University of Glasgow

MULTI-HIGGS IN THE BSM: IMPLICATIONS IN EWPT AND COLLIDERS

Wrishik Naskar

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

25th Sept. 2024 — **Higgs Hunting 2024**

IJC Lab, Orsay, and APC, Paris

INTRODUCTION

- hh has been a cornerstone for BSM physics at the LHC.

(ATLAS 2023; CMS 2023)

INTRODUCTION

- hh has been a cornerstone for BSM physics at the LHC.

  (ATLAS 2023; CMS 2023)

- hhh is gaining more focus, crucial for future collider strategies.

  (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)

INTRODUCTION

- hh has been a cornerstone for BSM physics at the LHC.

(ATLAS 2023; CMS 2023)

- hhh is gaining more focus, crucial for future collider strategies.

(Papaefstathiou et al. 2016; Fuks et al. 2016; Chen et al. 2016; Robens et al. 2020) ...

- We analysed **multi-Higgs production** related to strong first-order EWPT for BSM scalar extensions.

INTRODUCTION

- hh has been a cornerstone for BSM physics at the LHC.

  (ATLAS 2023; CMS 2023)

- hhh is gaining more focus, crucial for future collider strategies.

  (Papaefstathiou et al. 2016; Fuks et al. 2016; Chen et al. 2016; Robens et al. 2020) ...

- We analysed **multi-Higgs production** related to strong first-order EWPT for BSM scalar extensions.

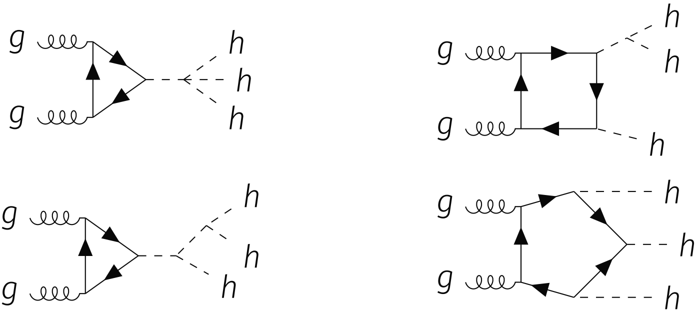
- Compared hh vs hhh: collider implications for scalar extensions.

THE MORE, THE MERRIER?

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

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

(Florian et al. 2020)

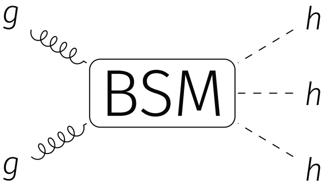


THE MORE, THE MERRIER?

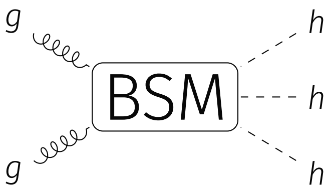
- SM cross-section for hhh (LO)

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

(Florian et al. 2020)



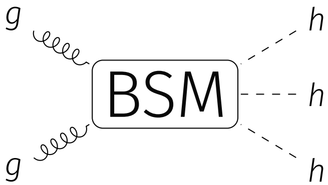
THE MORE, THE MERRIER?



- SMEFT vs HEFT.

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

THE MORE, THE MERRIER?



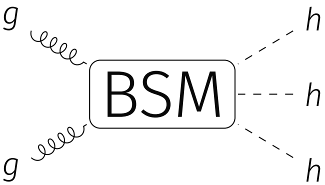
- SMEFT vs HEFT.

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

- **hhh** ⇒ Higgs potential ⇒ EW vacuum structure ⇒ EWPTs, baryogenesis, stability of the universe, etc.

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

THE MORE, THE MERRIER?



- SMEFT vs HEFT.

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

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

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

- Enhancements $\sim$ **$\mathcal{O}(100)$ 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)

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

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)

THE SCALAR EXTENSIONS

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

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)

Next-to-Minimal 2HDM (**N2HDM**): R2HDM + Φ_S $\leftarrow$ Singlet

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

THE SCALAR EXTENSIONS

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

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

- **R2HDM**: 2 Physical Mass Eigenstates (h, H)

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

- **C2HDM** and **N2HDM**: 3 Physical Mass Eigenstates (H_1, H_2, H_3).

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

METHODOLOGY

- `ScannerS`, `HiggsTools`: Vary exotic Higgs masses, mixing angles; apply theoretical & experimental constraints.

(Mühlleitner et al. 2022; Bechtle, Dercks, et al. 2020; Bechtle, Heinemeyer, et al. 2021; Bahl et al. 2023)

METHODOLOGY

- ScannerS, HiggsTools: Vary exotic Higgs masses, mixing angles; apply theoretical & experimental constraints.

(Mühlleitner et al. 2022; Bechtle, Dercks, et al. 2020; Bechtle, Heinemeyer, et al. 2021; Bahl et al. 2023)

- BSMPT: Finite temperature potential:

$$\boxed{V_{\text{eff}}(T) = V_0(T=0) + V_{\text{CW}}(T=0) + V_{\text{CT}}(T=0) + V_{\text{T}}(T) + V_{\text{daisy}}(T)}$$

(Basler, Biermann, et al. 2024; Basler, Mühlleitner, and Müller 2021; Basler and Mühlleitner 2019)

Focus on strong first-order phase transitions: $\xi_p = \frac{v_p}{T_p} > 1$.

METHODOLOGY

- `ScannerS`, `HiggsTools`: Vary exotic Higgs masses, mixing angles; apply theoretical & experimental constraints.

(Mühlleitner et al. 2022; Bechtle, Dercks, et al. 2020; Bechtle, Heinemeyer, et al. 2021; Bahl et al. 2023)

- `BSMPT`: Finite temperature potential:

$$V_{\text{eff}}(T) = V_0(T=0) + V_{\text{CW}}(T=0) + V_{\text{CT}}(T=0) + V_{\text{T}}(T) + V_{\text{daisy}}(T)$$

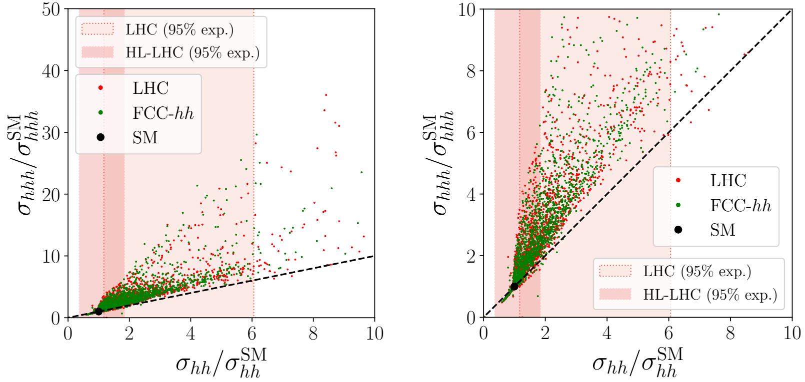
(Basler, Biermann, et al. 2024; Basler, Mühlleitner, and Müller 2021; Basler and Mühlleitner 2019)

Focus on strong first-order phase transitions: $\xi_p = \frac{v_p}{T_p} > 1$.

- `FeynRules` ⇒ `Ufo` ⇒ `MadGraph_aMC@NLO`: Implement the models, generate `hh(h)` cross-sections.

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

R2HDM AT THE LHC AND FCC-hh

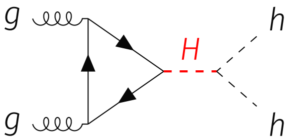


(CMS 2022)

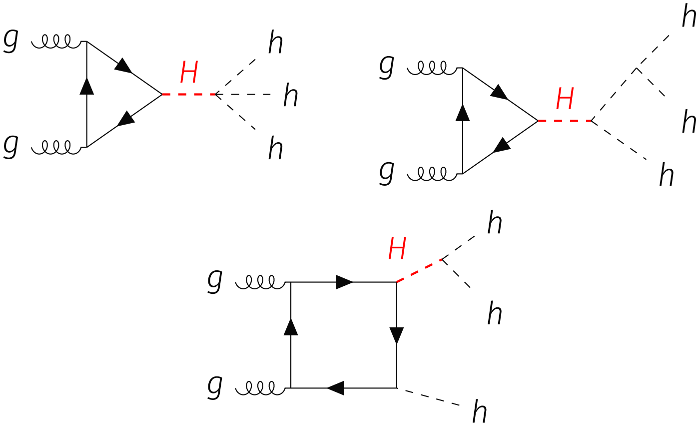
- hhh more enhanced compared to hh!
- Enhancements generalise to FCC-hh!

ENHANCING hh/hhh (R2HDM)

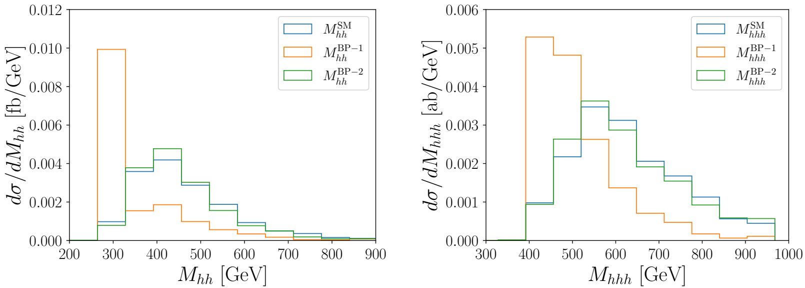
Resonant contributions to **hh**



Resonant contributions to **hhh**

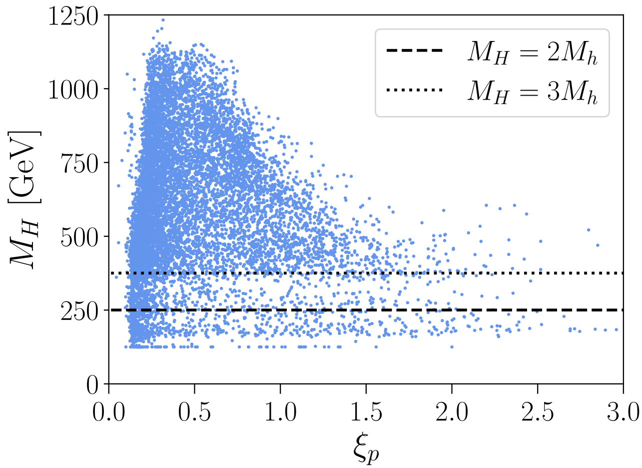


ENHANCEMENTS



BPs	$\sigma_{hh}/\sigma_{hh}^{\rm SM}$	$\sigma_{hhh}/\sigma_{hhh}^{\rm SM}$	M_H [GeV]	Γ_H [GeV]
Enhanced	3.24	15.26	274.29	0.20
SM-like	1.02	1.02	469.30	2.49

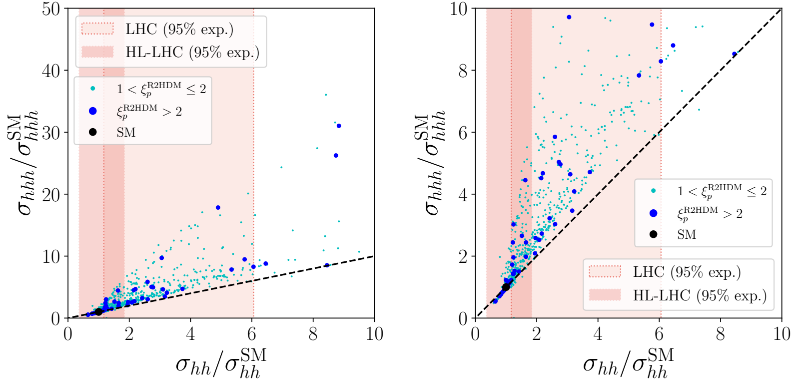
BPs	g_{hhh} [GeV]	g_{hhH} [GeV]	g_{hhhh}	g_{hhhH}
Enhanced	167.26	75.28	0.661	0.203
SM-like	190.54	-7.11	0.774	-0.011



EWPTs driven by the physics of light dofs

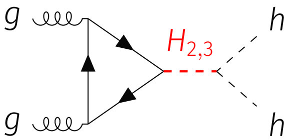
⇒ Stronger phase transitions proceed via lighter spectra!

R2HDM ($\xi_p \geq 1$)

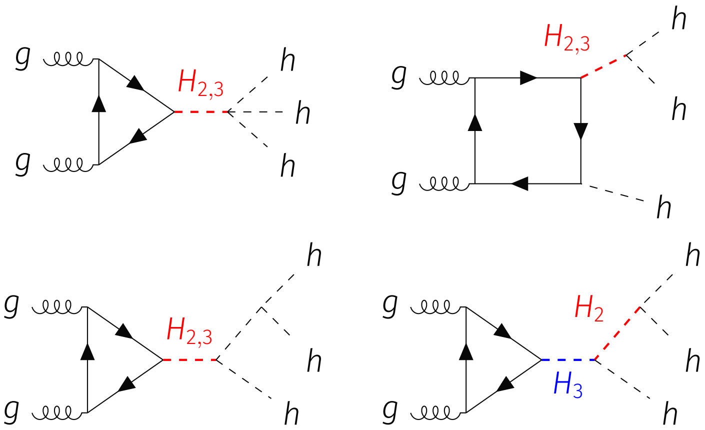


- Neutral Higgs rates alone **not** indicative of the strength of EWPTs.

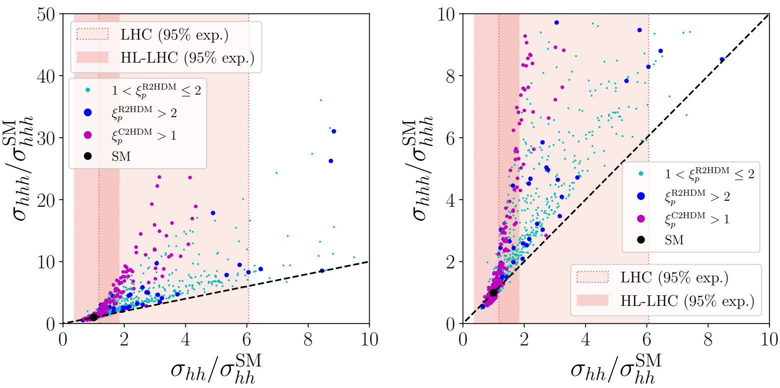
Resonant contributions to **hh**



Resonant contributions to **hhh**

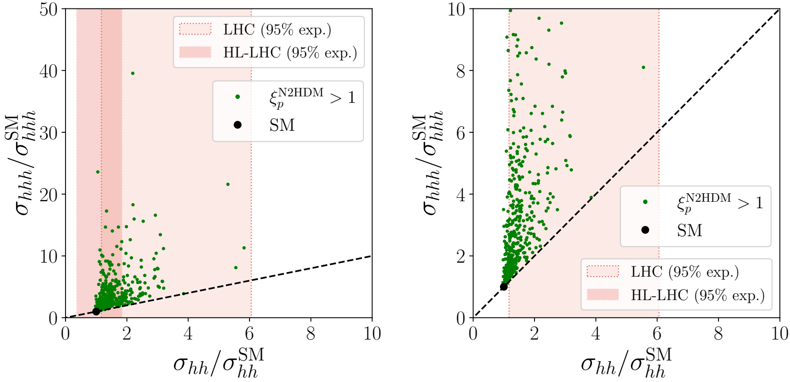


R2HDM + C2HDM



- 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; **can be accessible in FCC-hh**!

SUMMARISING

- hhh-production **enhanced** over the SM cross-section for extended scalar sectors.

SUMMARISING

- hhh-production **enhanced** over the SM cross-section for extended scalar sectors.
- Enhancements driven by $H \to hh$, $H \to hhh$, additional dofs, largest increases resulting from their combination.

SUMMARISING

- **hhh**-production **enhanced** over the SM cross-section for extended scalar sectors.
- Enhancements driven by $H \to hh$, $H \to hhh$, additional dofs, largest increases resulting from their combination.
- The lightness of the exotics affects EWPT, multi-Higgs production rates.

SUMMARISING

- **hhh**-production **enhanced** over the SM cross-section for extended scalar sectors.
- Enhancements driven by $H \to hh$, $H \to hhh$, additional dofs, largest increases resulting from their combination.
- The lightness of the exotics affects EWPT, multi-Higgs production rates.
- **hhh** sensitivity at HL-LHC is challenging, but still motivated!

SUMMARISING

- **hhh**-production **enhanced** over the SM cross-section for extended scalar sectors.
- Enhancements driven by $H \to hh$, $H \to hhh$, additional dofs, largest increases resulting from their combination.
- The lightness of the exotics affects EWPT, multi-Higgs production rates.
- **hhh** sensitivity at HL-LHC is challenging, but still motivated!

Thank you!