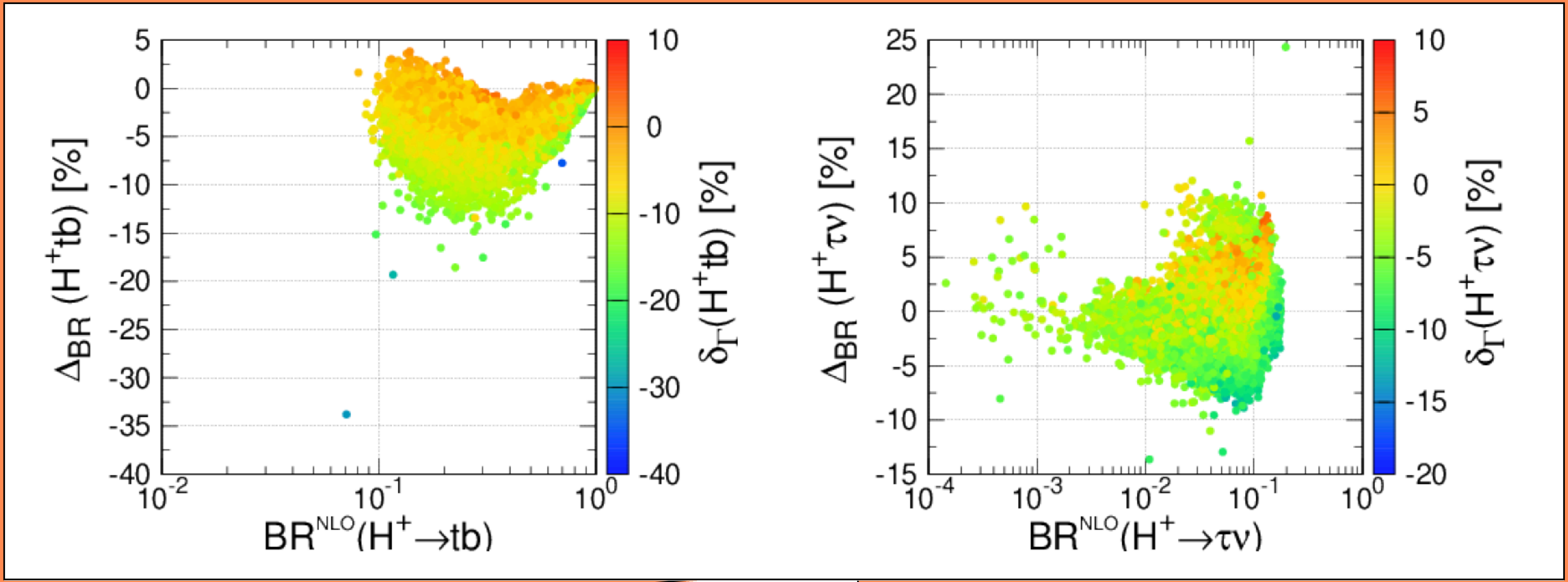
scan in C2HDM/N2HDM parameter space, retain points compatible with exp/theor constraints

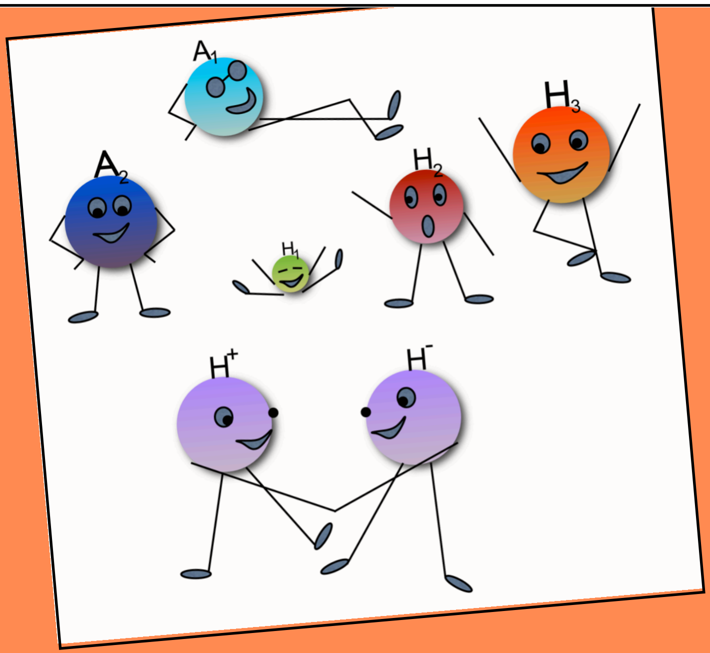
* grey points: compatible with constraints

* brown points: fulfill additionally NLO vacuum stability and NLO perturbative unitarity constraints

* color code: strength of phase transition

Higher-Order Corrections to NMSSM Higgs Decays





Higher-Order Corrections to Charged NMSSM Higgs Boson Decays

[Thi Nhung Dao, MM, Shruti Patel, Kodai Sakurai, in preparation]

* No direct sign of new physics yet -> search for indirect signs in Higgs sector

* Very SM-like nature of discovered Higgs boson -> precise theoretical predictions

* Status of higher-order corrections to NMSSM Higgs decays:

  - NLO SUSY-EW and SUSY-QCD corrections to A decays into stops [Baglio eal,'15]
  - Full one-loop renormalization of the NMSSM, 1-loop corrections to Higgs decays [Bélanger eal,'16,'17]
  - Generic calculation of one-loop corrections in $\overline{\text{DR}}$ scheme [Goodsell eal,'17]
  - One-loop corrections into fermions and gauge bosons in CP-violating NMSSM [Domingo eal,'18]
  - Effects of Sudakov logarithms on fermonic decays of heavy Higgs bosons [Domingo,Paßehr,'19]
  - NLO SUSY-EW and SUSY-QCD corrections to neutral on-shell Higgs decays in the CP-violating NMSSM [Baglio,Dao,MM,'19]
  - Complete one-loop and two-loop $O(\alpha_t\alpha_s)$ corrections to trilinear Higgs self-couplings [Nhung eal,'13,MM eal,'15]
  - EW corrections to H^+ decays into gauge plus Higgs bosons [Dao eal,'19]
  - Strategies to preserve gauge invariance in these decays [Domingo,Paßehr,'20]

The NMSSM Higgs Sector

* Next-to-Minimal Supersymmetric Extension (NMSSM) Higgs Sector:
2 complex Higgs doublets (ensure supersymmetry and that no anomalies occur)
plus gauge-singlet chiral superfield (relaxed stop mass bound, rich phenomenology, relaxed EDM bounds, no mu-problem)

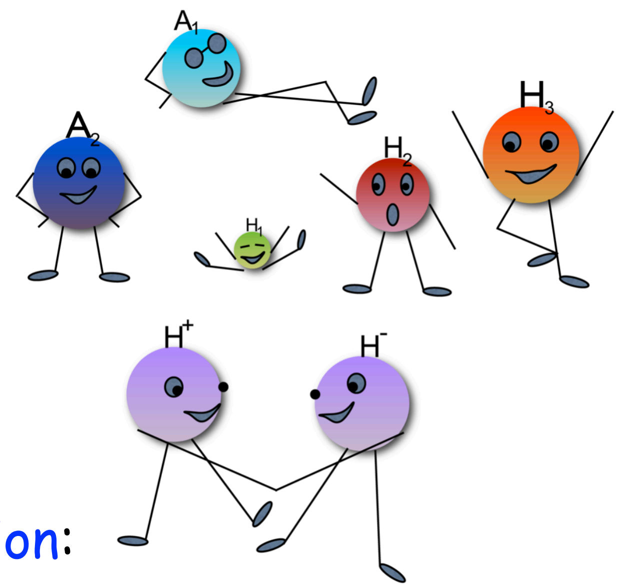
* Tree-level Higgs potential in the CP-violating (complex) NMSSM:

$$\begin{aligned} V_H &= (|\lambda S|^2 + m_{H_d}^2) H_d^\dagger H_d + (|\lambda S|^2 + m_{H_u}^2) H_u^\dagger H_u + m_S^2 |S|^2 \\ &+ \frac{1}{8}(g_2^2 + g_1^2)(H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{1}{2} g_2^2 |H_d^\dagger H_u|^2 \\ &+ |-\epsilon^{ij} \lambda H_{d,i} H_{u,j} + \kappa S^2|^2 + \left[-\epsilon^{ij} \lambda A_\lambda S H_{d,i} H_{u,j} + \frac{1}{3} \kappa A_\kappa S^3 + \mathrm{h.c.} \right] \end{aligned}$$

* Higgs fields after electroweak symmetry breaking

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

Renormalization



* Higgs Mass Spectrum:

CP-conserving: 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: 5 CP-mixing Higgs bosons H_k (k=1,...,5),

2 charged Higgs bosons H^+, H^-

* UV divergences of one-loop charged Higgs boson decays require renormalization: introduce counterterm parameters and wave function renormalization constants

$$p_0 = p + \delta p \qquad\qquad \phi_0 = \sqrt{Z_\phi}\phi = \left(1 + \frac{\delta Z_\phi}{2}\right)\phi.$$

* Input parameters (renormalization schemes): - Higgs sector (mixed on-shell (OS)-$\overline{\text{DR}}$):

$$\{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, M^2_{H^\pm}, v, s_{\theta_W}, e, \tan\beta, |\lambda|, v_s, |\kappa|, \text{Re}\, A_\kappa, \varphi_\lambda, \varphi_\kappa, \varphi_u, \varphi_s\}$$

tadpole parameters: $(t)_\Phi = t_\Phi = \dfrac{\partial V_H}{\partial \Phi}, \;\; \Phi = h_d, h_u, h_s, a_d, a_u, a_s$

[Baglio,Dao,MM,´19]

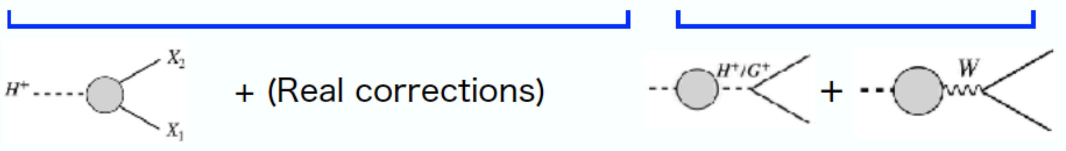
- Electroweakino sector: $|M_1|, |M_2|$ and their complex phases (OS or $\overline{\text{DR}}$)

- Squark sector $m_t, m_b, m^2_{\tilde{Q}_3}, m^2_{\tilde{t}_R}, m^2_{\tilde{b}_R}, A_t, A_b,$ (OS or $\overline{\text{DR}}$) slepton sector $m_\tau, m^2_{\tilde{L}_3}, m^2_{\tilde{\tau}_R}, A_\tau$ (OS)

Loop-Corrected Charged NMSSM Higgs Boson Decays

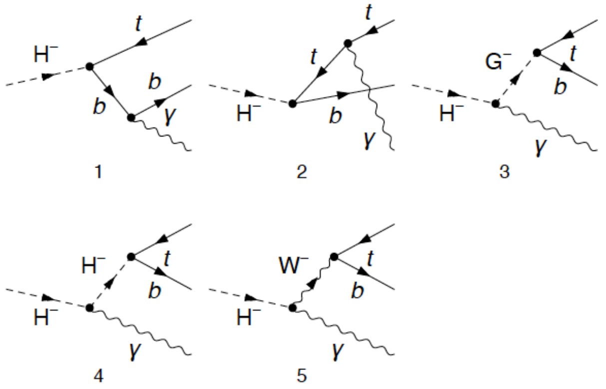
* SUSY-EW and SUSY-QCD loop Corrections to H^+ decays into on-shell particles: quark and lepton pair final states, electroweakino pairs, squark and slepton pairs, Higgs plus charge W boson final state

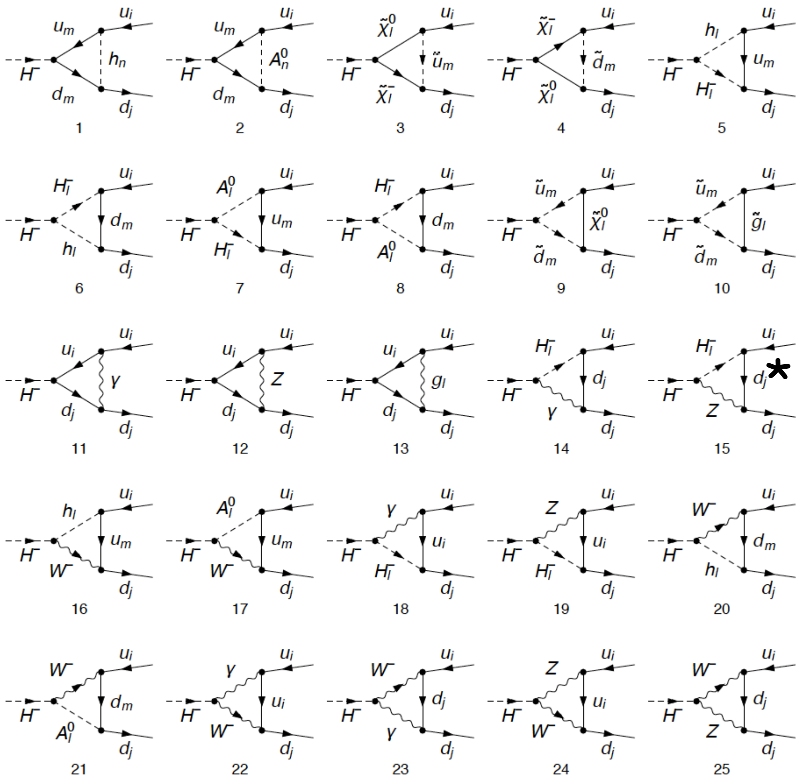
$$\Gamma(H^\pm \to X_1 X_2) = (\text{Resummed factors}) \times \Gamma_{\text{LO}}(H^\pm \to X_1 X_2)$$
$$\times \left[1 + \Delta_{\text{QCD}} + \Delta_{\text{SUSYQCD}} + \Delta_{(\text{SUSY+})\ \text{EW}} + \Delta^{\text{ext.}}_{\text{H}^+\text{H}^-} + \Delta^{\text{ext.}}_{\text{H}^+\text{G}^-/\text{W}^-}\right]$$



* Resummed factors: Δ_b corrections H^+ into (s)quarks, Z factors for H^+-> WH_i

* Real corrections: to cancel infrared divergences





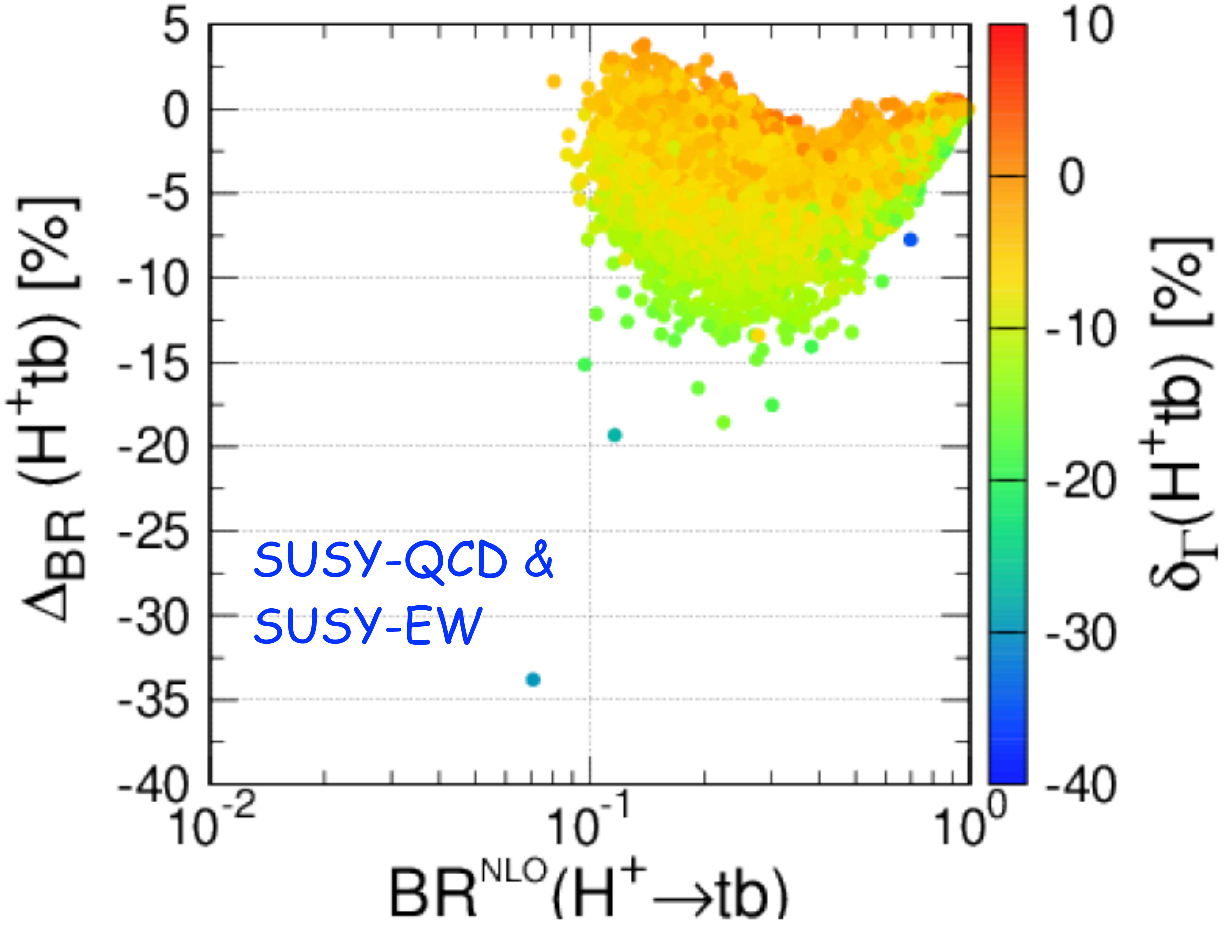
Newly calculated:

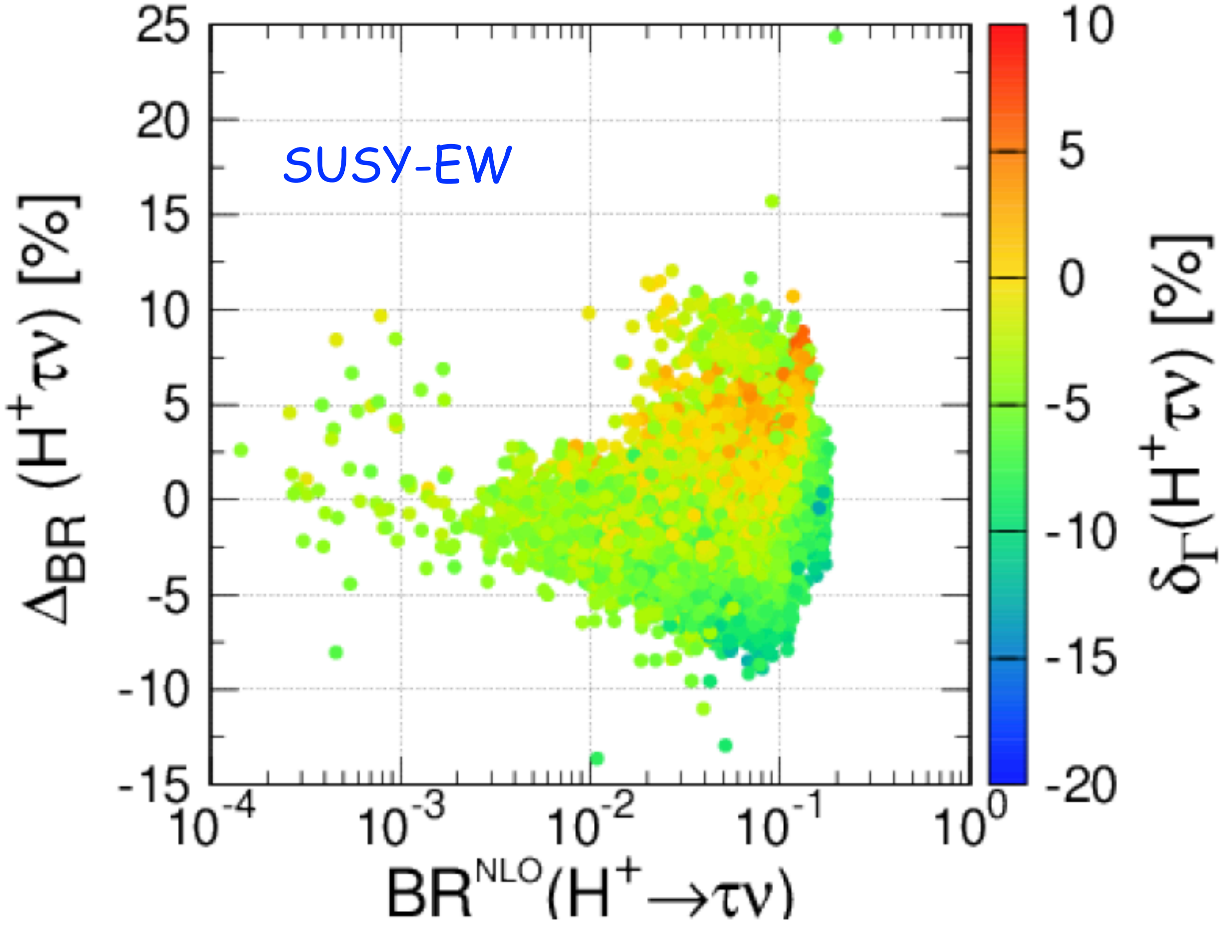
$$\Delta_{\text{SUSYQCD}} + \Delta_{(\text{SUSY+})\ \text{EW}} + \Delta^{\text{ext.}}_{\text{H}^+\text{H}^-} + \Delta^{\text{ext.}}_{\text{H}^+\text{G}^-/\text{W}^-}$$

Numerical Results

Preliminary

[Dao,MM,Patel,Sakurai]



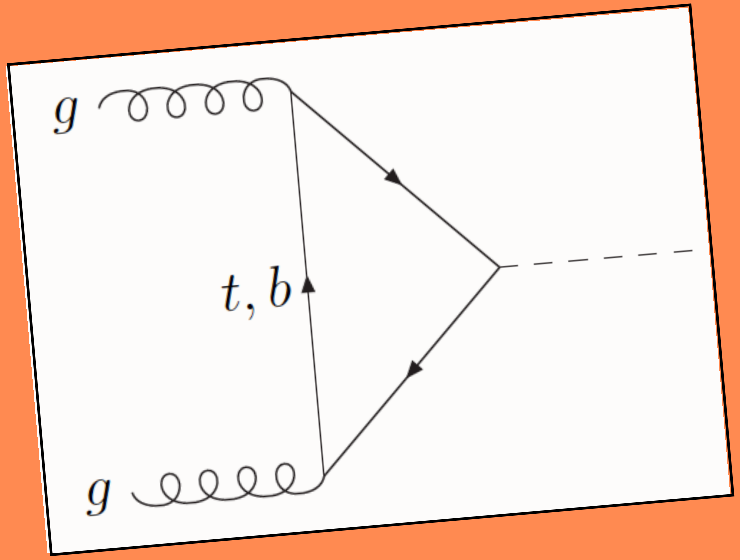


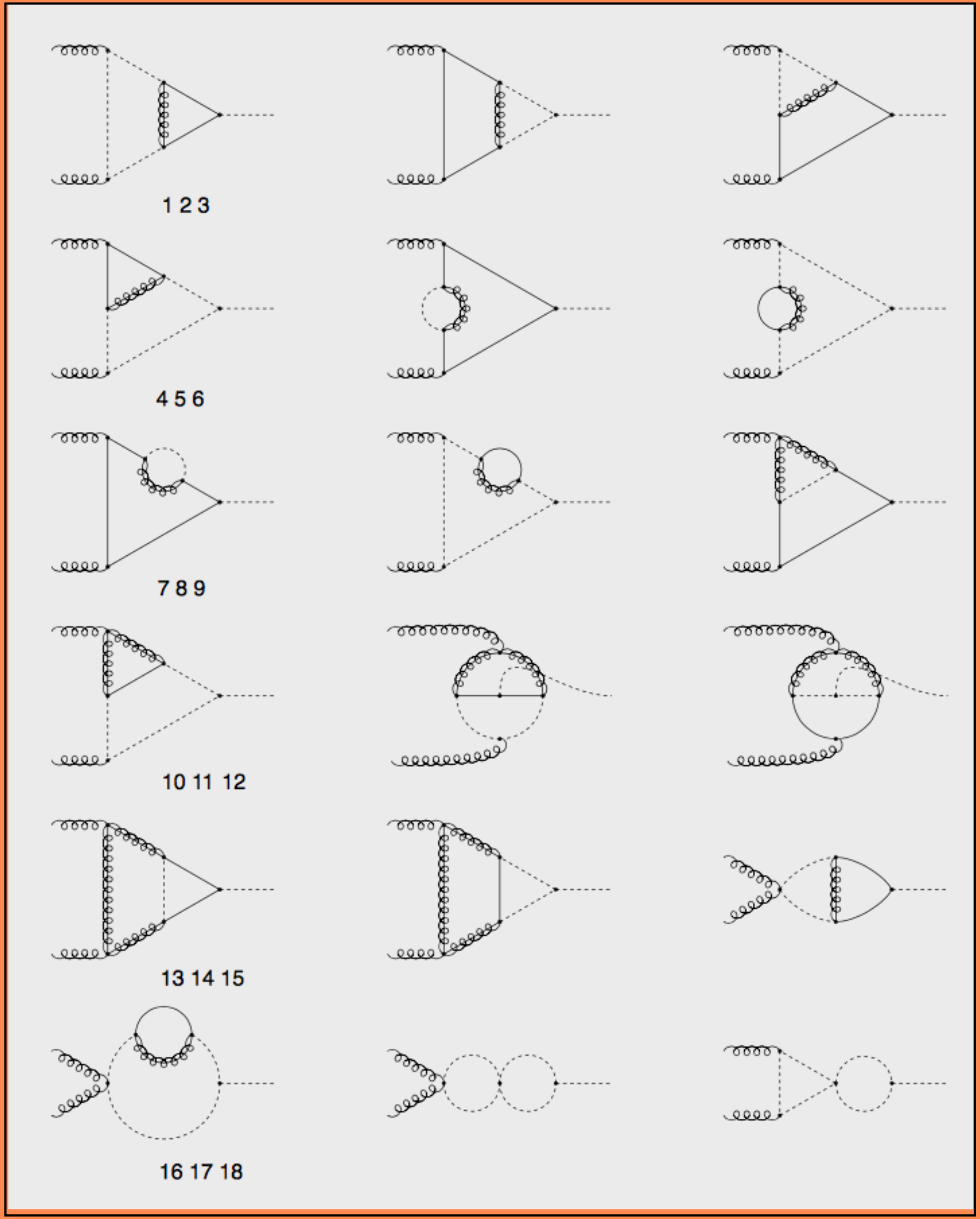
$$\Delta_{\rm BR}(H^\pm XX) = \frac{{\rm BR}^{\rm NLO}(H^\pm \to XX) - {\rm BR}^{\rm LO}(H^\pm \to XX)}{\max({\rm BR}^{\rm NLO}(H^\pm \to XX), {\rm BR}^{\rm LO}(H^\pm \to XX))}$$

$$\delta_\Gamma(H^\pm XX) = \frac{\Gamma(H^\pm \to XX)^{\rm NLO}}{\Gamma(H^\pm \to XX)^{\rm LO}} - 1$$

Scan in NMSSM parameter space keep points compatible with Higgs data

NLO SUSY-QCD Corrections to gg->A





NLO SUSY-QCD Corrections to Gluon Fusion into A

[Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira, in preparation]

✦ Goal:

Compute SUSY-QCD corrections to gluon fusion into pseudoscalar MSSM Higgs boson including the full quark, squark and gluino mass dependences

✦ Status:

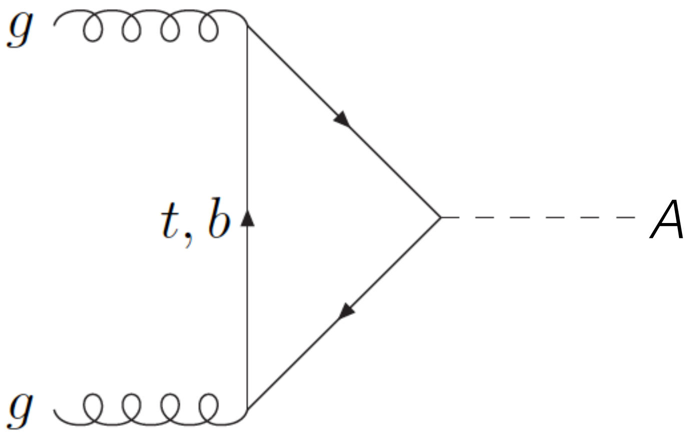
- QCD corrections to gg->H up to N^3LO in the limit of heavy top quarks [Djouadi eal,’91;Dawson,’91;Dawson,Kauffmann,’94;Harlander,Kilgore,’01,’02;Anastasiou,Melnikov,’02;Ravindran eal,’03; Marzani eal,’08;Gehrmann eal,’12;Anastasiou eal,’13;Kilgore,’14;Li eal,”15;Anastasiou eal,’15,’16]
- Full quark-mass dependence at NLO [Graudenz eal,’93;Spira eal,’95;Harlander,Kant,’05;Aglietti eal,’07;Anastasiou eal,’07]
- Subleading NNLO terms in the heavy top expansion [Harlander,Ozeren,’09;Pak,Rogal,Steinhauser,’09,’10]
- Threshold resummation in heavy top limit [Krämer eal,’98;Spira,’98;Catani eal,’03;Moch,Vogt,’05;Ravindran,’06, Idilbi eal,’06;Ahrens eal,’09;deFlorian,Grazzini,’09;deFlorian eal,’14;Catani eal,’14,Bonvini,Rottoli,’15]
- Finite quark mass effects in resummation [deFlorian,Grazzini,’12;Bonvini,Marzani,’14;Spira,’16]
- Electroweak corrections [Degrassi,Maltoni,’04,´ 05;Aglietti eal,’04;Actis,Passarino,Sturm,Uccirati,’08,’09]
- QCD corrections to quark loops in gg->A [Djouadi eal,’91;Graudenz eal,’93;Spira eal,’93,’95;Dawson eal,’96; Krämer eal,’98;Schmidt,Spira,’16], to squark loops in gg->H [MM,Spira,’06;Aglietti eal,’07]
- SUSY-QCD correction through gluino exchange in heavy loop mass limit [Harlander,Steinhauser,’03, Degrassi,Slavich,’08;Harlander,Hofmann,Mantler,’11]
- Genuine SUSY-QCD corrections including full mass dependence in gg->H [Anastasiou eal,’08;MM,Rzehak,Spira,’1

NLO SUSY-QCD Corrections to Gluon Fusion into A

[Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira, in preparation]

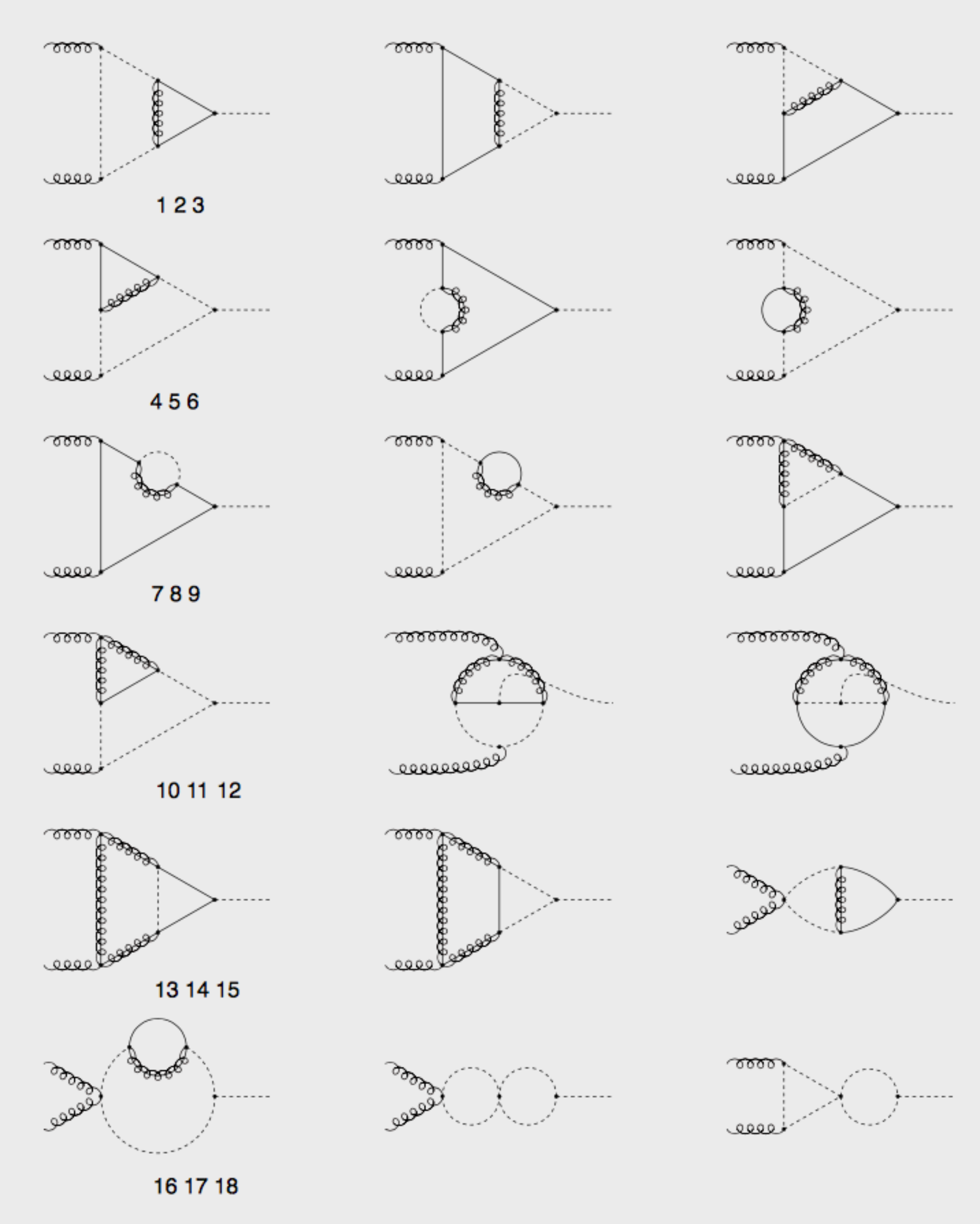
QCD corrections to quark and squark loops increase cross section by 100%,
EW corrections amount to 5%,
genuine SUSY-QCD corrections are large, mass effects are important

Extension to gg-A: Mediated by heavy top quarks at LO (no squark loops)



The Calculation

Computation of full set of diagrams contributing to the SUSY-QCD corrections:



Numerical Evaluation

* Evaluation of massive two-loop diagrams:

- at present no mathematical algorithm to calculate the massive two-loop diagrams analytically ->
- numerical integration of the five-dimensional Feynman integrals
- UV singularities have to be separated from regular finite remainder (no IR or collinear singularities) -> suitable endpoint subtractions - example:

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}}$$ singular for $x = 1$ for $\epsilon \to 0$ rewriting integral ->

$$\begin{aligned}\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} &= \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} \\ &= \boxed{\frac{f(1)}{\epsilon}} + \boxed{\int_0^1 dx\, \frac{f(x)-f(1)}{1-x}} + \mathcal{O}(\epsilon)\end{aligned}$$

singular and finite part

- virtual particle threshold: $m^2 \to m^2(1-i\bar{\epsilon})$, instabilities removed by integrations by parts (reduce power of denominator responsible for these instabilities) - example:

$$\int_0^1 dx\, \frac{f(x)}{(a+bx)^2} = \frac{f(0)}{ab} - \frac{f(1)}{b(a+b)} + \int_0^1 \frac{dx}{b}\, \frac{f'(x)}{a+bx}$$

(a+bx=0 at virtual thresholds)

* Special attention: treatment of gamma 5 within dimensional regularization

($\overline{\text{MS}}$ α_s w/ 5 active flavours (SUSY-restoring counterterms [Martin,Vaughn,'93]), y_b, A_b as in [Accomando eal,'12])

Numerical Evaluation

* No real corrections related to SUSY-QCD (<- only massive particles in virtual diagrams)

* NLO result for gg->A:

$$\sigma_{\rm NLO}(pp \to A + X) = \sigma_{\rm LO} + \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}:$$ with

our calculation

$$\begin{aligned}
\sigma_{\rm LO} &= \sigma_0 \tau_A \frac{d\mathcal{L}^{gg}}{d\tau_A} \\
\Delta\sigma_{\rm virt} &= \frac{\alpha_s(\mu)}{\pi} \sigma_0 \tau_A \frac{d\mathcal{L}^{gg}}{d\tau_A} \left(\boxed{C_{QCD}} + \boxed{C_{SQCD}}\right) \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \sigma_0 \int_{\tau_A}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \left\{ -z P_{gg}(z) \log\frac{M^2}{\tau s} \right. \\
&\qquad \left. + \boxed{d_{gg}(z)} + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z}\right)_+ \right\} \\
\Delta\sigma_{gq} &= \frac{\alpha_s(\mu)}{\pi} \sigma_0 \int_{\tau_A}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \left\{ -\frac{z}{2} P_{gq}(z) \log\frac{M^2}{\tau s(1-z)^2} + \boxed{d_{gq}(z)} \right\} \\
\Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu)}{\pi} \sigma_0 \int_{\tau_A}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \boxed{d_{q\bar{q}}(z)}
\end{aligned}$$

☐ contain mass effects

Status

Done:

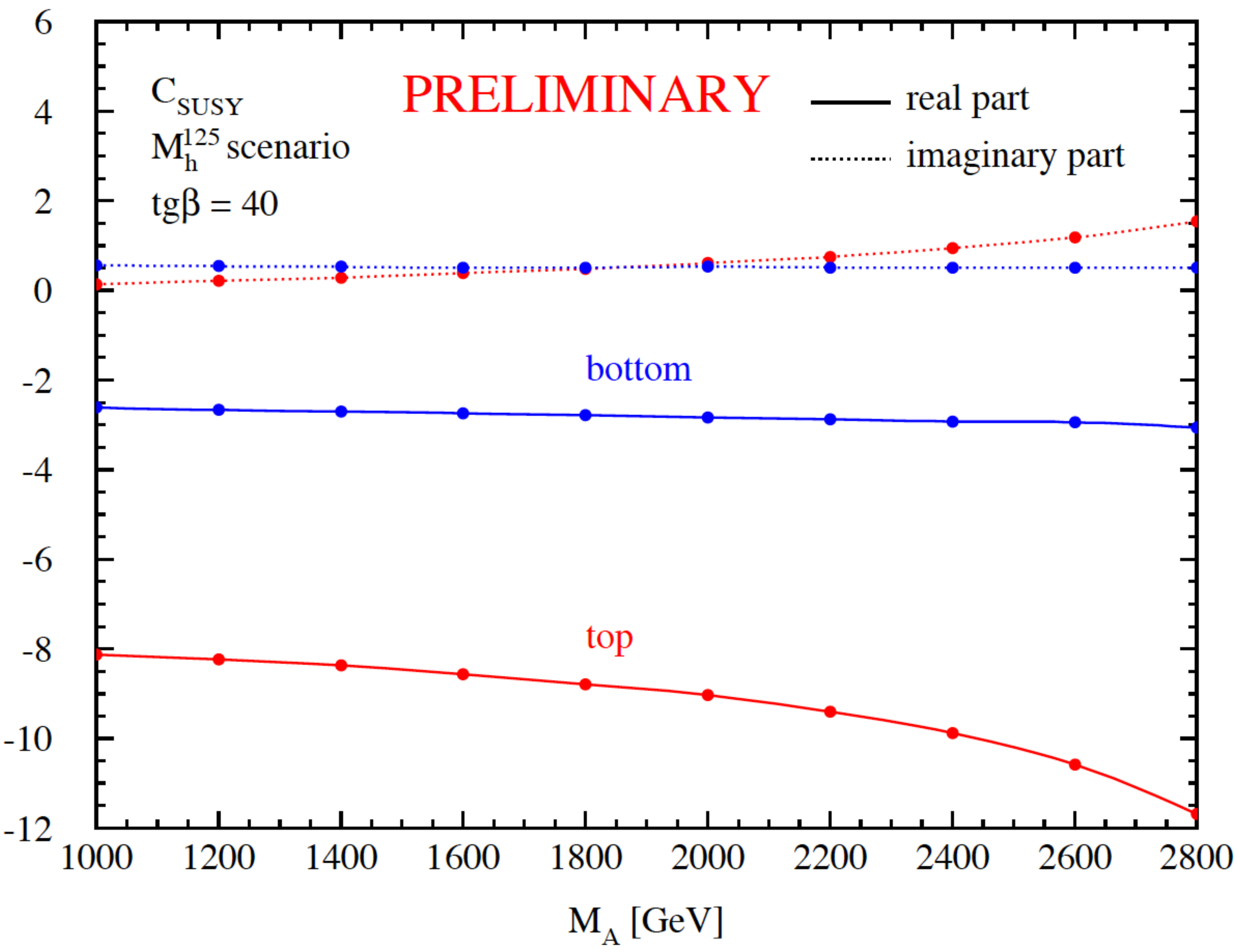
- computation of virtual two-loop integrals finished and cross-checked
- applied γ_5 scheme: Larin

Next steps:

- γ_5 : comparison with Breitenlohner-Maison scheme; application of Pauli-Villars regularization
- inclusion of Δ_b and Δ_t effects
- transfer results to A->$\gamma\gamma$
- implementation in Higlu [Spira] and SusHi [Harlander,Liebler,Mantler] for computation of cross section
- comparison with approximate calculations [Degrassi,Slavich;Harlander,Steinhauser]
- perform numerical analysis

Preliminary Results

[Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira]



$$\sigma_0^A = \frac{G_F\alpha_s^2}{128\sqrt{2}\pi}\left|\sum_Q g_Q^A A_Q^A(\tau_Q)\right|^2$$

$$A_Q^A(\tau_Q) \to A_Q^A(\tau_Q)\left[1 + C_{SUSY}^Q\frac{\alpha_s}{\pi}\right]$$

Summary

* Vacua of Extended Higgs Sectors:

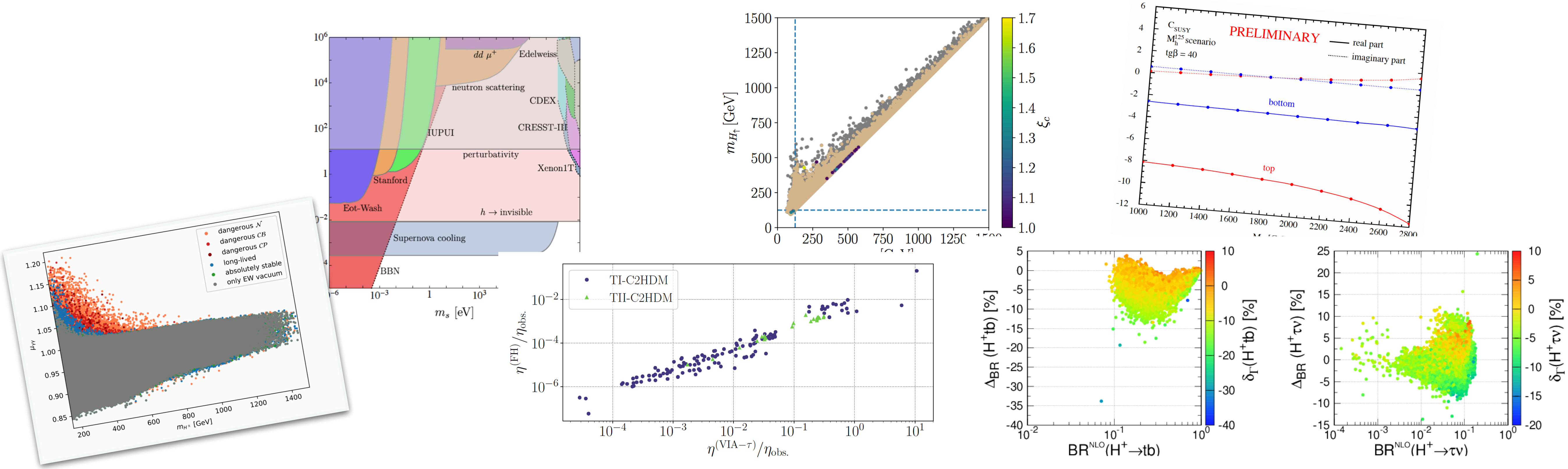
- at zero temperature [Ferreira,Santos,MMM,Weiglein,Wittbrodt, JHEP09 (2019),006]
- at non-zero temperature - EWPT [Basler,MM,Müller, submitted to Comput.Phys.Commun.] [Basler,MM,Müller, JHEP05 (2020) 016]

* Higgs Portal: [Bauer,Foldenauer,Reimitz,Plehn, 2005.13551]

* SUSY-QCD and SUSY-EW corrections to NMSSM H^+ decays:

[Thi Nhung Dao, MM, Shruti Patel, Kodai Sakurai, in preparation]

* NLO SUSY-QCD corrections to gg->A: [Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira, in preparation]



Congratulations

Nobel Prize for Physics 2020

Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy"

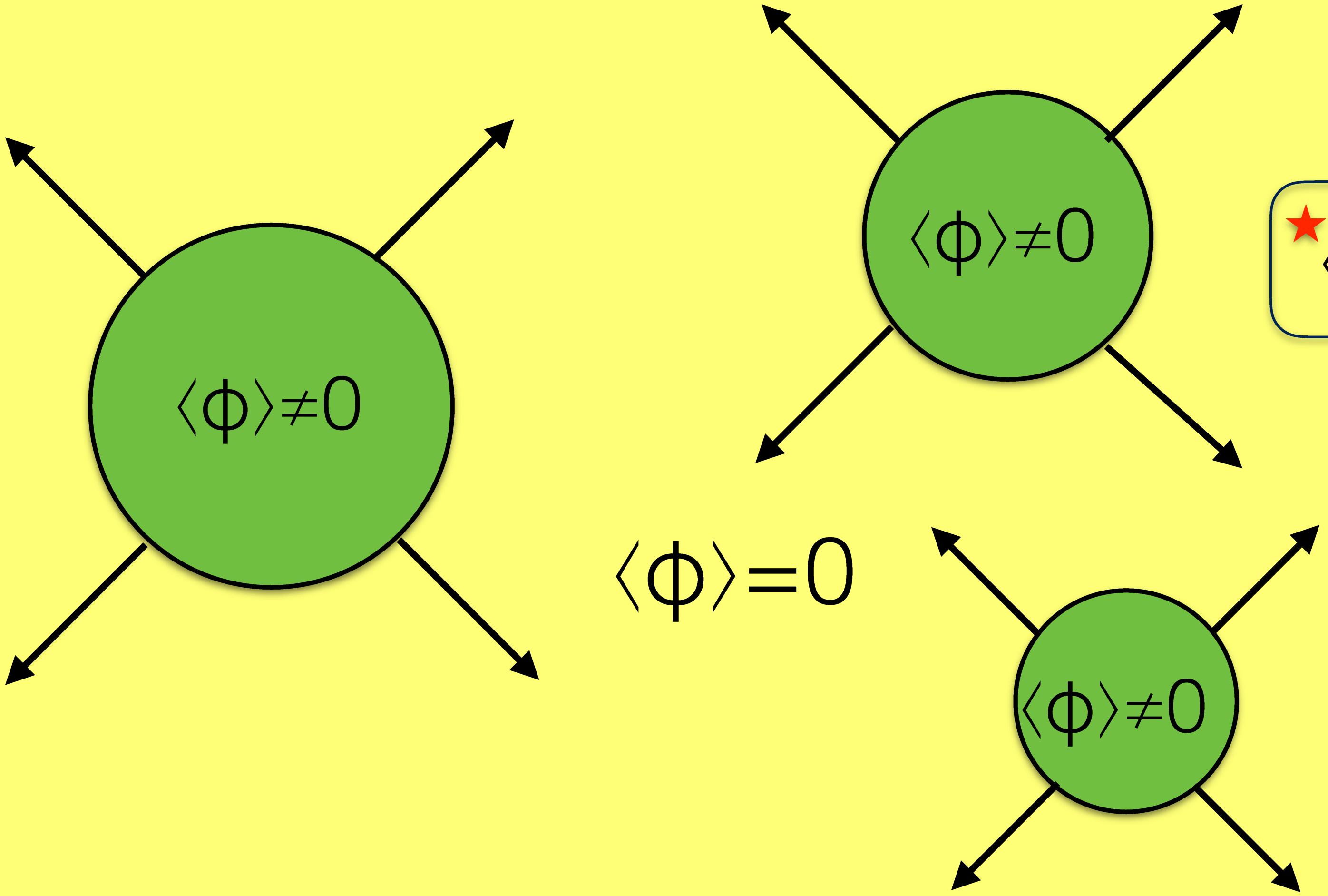
Nobel Prize for Chemistry 2020

Emmanuelle Charpentier and
Jennifer A. Doudna
"for the development of a method for genome editing“

Baryogenesis in a nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle\phi_c(T_c)\rangle/T_c \geq 1$

ϕ_c, T_c

VEV and *T* at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall ★

Renormalization

* Complex phases $\varphi_u, \varphi_s, \varphi_\lambda, \varphi_\kappa, \varphi_{M_1}, \varphi_{M_2}$ need not be renormalized at one-loop level

[Baglio eal,´19;Graf eal,´12]

* Tadpole renormalization: $\delta t_{\phi_i} = t^{(1)}_{\phi_i}, \quad \phi_i = h_d, h_u, h_s, a_d, a_s$

* SM electroweak parameters: e, M_W, M_Z renormalized on-shell (OS)

* Charged Higgs mass: renormalized OS

* Parameters: tanβ, $|\lambda|, |\kappa|, v_s, \mathrm{Re}A_\kappa$ renormalized $\overline{\text{DR}}$

* Gaugino mass parameters: $|M_1|, |M_2|$ renormalized OS (OS1,OS2) or $\overline{\text{DR}}$ [Baglio,Dao,MM,´19]

* Squark sector: $m_t, m_b, m^2_{\tilde{Q}_3}, m^2_{\tilde{t}_R}, m^2_{\tilde{b}_R}, A_t, A_b$ renormalized OS or $\overline{\text{DR}}$ [Baglio,Dao,MM,´19]
Slepton sector renormalized OS

* Neutral and charged Higgs fields: $\overline{\text{DR}}$, fermion, neutralino, chargino fields: OS