

Prospects for three-body Higgs decays into extra light scalars

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in collaboration with M. Lindner
based on [arXiv:1609.08127]



MAX-PLANCK-INSTITUT
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MAX-PLANCK-GESellschaft

Motivation

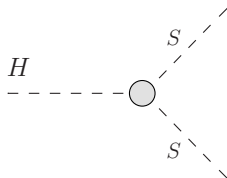
- Enlarged scalar sector
- Exotic/invisible Higgs decays

Scalar portal

new scalar field

$$\mathcal{L} \supseteq -\lambda_p (\Phi^\dagger \Phi) (S^\dagger S)$$

SM Higgs doublet



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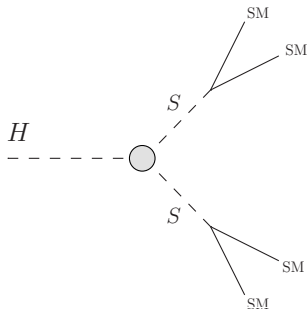
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- $H \rightarrow 2S \rightarrow 4 \times \text{SM}$

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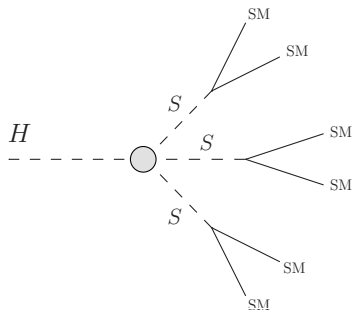
- Enlarged scalar sector
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- $H \rightarrow 2S \rightarrow 4 \times \text{SM}$
- $H \rightarrow 3S \rightarrow 6 \times \text{SM}$

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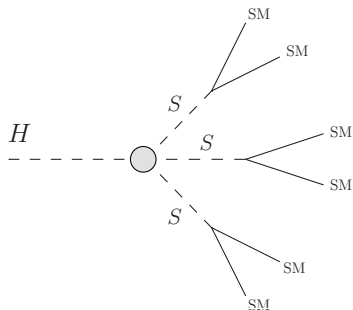
- Enlarged scalar sector
- Exotic/invisible Higgs decays
- $H \rightarrow 2S \rightarrow 4 \times \text{SM}$
- $H \rightarrow 3S \rightarrow 6 \times \text{SM}$
- **6μ** or **6τ** final states
- very clean signature
- virtually no SM background

Scalar portal

new scalar field

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SM Higgs doublet



Scalar three-body Higgs decays

Generic scalar sector after EWSB

$$m_h \ll m_H = 125.09 \text{ GeV}$$

$$\begin{aligned} V(H, h) = & \frac{m_H^2}{2} H^2 + \frac{m_h^2}{2} h^2 + \lambda_{4H} H^4 + \lambda_{4h} h^4 \\ & + \kappa_{3H} H^3 + \kappa_{3h} h^3 + \kappa_{2Hh} H^2 h + \kappa_{H2h} H h^2 \\ & + \lambda_{2H2h} H^2 h^2 + \lambda_{3Hh} H^3 h + \lambda_{H3h} H h^3 \end{aligned}$$

$$\mathcal{M}(H \rightarrow 3h) =$$

The image shows two Feynman diagrams for the decay $H \rightarrow 3h$. The first diagram on the left features a central green circle vertex. A dashed line labeled H enters from the left, and three dashed lines labeled h exit to the right and bottom-right. The second diagram on the right features two vertices: a top orange circle and a bottom blue circle. A dashed line labeled H enters from the top-left and connects to the orange vertex. From the orange vertex, two dashed lines labeled h exit to the right and bottom-right. A dashed line labeled h enters from the bottom-left and connects to the blue vertex. From the blue vertex, two dashed lines labeled h exit to the right and bottom-right. A plus sign is placed between the two diagrams.

Real scalar singlet extension of the SM

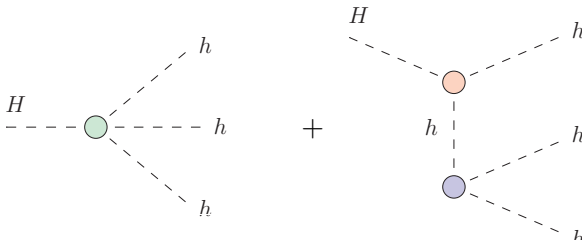
Add a real scalar gauge singlet S to the SM

$$V(\Phi, S) = \frac{1}{2}\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{\delta_1}{2}(\Phi^\dagger\Phi)S + \frac{\delta_2}{2}(\Phi^\dagger\Phi)S^2 + \kappa_1 S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4$$

Scalar mixing

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \phi \\ S \end{pmatrix}$$

Experiments $\Rightarrow \theta \ll 1$

$$\mathcal{M}(H \rightarrow 3h) = \text{diagram 1} + \text{diagram 2}$$


Real scalar singlet extension of the SM

Add a real scalar gauge singlet S to the SM

$$V(\Phi, S) = \frac{1}{2}\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{\delta_1}{2}(\Phi^\dagger\Phi)S + \frac{\delta_2}{2}(\Phi^\dagger\Phi)S^2 + \kappa_1 S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4$$

$$\kappa_{H2h} \simeq \frac{1}{2}\delta_2 v + \kappa_3 \theta$$

$$\kappa_{3h} \simeq \frac{1}{3}\kappa_3 - \frac{1}{2}\delta_2 v \theta$$

$$\lambda_{H3h} \simeq (\kappa_4 - \frac{1}{2}\delta_2)\theta$$

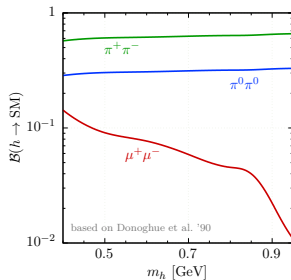
$$\mathcal{M}(H \rightarrow 3h) = \text{diagram 1} + \text{diagram 2}$$

The diagram shows the decay amplitude $\mathcal{M}(H \rightarrow 3h)$ as the sum of two Feynman diagrams. The first diagram features a central green vertex with an incoming dashed line labeled H from the left and three outgoing dashed lines labeled h extending to the right and bottom-right. The second diagram features two vertices: a top orange vertex and a bottom blue vertex. The top vertex has an incoming dashed line labeled H from the left and two outgoing dashed lines labeled h extending to the right and top-right. The bottom vertex has an incoming dashed line labeled h from the top and two outgoing dashed lines labeled h extending to the right and bottom-right. A vertical dashed line connects the two vertices.

Interesting mass ranges for h

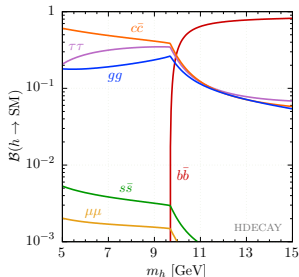
Low-mass scenario

- $m_h \lesssim 1 \text{ GeV} \Rightarrow \theta \lesssim 10^{-3}$
(Constraints from B -meson decays)
- h decays to π and μ pairs
- Pion channel enhanced by final-state interactions (Raby, West '88)

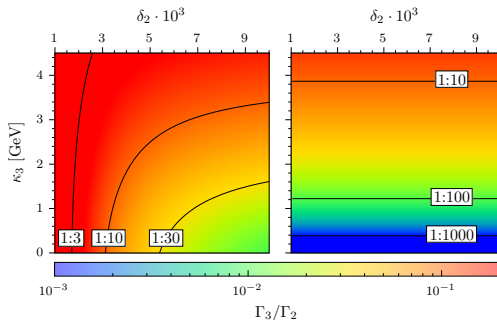


High-mass scenario

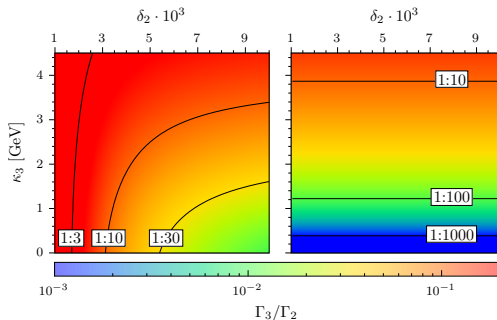
- $5 \text{ GeV} \lesssim m_h \ll m_H \Rightarrow \theta \lesssim 0.1$
(Constraints from LEP searches)
- h decays to heaviest open final state



Low-mass scenario – results for $m_h = 500$ MeV



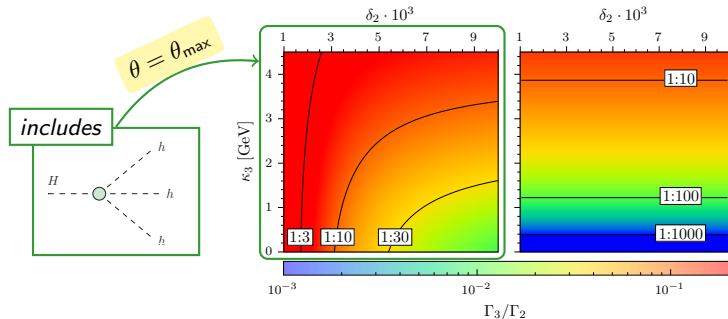
Low-mass scenario – results for $m_h = 500$ MeV



Consistency requirements

- ✓ perturbative unitarity
- ✓ perturbativity
- ✓ non-standard Higgs decays
- ✓ vacuum stability

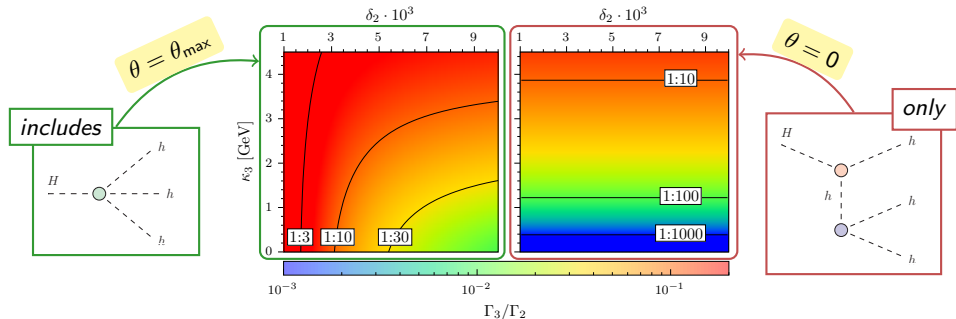
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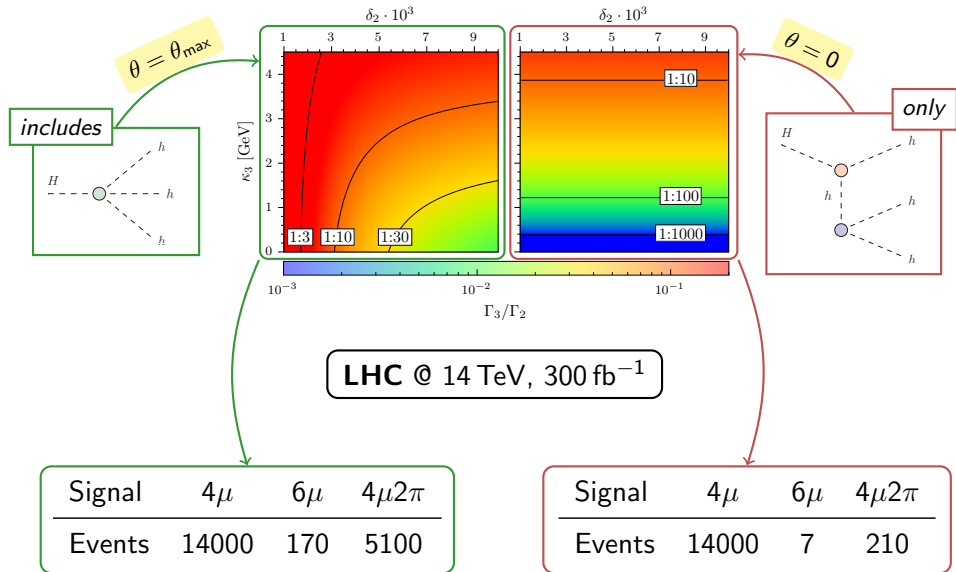
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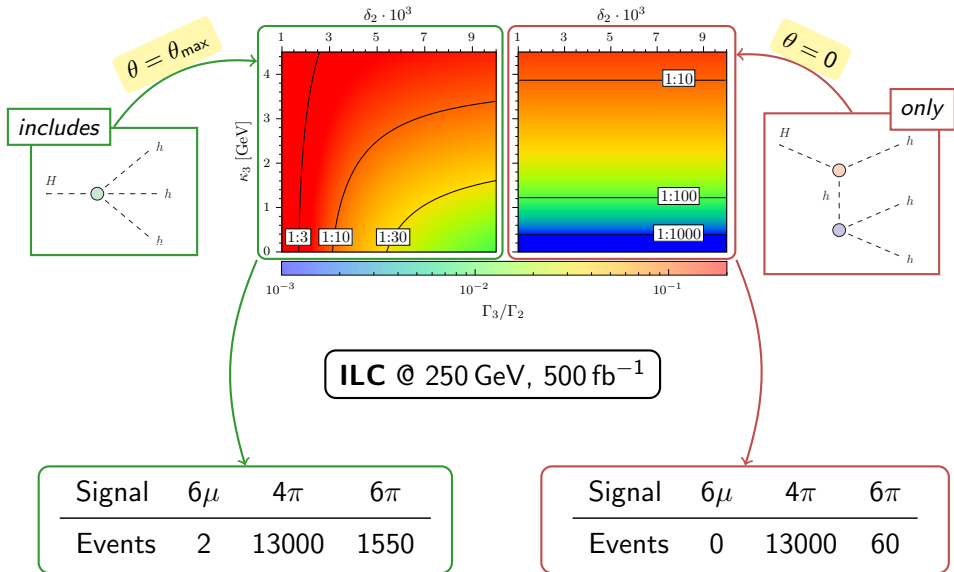
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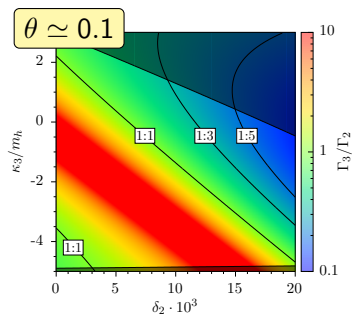
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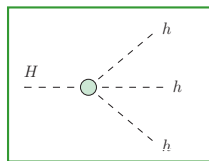
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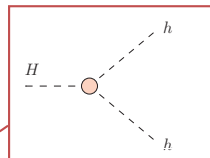
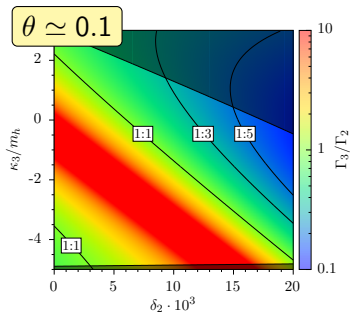
High-mass scenario – results for $m_h = 5 \text{ GeV}$



High-mass scenario – results for $m_h = 5$ GeV



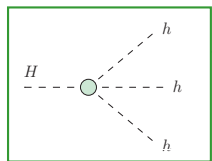
can contribute significantly



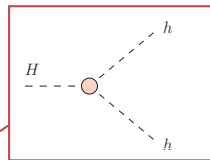
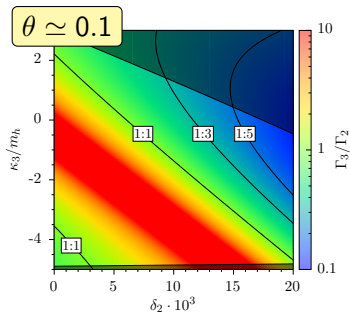
may become anomalously small

$$\kappa_{H2h} \simeq \frac{\delta_2}{2} v + \kappa_3 \theta$$

High-mass scenario – results for $m_h = 5 \text{ GeV}$



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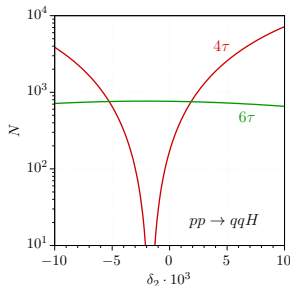


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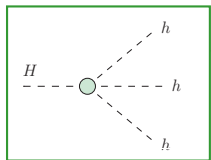
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LHC @ 14 TeV, 300 fb^{-1}

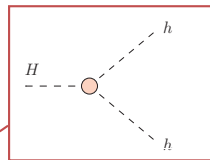
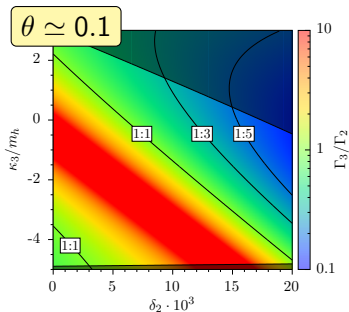
- here: $\mathcal{B}(h \rightarrow \tau^+ \tau^-) \simeq 21\%$
- possibly discovery channel



High-mass scenario – results for $m_h = 5 \text{ GeV}$



can contribute significantly

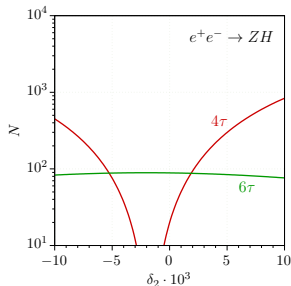


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ILC @ 250 GeV, 500 fb^{-1}

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Conclusion

- First detailed study of Higgs decays to **three** light scalars.
- May be observable both at the LHC and at future e^+e^- machines.
- Need to understand final-state **kinematics** and **detector response**.
- Need to understand SM **background**.

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Thank you!