University of Glasgow

BSM MULTI-HIGGS: IMPLICATIONS IN EWPT AND COLLIDERS

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(based on L. Biermann, C. Borschensky, C. Englert, M. Mühlleitner, **WN** 2408.08043)

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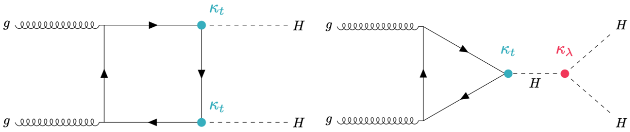
IPPP, Durham

INTRODUCTION

MULTI-HIGGS PROCESSES

- hh has been a cornerstone for physics Beyond the Standard Model (BSM) at the LHC.

(ATLAS 2023; CMS 2023)



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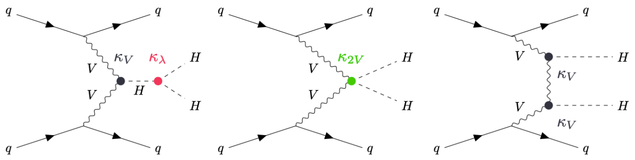

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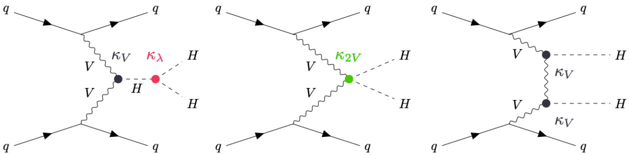


- hhh is gradually gaining more focus.

(Papaefstathiou et al. 2016; Fuks et al. 2016; Chen et al. 2016; Robens et al. 2020; Papaefstathiou et al. 2019; Papaefstathiou et al. 2021; Florian et al. 2020; Papaefstathiou and Tetlalmatzi-Xolocotzi 2023; Stylianou et al. 2023; Delgado et al. 2023; Anisha et al. 2024; Brigljevic et al. 2024; Karkout et al. 2024; ATLAS 2024)

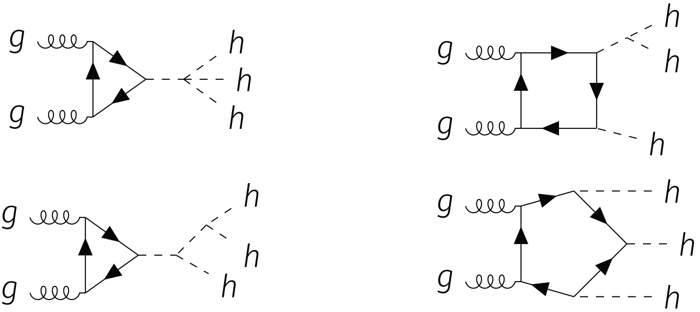
⇒ Crucial for future collider search strategies.

THE MORE, THE MERRIER?

- SM cross-section for **hhh** (LO)

$$\boxed{\sigma_{hhh}^{ggF} = \mathcal{O}(50\ \text{ab})} \sim \textbf{4 (10) events} \quad \text{(HL-LHC)}$$

(Florian et al. 2020)



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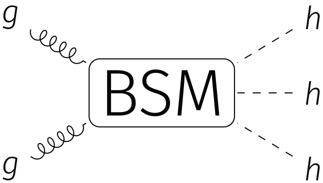

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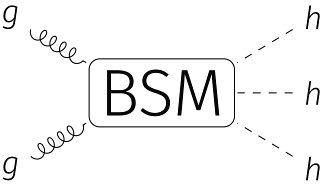
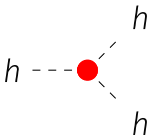
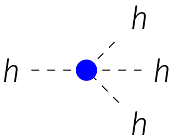


- SMEFT vs HEFT.

(Delgado et al. 2023; Anisha et al. 2024)

SMEFT VS HEFT





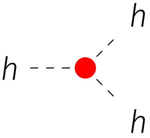
SMEFT VS HEFT

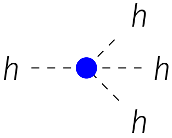
- SMEFT is a linear extension around the SM point.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{d\leq 4} + \sum_{i,d=5,6,\ldots} \frac{C_i^{(d)}\mathcal{O}_i^{(d)}}{\Lambda^{d-4}}.$$

(Henning et al. 2016; Ilaria Brivio et al. 2019) ...

SMEFT VS HEFT





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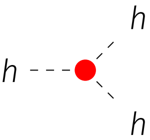
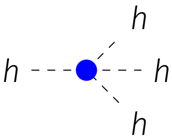
$$\mathcal{L}_{\text{SMEFT}}^{\text{Higgs},d\geq 6} \supset \frac{1}{\Lambda^2} C_6 |\Phi|^6 + \frac{1}{\Lambda^4} C_8 |\Phi|^8, \quad \Phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

SMEFT VS HEFT





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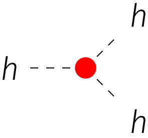

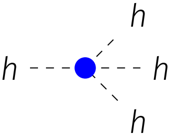

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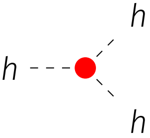
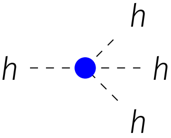
- **HEFT** is a non-linear realisation of EWSB.

$$\Phi \to \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}, \qquad \mathbf{U} = \exp\left(\frac{i\sigma^j\pi_j}{v}\right)$$

(Alonso et al. 2013; I. Brivio et al. 2014; Gerhard Buchalla et al. 2014; G. Buchalla et al. 2016)

SMEFT VS HEFT





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$$\mathcal{L}_{\text{HEFT}}^{\text{Higgs}} \supset -\left(\frac{1}{2}m_h^2 h^2 + \frac{1}{2}\kappa_3\frac{m_h^2}{v}h^3 + \frac{1}{2}\kappa_4\frac{m_h^2}{v^2}h^4\right)$$

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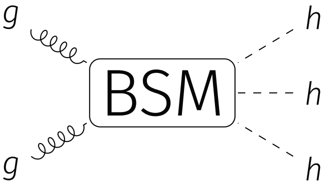
$\Rightarrow$ HEFT can effectively capture any decorrelated new physics effects in **hhh** that is absent in di-/single Higgs.

THE MORE, THE MERRIER?



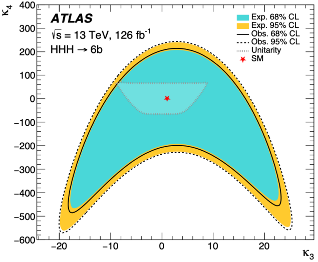
- SMEFT vs HEFT.

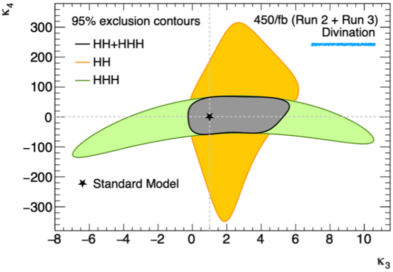
(Delgado et al. 2023; Anisha et al. 2024)

- **hhh** $\Rightarrow$ Higgs potential (κ_3, κ_4)

COUPLING CONSTRAINTS

- hhh significantly improves constraints on κ_4 .





(ATLAS 2024; Fuks et al. 2016)

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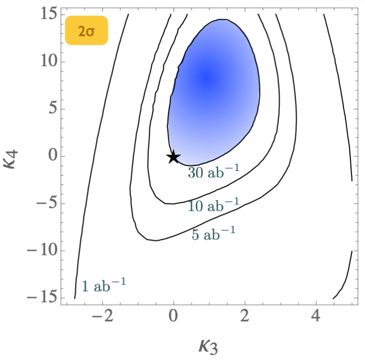

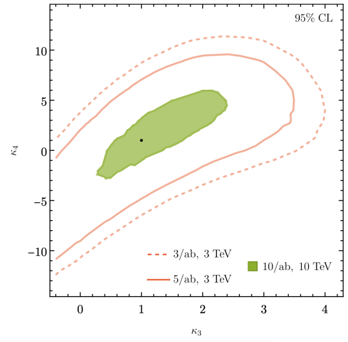

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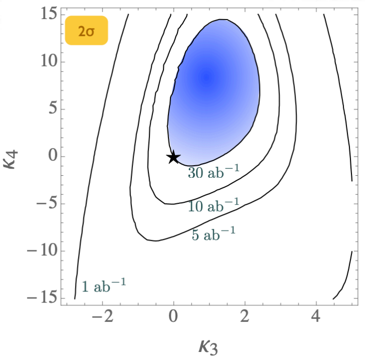

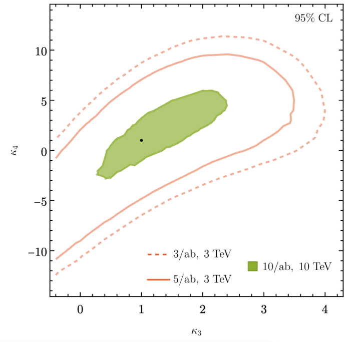

(Fuks et al. 2016; Stylianou et al. 2023)

- Order of magnitude **improvement** in precision at FCC-hh and high energy lepton colliders.

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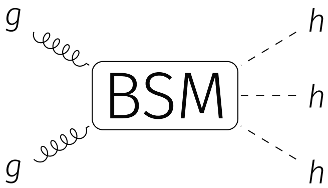

- SMEFT vs HEFT.

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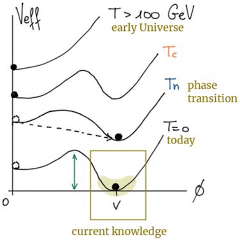
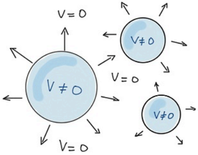
- hhh $\Rightarrow$ Higgs potential $\Rightarrow$ EW vacuum structure $\Rightarrow$ EWPTs, baryogenesis, stability of the universe, etc.

(Papaefstathiou and Tetlalmatzi-Xolocotzi 2023; Stylianou et al. 2023; Karkout et al. 2024)

ELECTROWEAK PHASE TRANSITIONS

- EW symmetry breaking in the Early Universe at $T \sim \mathcal{O}(100)$ GeV $\Rightarrow$ activation of the Higgs Mechanism.





(Credits: Lisa Biermann)

(Sakharov 1967)

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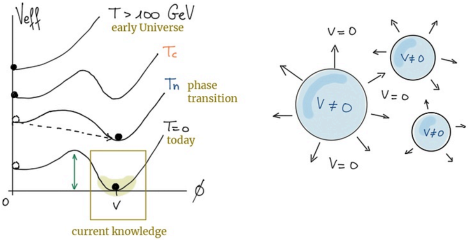


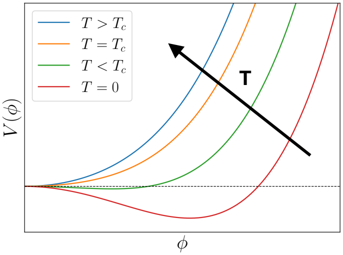
(Credits: Lisa Biermann)

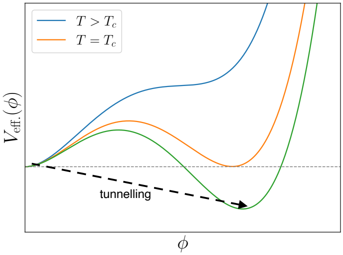
- Strong First Order PTs required to explain **EW Baryogenesis** $\Rightarrow$ Matter-antimatter asymmetry.

(Sakharov 1967)

ELECTROWEAK PHASE TRANSITIONS

- SM predicts smooth crossover for the Higgs mass, NO FOPTs!
  $\Rightarrow$ insufficient for the required baryogenesis.





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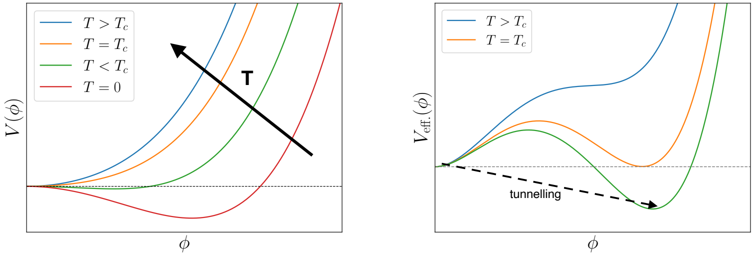

- Modifications to the scalar potential / couplings $\Rightarrow$ modified EW vacuum structure $\Rightarrow$ **Strong FOPTs**.

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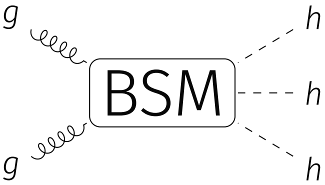

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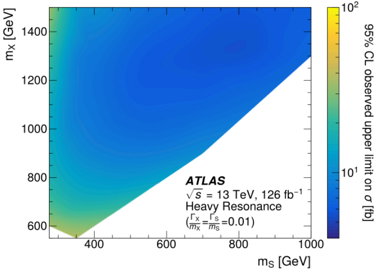
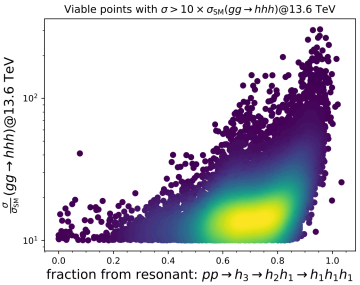
(Papaefstathiou and Tetlalmatzi-Xolocotzi 2023; Stylianou et al. 2023; Karkout et al. 2024)

- Enhancements in σ^{ggF}_{hhh}

hhh ENHANCEMENTS





(ATLAS 2024; Karkout et al. 2024)

- Upper limit on SM hhh cross-section = 59 fb.

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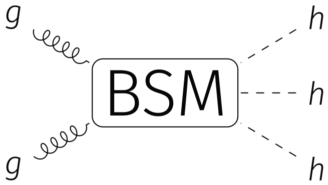

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- Enhancements in $\sigma_{hhh}^{ggF} \sim \mathcal{O}(100)$ **events** at HL-LHC, can be relevant at FCC-hh.

(Papaefstathiou et al. 2019; Papaefstathiou et al. 2021; Papaefstathiou et al. 2016; Fuks et al. 2016; ATLAS 2024)

METHODOLOGY

THE SCALAR EXTENSIONS

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

(softly broken $\mathbb{Z}_2$ symmetry)

R2HDM : $m_{11}^2, m_{22}^2, m_{12}^2, \lambda_{1,\dots,4}, \lambda_5 \in \mathbb{R}$ (CP-Conserving)

C2HDM : $m_{11}^2, m_{22}^2, \lambda_{1,\dots,4} \in \mathbb{R}, \; m_{12}^2, \lambda_5 \in \mathbb{C}$ (CP-Violating)

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Next-to-Minimal 2HDM (**N2HDM**): R2HDM + Φ_S ← Singlet

$$V_{N2HDM} = V_{R2HDM} + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2}\left(\Phi_1^\dagger \Phi_1\right)\Phi_S^2 + \frac{\lambda_8}{2}\left(\Phi_2^\dagger \Phi_2\right)\Phi_S^2$$

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$$V_{N2HDM} = V_{R2HDM} + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \left(\Phi_1^\dagger \Phi_1 \right) \Phi_S^2 + \frac{\lambda_8}{2} \left(\Phi_2^\dagger \Phi_2 \right) \Phi_S^2$$

- R2HDM: 2 **CP-Even** neutral mass eigenstates (h, H)

$$\boxed{m_h \approx 125 \text{ GeV} < m_H}$$

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- C2HDM and N2HDM : 3 neutral mass eigenstates (H_1, H_2, H_3).

$$m_{H_1} \cong m_h \approx 125 \text{ GeV} < m_{H_2} < m_{H_3}$$

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- **Parameter scans:**

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THE SCALAR EXTENSIONS

- R2HDM: 2 **CP-Even** neutral mass eigenstates (h, H).

$$\boxed{m_h \approx 125 \text{ GeV} < m_H}$$

- C2HDM and N2HDM : 3 neutral mass eigenstates (H_1, H_2, H_3).

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- `FeynRules` $\Rightarrow$ `MadGraph_aMC@NLO`: Model implementations, generate **hh(h)** cross-sections.

(Alloul et al. 2014; Degrande et al. 2012; Darmé et al. 2023; Alwall et al. 2014)

PHASE TRANSITIONS WITH BSMPT

- **Model-independent** implementation of the one-loop daisy-resummed effective potential at finite temperature.

$$V_{\text{eff.}}(T) = \underbrace{V_0}_{\text{tree-level}} + \underbrace{V_{\text{CW}}}_{\substack{\text{One-loop potential} \\ \textit{Coleman-Weinberg}}} + \underbrace{V_{\text{CT}}}_{\substack{\text{Counter-term} \\ \text{potential}}} + \underbrace{V_{\text{T}}(T) + V_{\text{daisy}}(T)}_{T-\text{dependent}}$$

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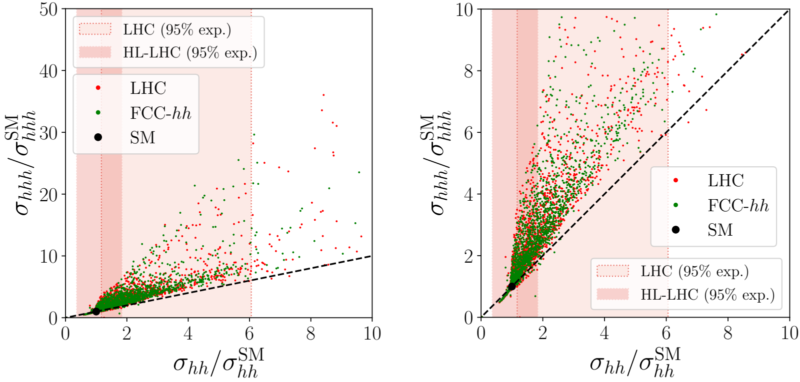
- Minimising $V_{\text{eff.}} \Rightarrow (g_{hhh},\ g_{hhhh},\ \dots) \Rightarrow$ `MadGraph`

RESULTS

R2HDM AT THE LHC AND FCC-hh

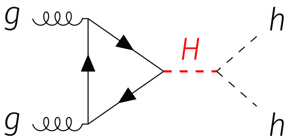


(CMS 2022)

- hhh enhanced compared to hh, although clearly correlated!
- Enhancements generalise to FCC-hh!

ENHANCING hh/hhh (R2HDM)

Resonant contributions to **hh**



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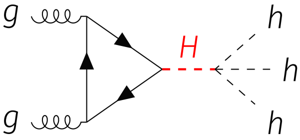
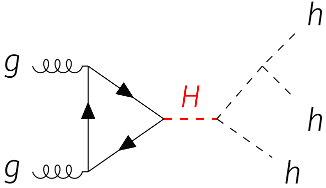
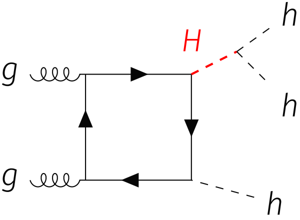
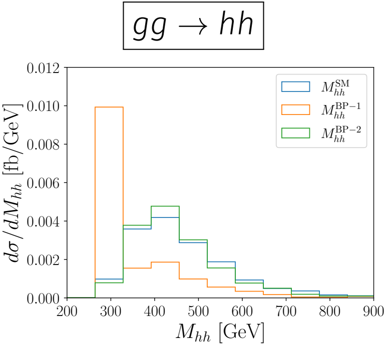
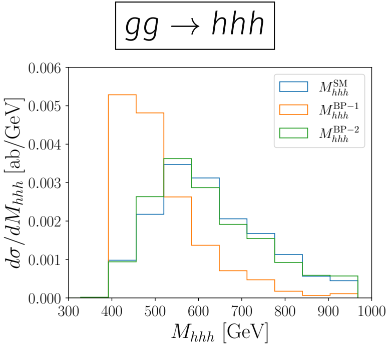






ENHANCEMENTS IN R2HDM

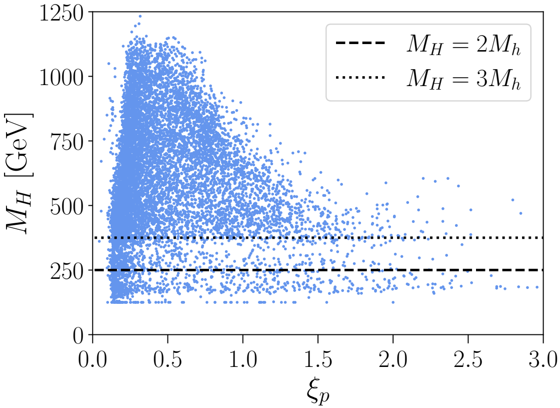




- **BP-1:** largely enhanced ($m_H \simeq 2m_h$).
- **BP-2:** SM-like.

BPs	$\sigma_{hh}/\sigma_{hh}^{\rm SM}$	$\sigma_{hhh}/\sigma_{hhh}^{\rm SM}$	M_H [GeV]	g_{hhH} [GeV]	g_{hhhH}
BP-1	3.24	15.26	274.29	75.28	0.203
BP-2	1.02	1.02	469.30	-7.11	-0.011

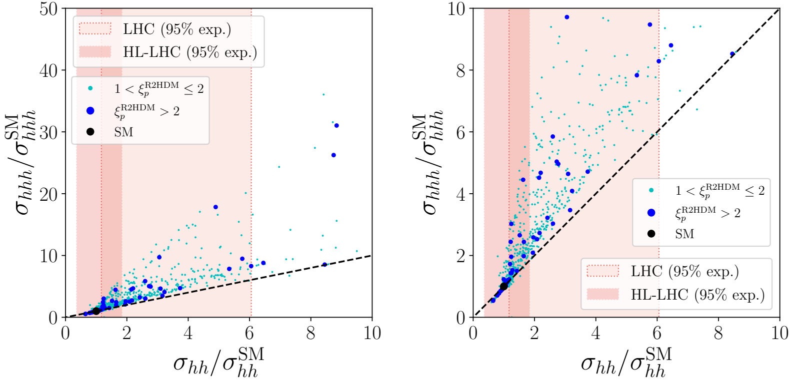
MASS SPECTRA OF R2HDM



- EWPTs driven by the physics of light dofs.

$\Rightarrow$ Stronger phase transitions proceed via lighter spectra!

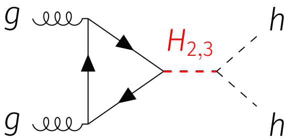
R2HDM ($\xi_p \geq 1$)



⇒ Neutral Higgs rates alone **NOT** indicative of the strength of EWPTs.

ENHANCING hh/hhh (3 DOFS)

Resonant contributions to **hh**



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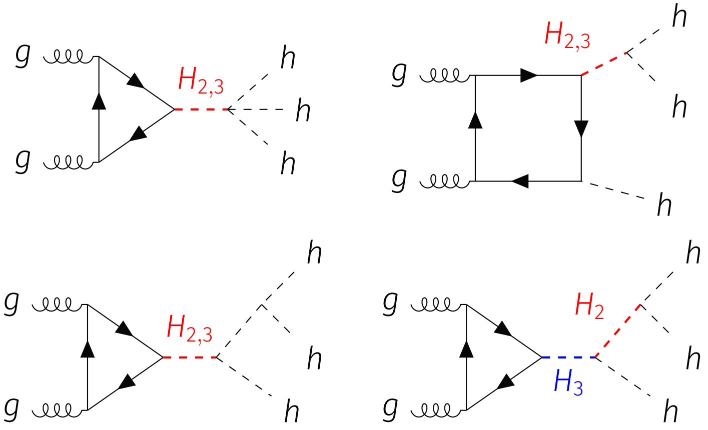
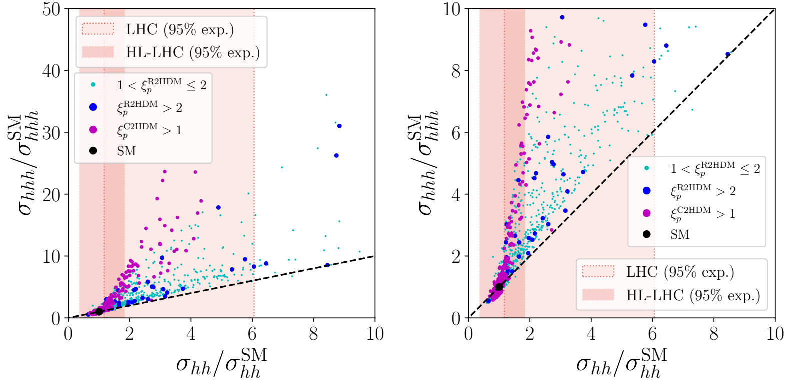
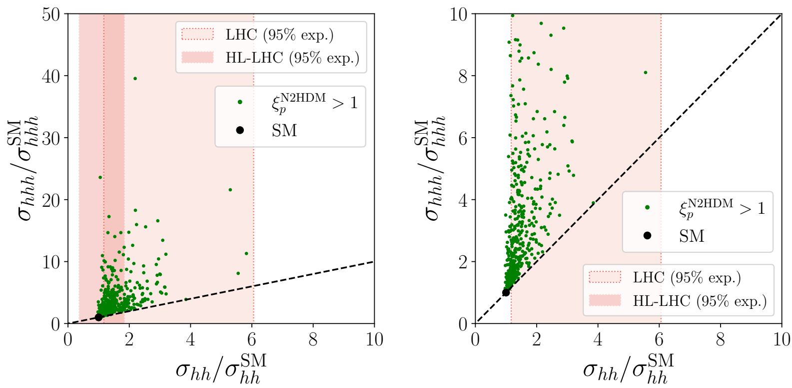


R2HDM + C2HDM



- Additional dof ⇒ hhh more enhanced.
- Stringent EDMs ⇒ Minimal CP admixture ($\lesssim 10\%$), thus no dramatic changes.

N2HDM



- The additional dof enhances hhh, like C2HDM.
- Enhancements $\sim 10 - 25$ in hhh, within HL-LHC hh sensitivity

$\Rightarrow$ can be accessible in FCC-hh!

SUMMARISING

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Thank you!