Prospects for three-body Higgs decays into extra light scalars

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in collaboration with Manfred Lindner
based on [arXiv:1609.08127]

Higgs Couplings 2017

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Motivation – scalar Higgs decays

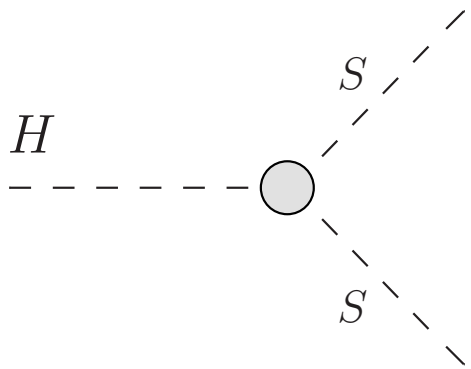
- Enlarged scalar sector
- Exotic/invisible Higgs decays

Scalar portal

new scalar field

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

SM Higgs doublet



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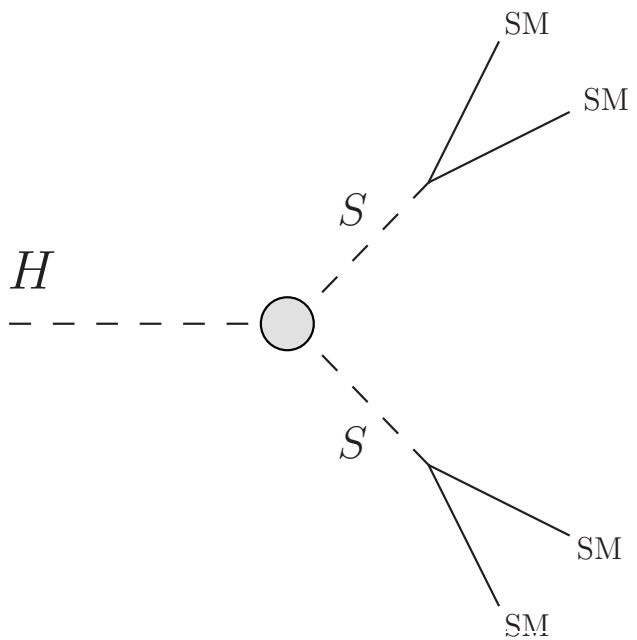

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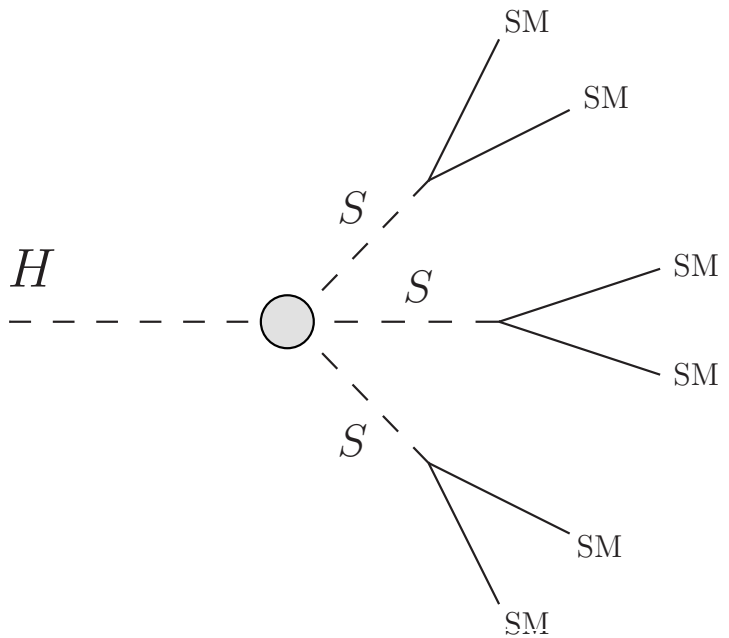

Motivation – scalar Higgs decays

- Enlarged scalar sector
- Exotic/invisible Higgs decays
- $H \to 2S \to 4 \times \text{SM}$
- $H \to 3S \to 6 \times \text{SM}$
- $\mathbf{6\mu}$ or $\mathbf{6\tau}$ final states
- very clean signature
- virtually no SM background

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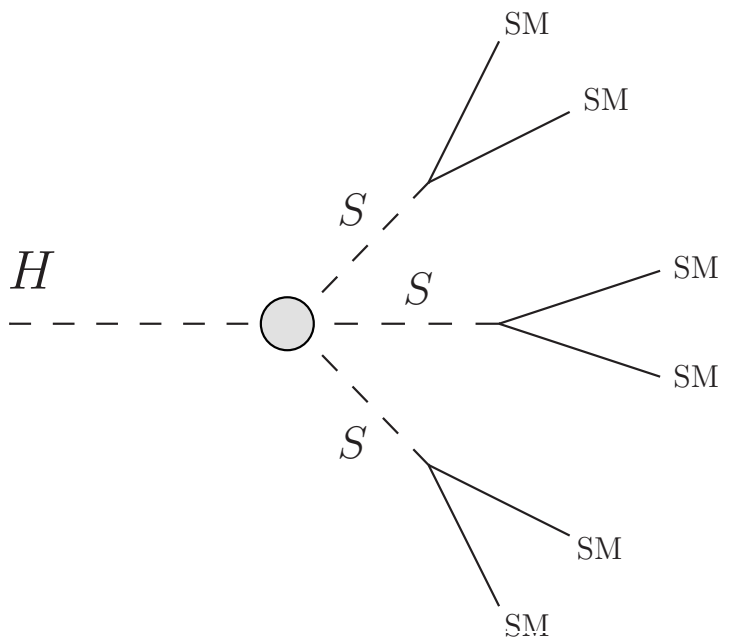


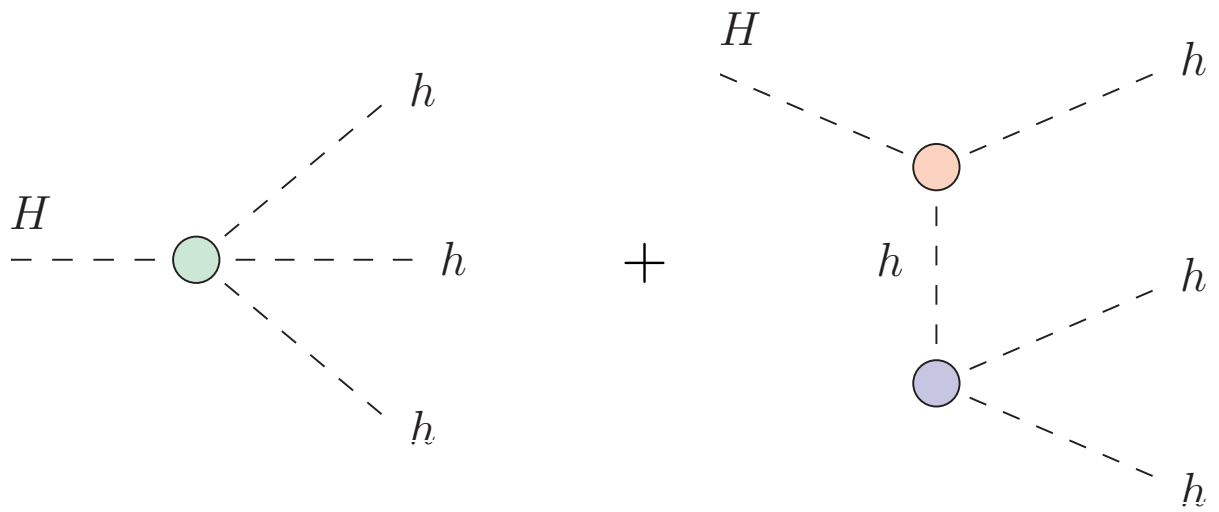
Scalar three-body Higgs decays

Generic scalar sector after EWSB

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

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

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



Real scalar singlet extension of the SM

Add a real scalar gauge singlet S to the SM

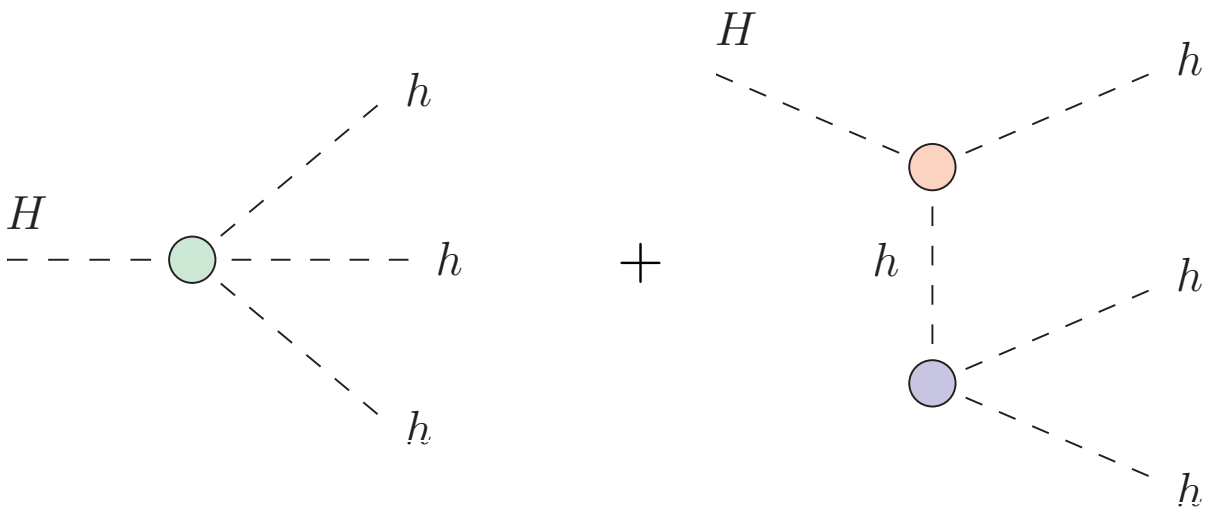
$$V(\Phi, S) = \tfrac{1}{2}\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{\delta_1}{2}(\Phi^\dagger\Phi)S + \frac{\delta_2}{2}(\Phi^\dagger\Phi)S^2 + \kappa_1 S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4$$

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 $\Rightarrow$ $\theta \ll 1$

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



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

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

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

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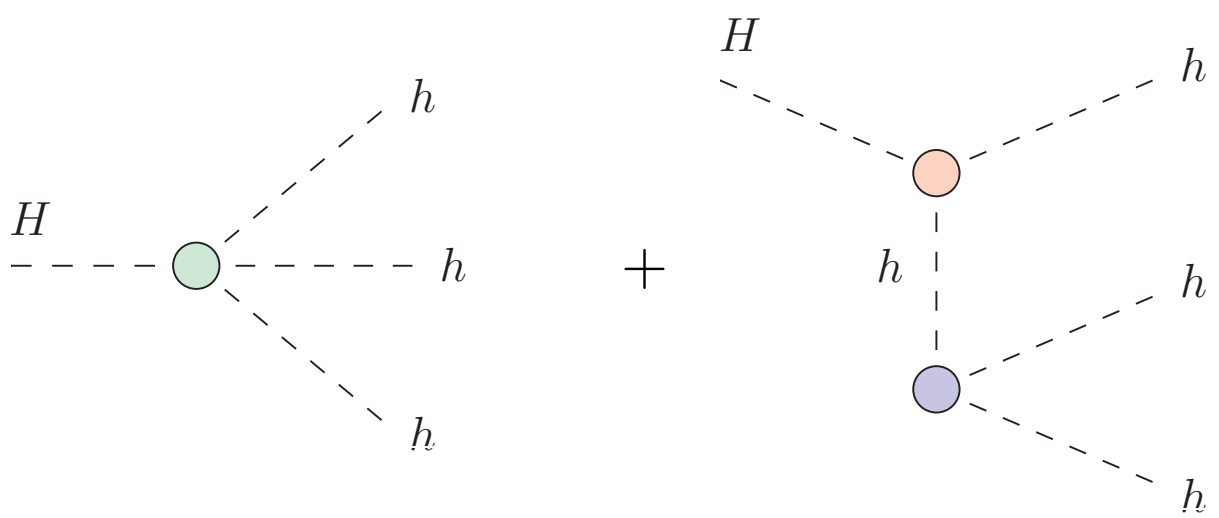

Existing constraints on the parameter space

Theoretical

- (perturbative) unitarity → $|\kappa_3|/m_h \lesssim 5$
- vacuum stability → $\lambda \geq 0,\ \kappa_4 \geq 0,\ \delta_2 \geq -\sqrt{\lambda\kappa_4}$
- perturbativity of couplings → $|g|/4\pi \lesssim 1$

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Experimental

- indirect bounds from B decays → $\theta \lesssim 10^{-3}$ [Clarke et al. '13]
  → relevant for $360\,\text{MeV} \lesssim m_h \lesssim 5\,\text{GeV}$
- direct bounds from LEP searches → $\theta \lesssim 0.1$ [Clarke et al. '13]
  → relevant for $5\,\text{GeV} \lesssim m_h \ll m_H$
- Higgs signal strength measurements at LHC → $\mathcal{B}(H \to \text{BSM}) \leq 34\,\%$ [ATLAS, CMS '16]

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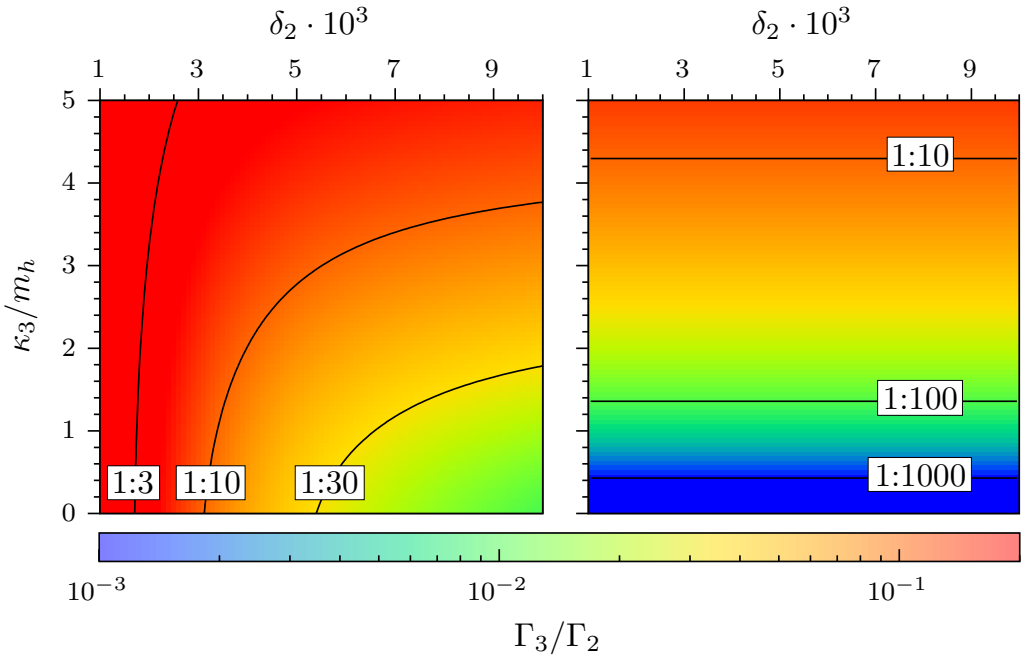
For a detailed account, see our paper.

Low-mass scenario – results for $m_h = 500\,\mathrm{MeV}$



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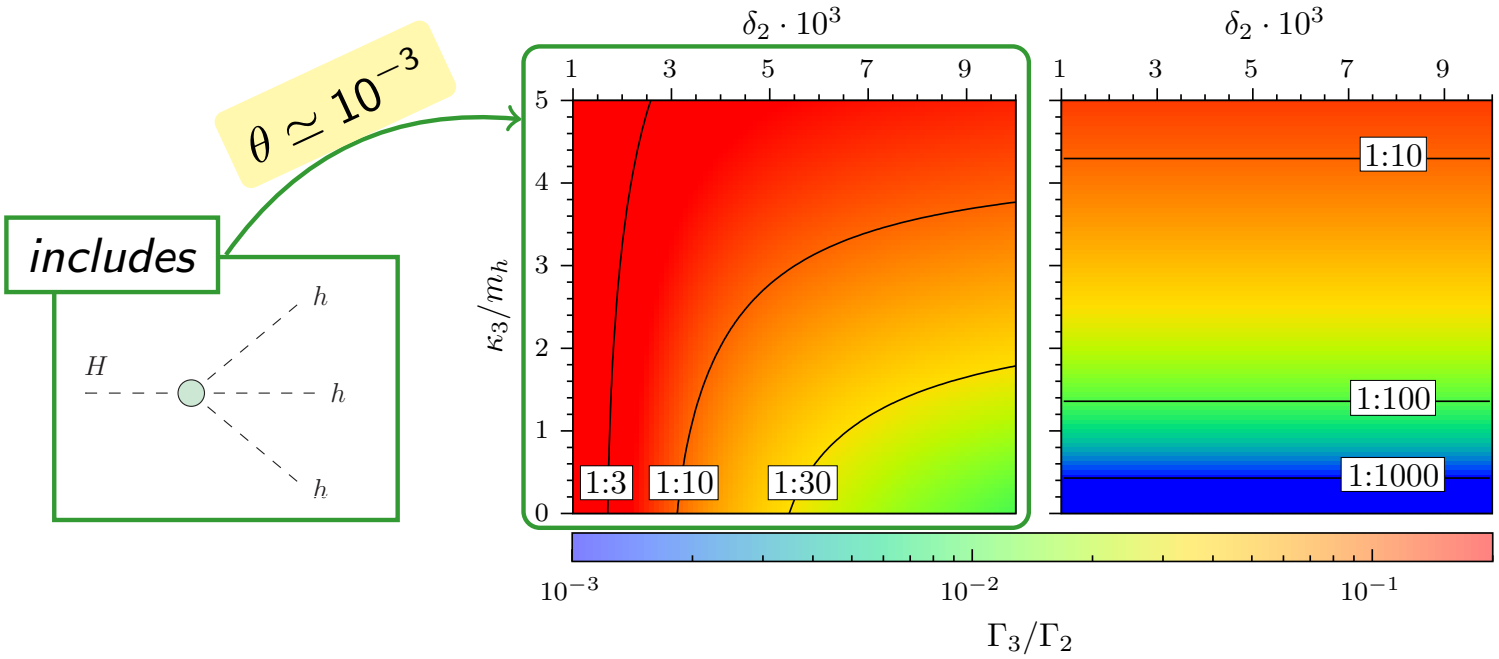

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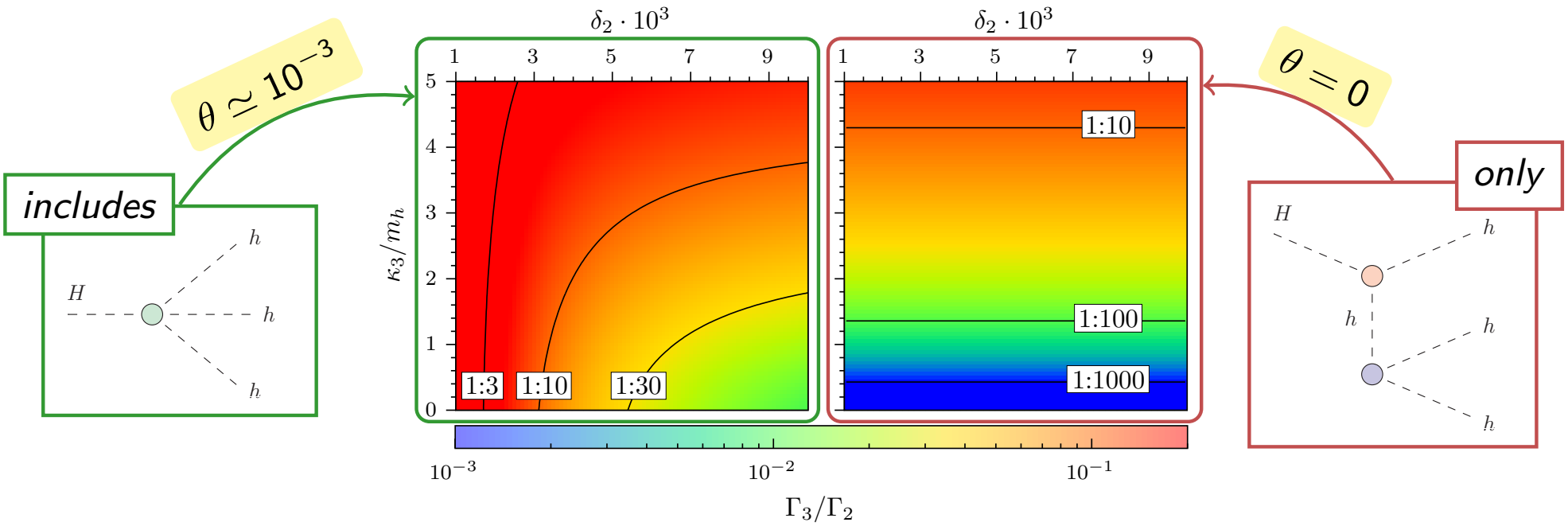

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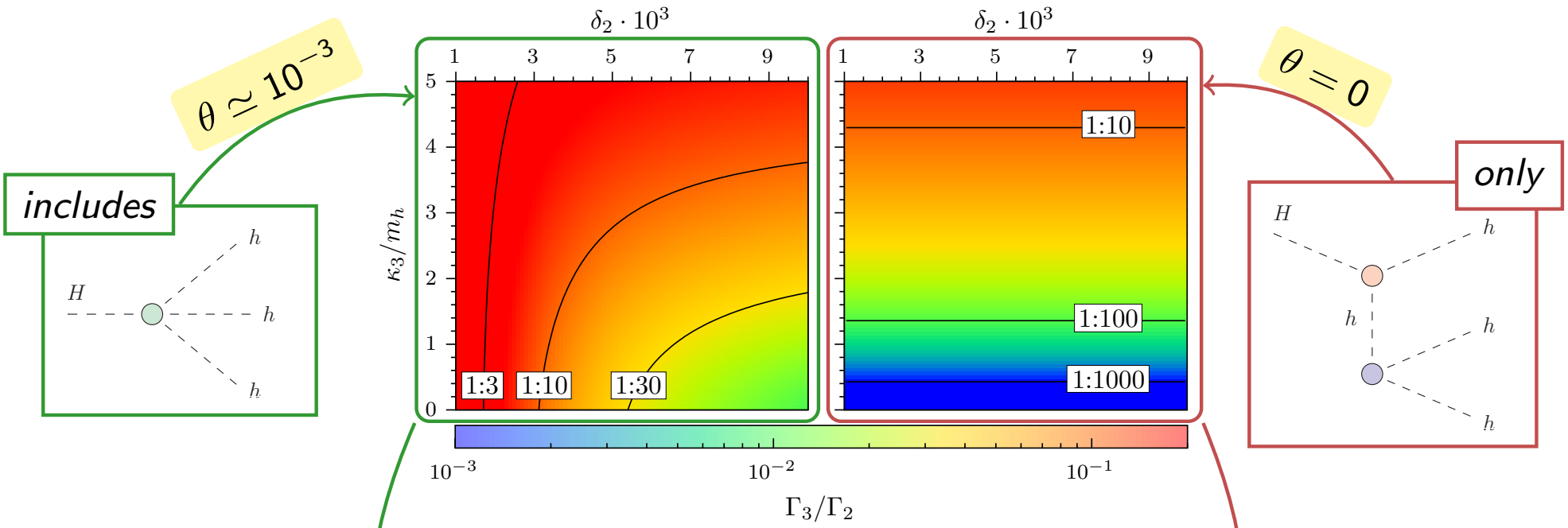

$\mathcal{B}(h \to \mu\mu) \sim 10\,\%$
$\mathcal{B}(h \to \pi\pi) \sim 90\,\%$

[Donoghue et al. '90]

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

Signal	4μ	6μ	$4\mu 2\pi$
Events	14000	170	5100

Signal	4μ	6μ	$4\mu 2\pi$
Events	14000	7	210

Low-mass scenario – results for $m_h = 500\,\text{MeV}$

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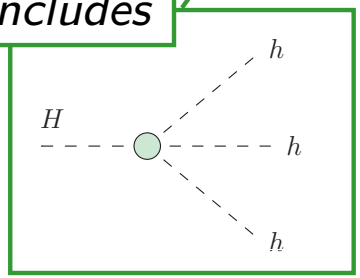
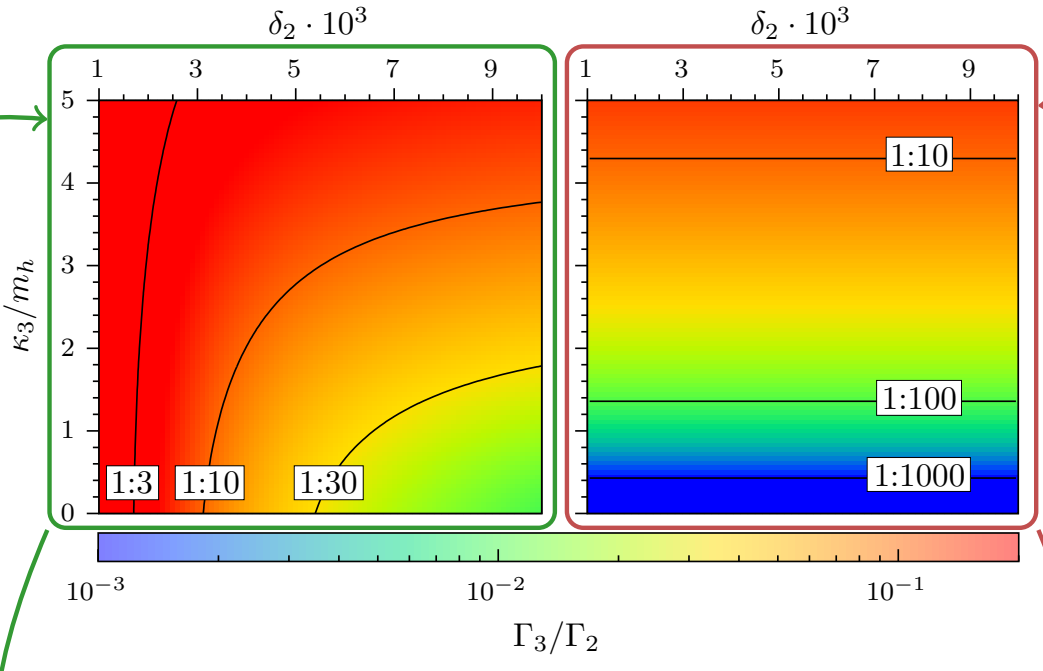
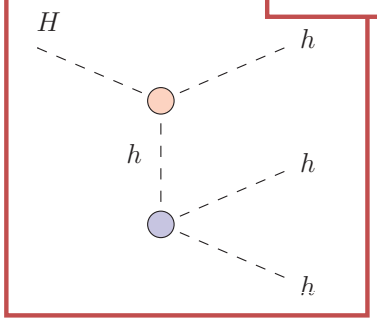
includes





$\theta = 0$

only



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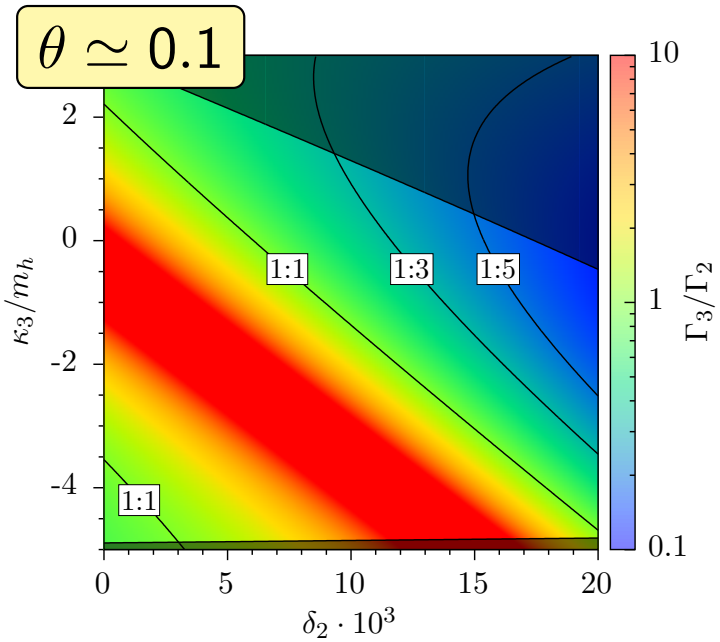
ILC @ 250 GeV, 500 fb^{-1}

Signal	6μ	4π	6π
Events	2	13000	1550

Signal	6μ	4π	6π
Events	0	13000	60

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



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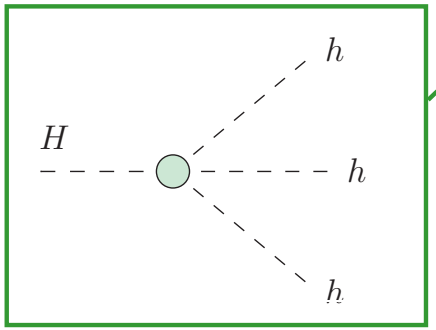
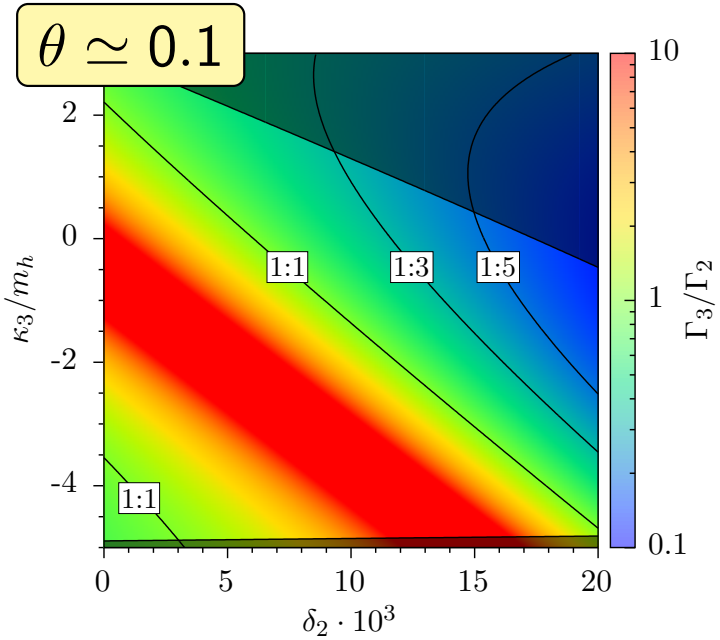
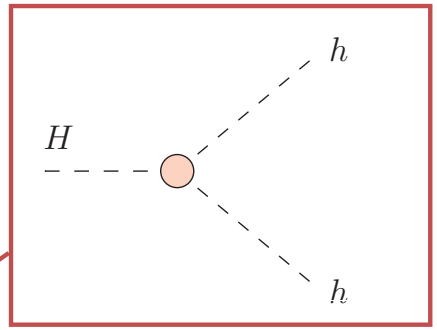


can contribute significantly





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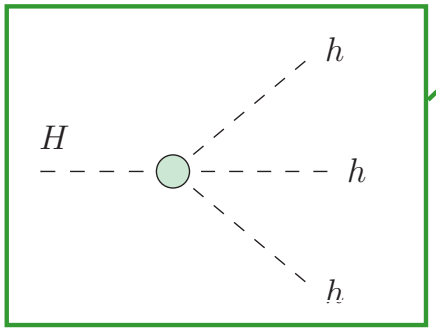

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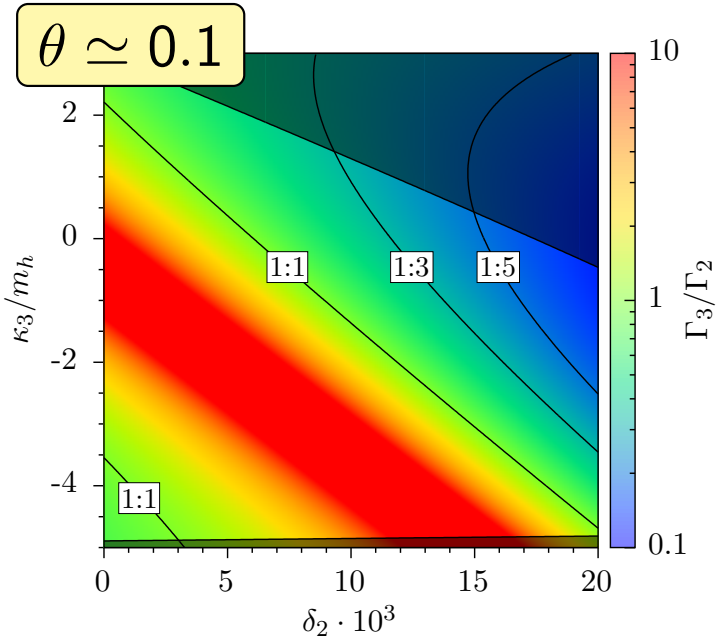

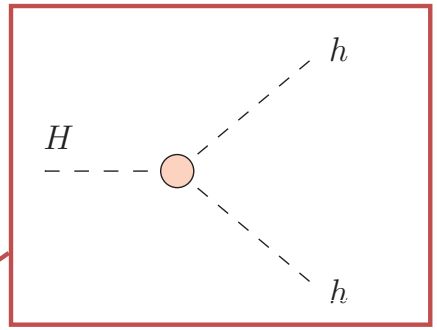

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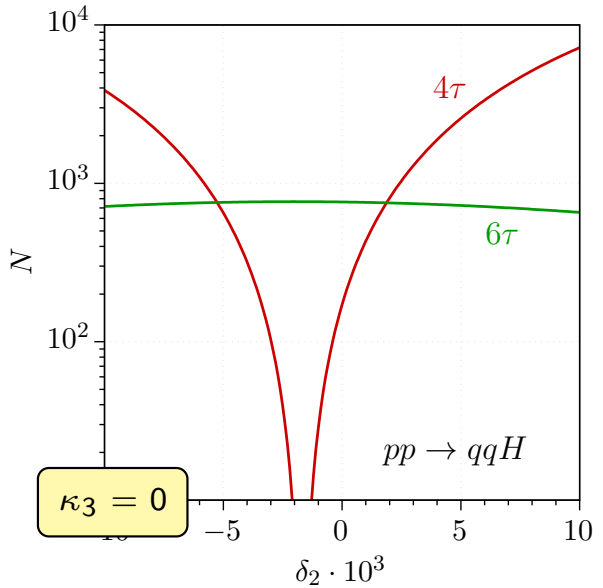
LHC @ 14 TeV, 300 fb^{-1}

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



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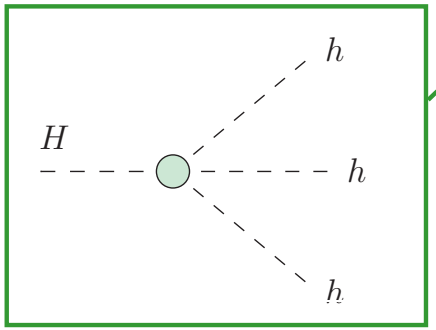

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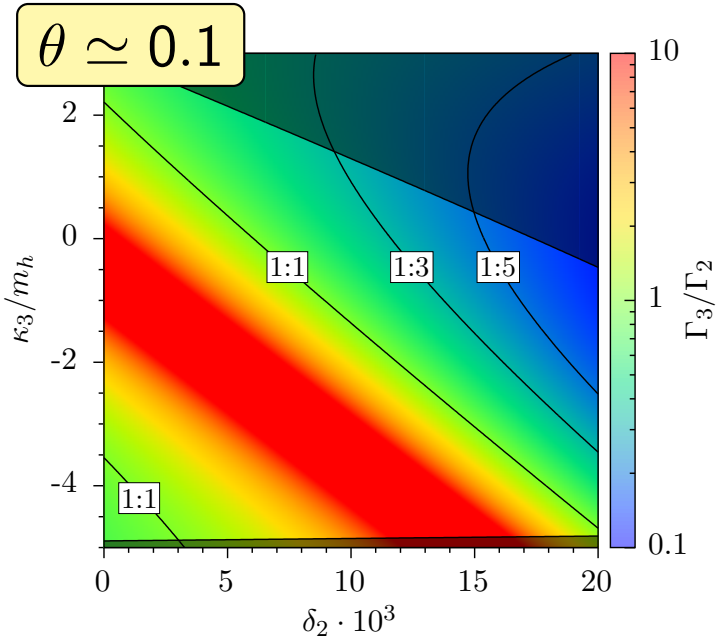

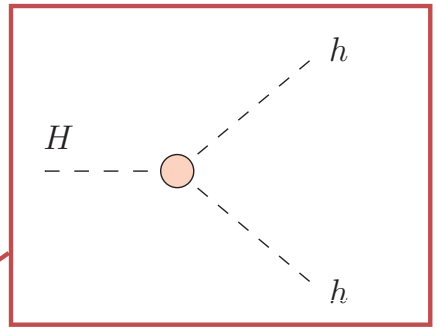

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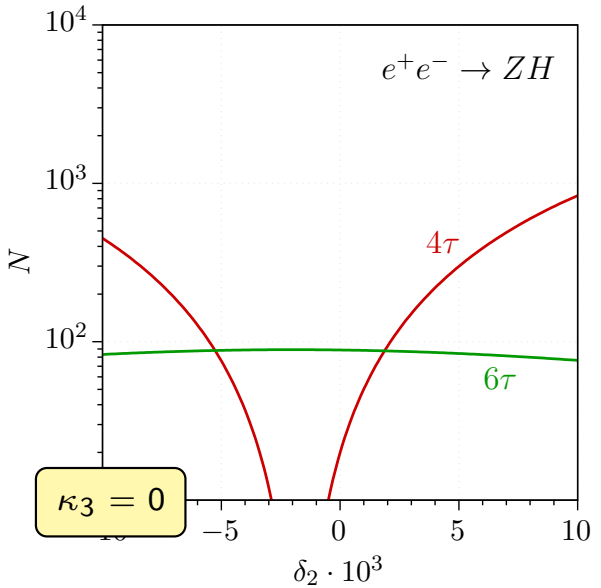

Conclusion

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- May be observable both at the **LHC** and at future e^+e^- machines.
- May help to experimentally **distinguish** BSM models.
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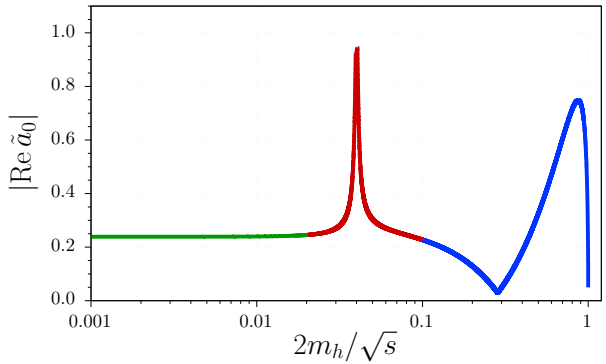
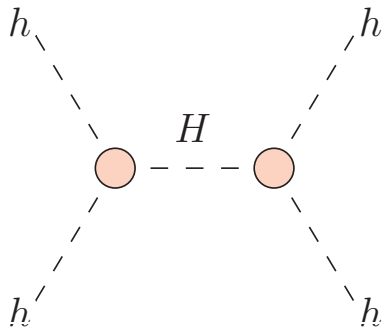
Thank you!

Backup

Constraints from perturbative tree-level unitarity

- Strongest limits from s-wave amplitude of $hh \to hh$.
- $\left| \sqrt{1 - 4m_h^2/s} \cdot \mathrm{Re}\, a_0(s) \right| \leq 1$

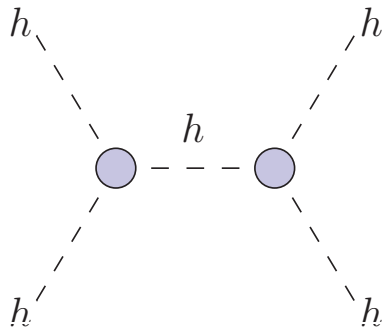




- $s \simeq m_H^2$
- s-channel dominates

$|\kappa_{H2h}| \leq \sqrt{8\pi m_H \Gamma_H}$

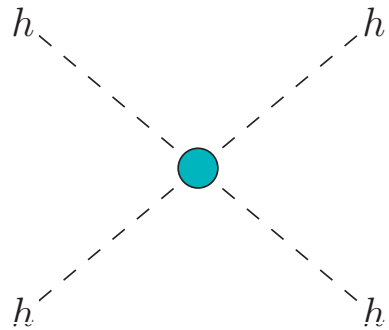
$\theta \to 0$ $\quad |\delta_2| \lesssim 0.03$



- $s \gtrsim 4m_h^2$
- t- and u-channels dominate

$|\kappa_{3h}|/m_h \leq 1.64$

$\theta \to 0$ $\quad |\kappa_3|/m_h \lesssim 5$



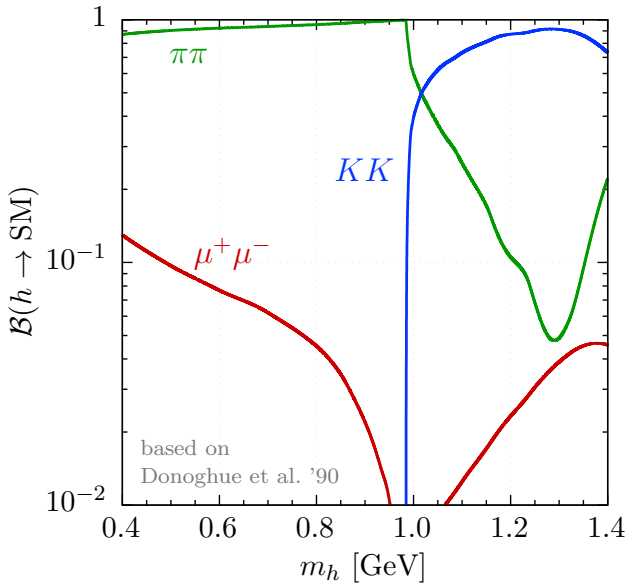
- $s \to \infty$
- only finite contribution

$\lambda_{4h} \leq \frac{2\pi}{3}$

$\theta \to 0$ $\quad \kappa_4 \lesssim 8.4$

Constraints on the mixing angle – low-m_h regime

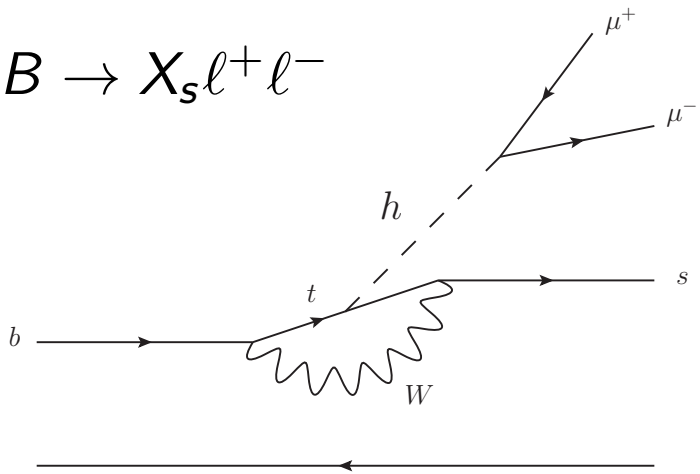
- $360\,\text{MeV} \lesssim m_h \lesssim 5\,\text{GeV}$
- h decays to μ, π and K pairs
- Hadronic channels enhanced by final-state interactions [Raby, West '88]



Allowed mixing angles

[PDG '15]

$B \to X_s \ell^+ \ell^-$



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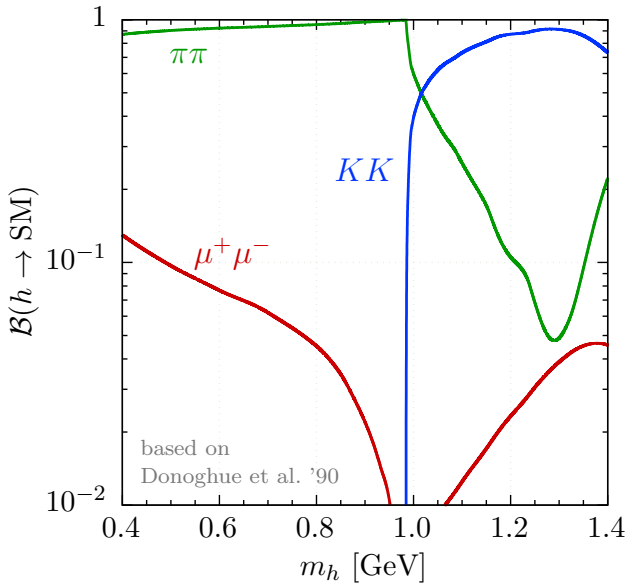

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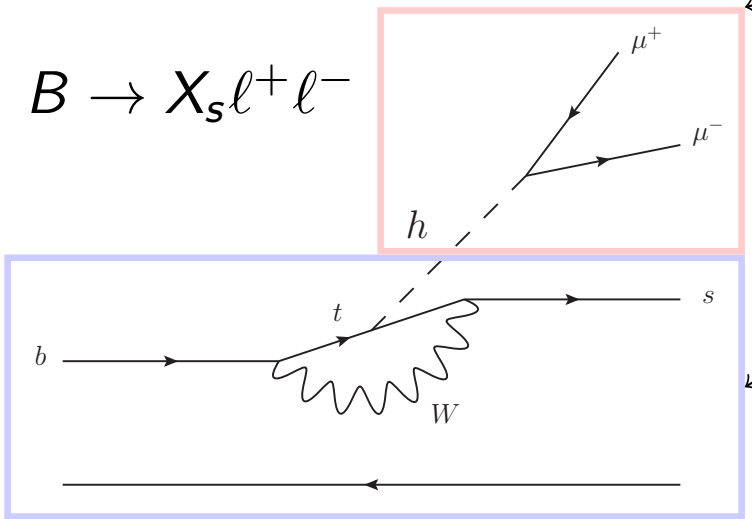

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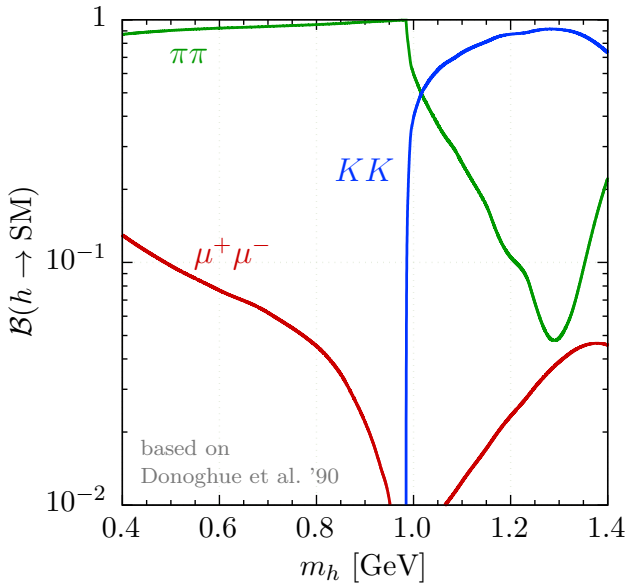

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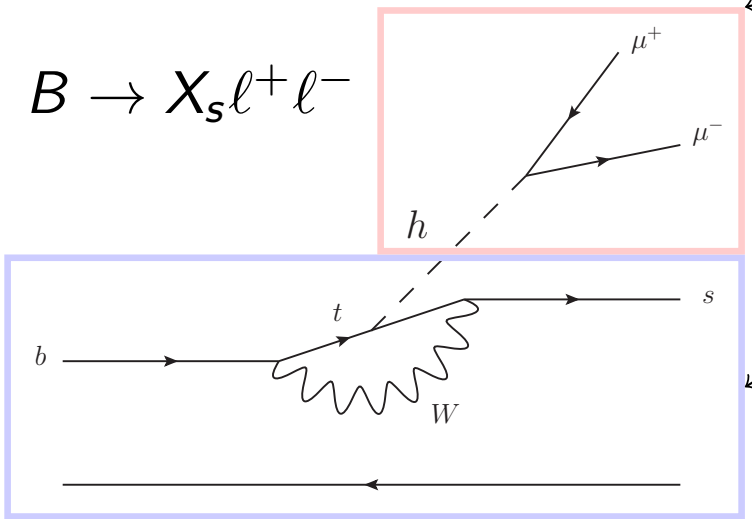

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- $\sin^2\theta \cdot \mathcal{B}(h \to \mu^+\mu^-) \lesssim 0.51 \times 10^{-6}$
- Similar constraints from exclusive channel $B \to K\mu^+\mu^-$

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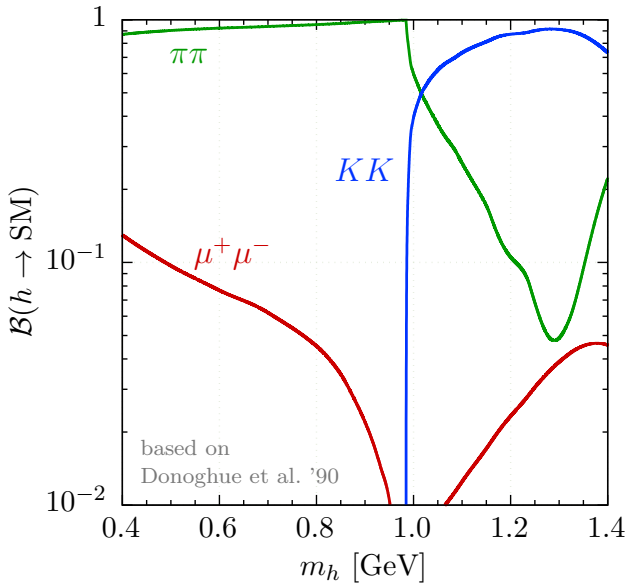
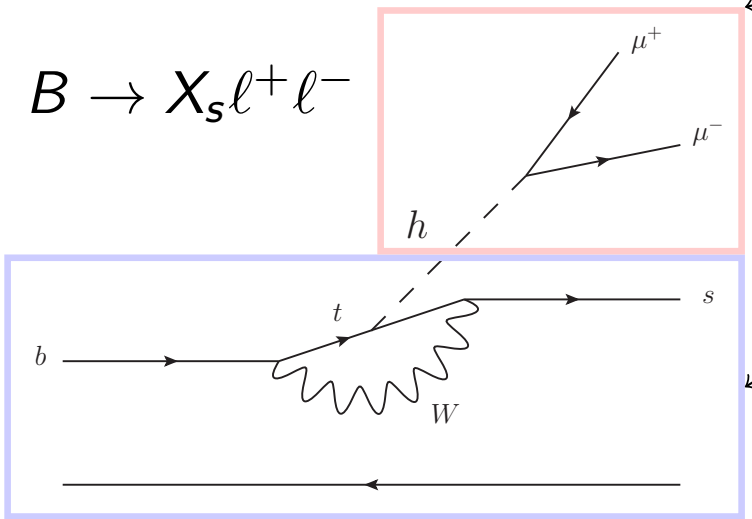


Allowed mixing angles

[PDG '15]

$B \to X_s \ell^+ \ell^-$

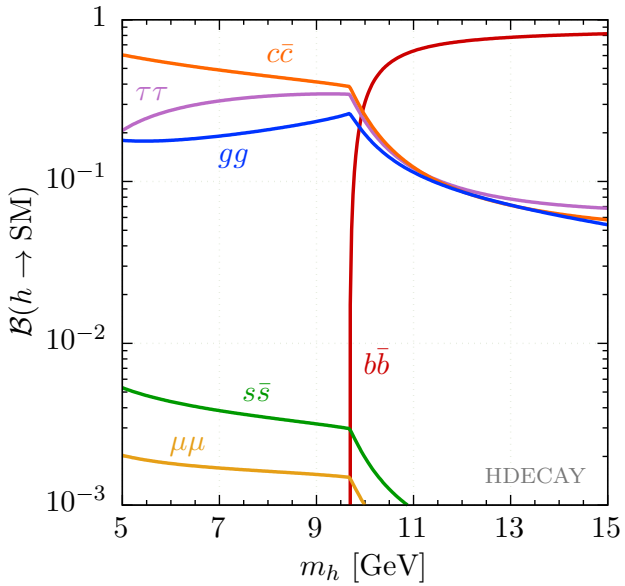


$$\mathcal{B}(B \to X_s h)\,\mathcal{B}(h \to \mu^+\mu^-) < \left(3.66^{+0.76}_{-0.77}\right) \cdot 10^{-6}$$

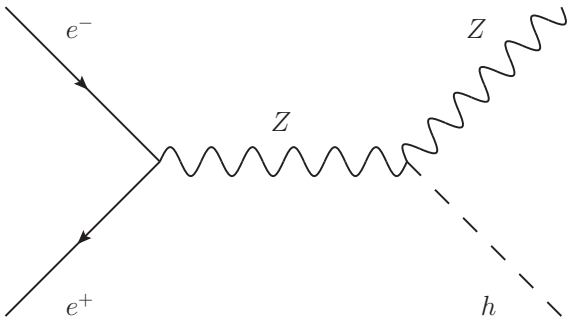
$$\theta \lesssim 10^{-3}$$

Constraints on the mixing angle – high-m_h regime

- $5\,\text{GeV} \lesssim m_h \ll m_H$
- rich variety of possible final states



Allowed mixing angles



$e^+e^- \to Zh$

- Model-independent constraints from **OPAL** analysis [OPAL '03]
- Strongest constraints from **L3** analysis (assumes hadronic decays of h) [L3 '96]
- Weaker limits from Υ-decays $\Upsilon \to h\gamma$

Constraints on the mixing angle – high-m_h regime

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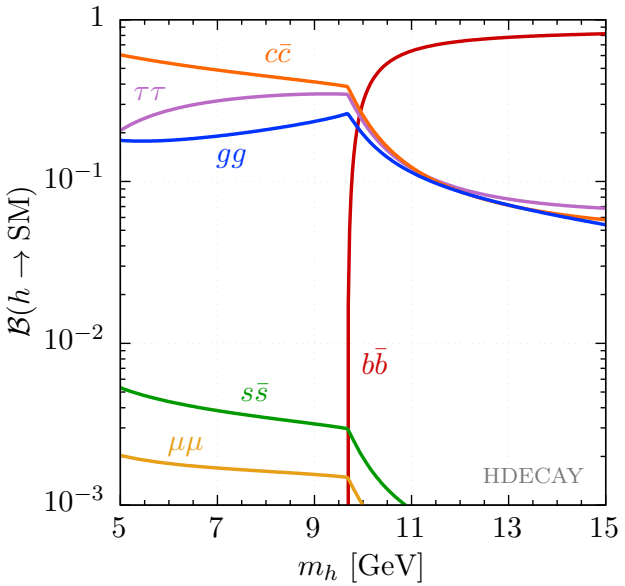
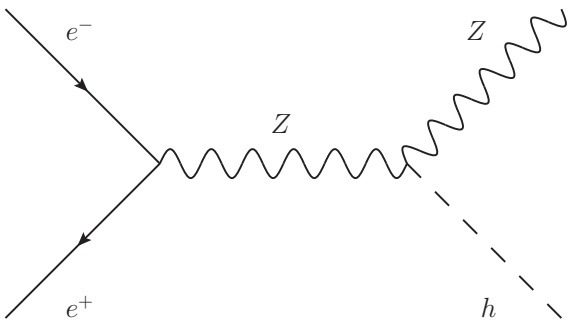


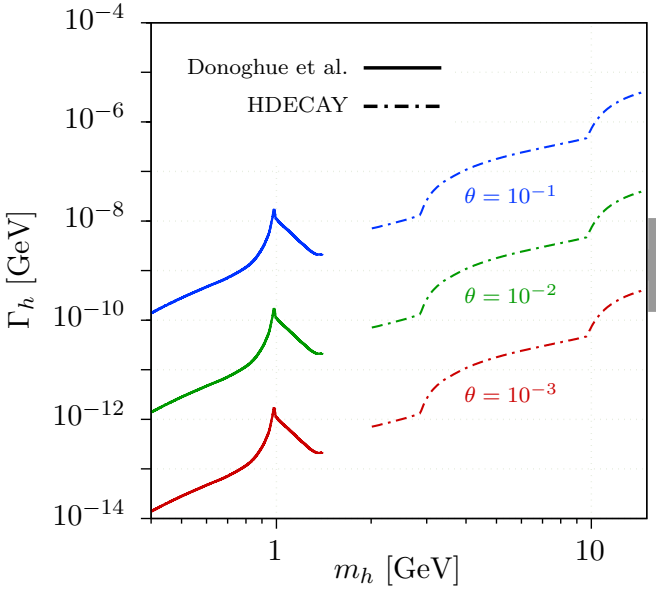
Allowed mixing angles



$e^+e^- \to Zh$

$$\theta \lesssim 0.1$$

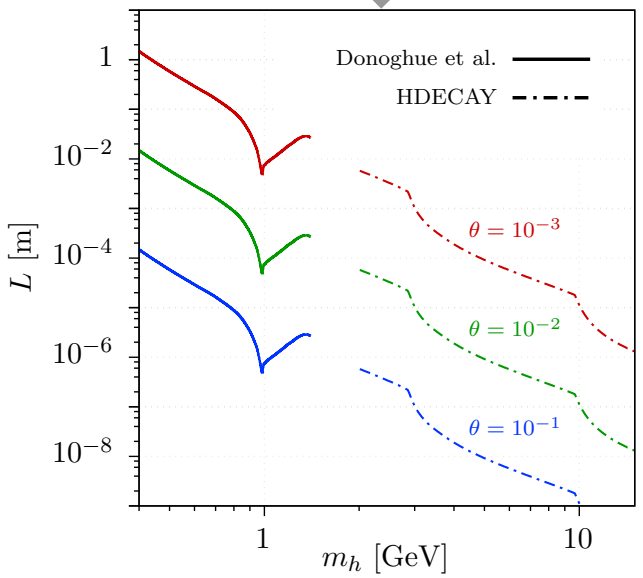
Decay widths and decay lengths



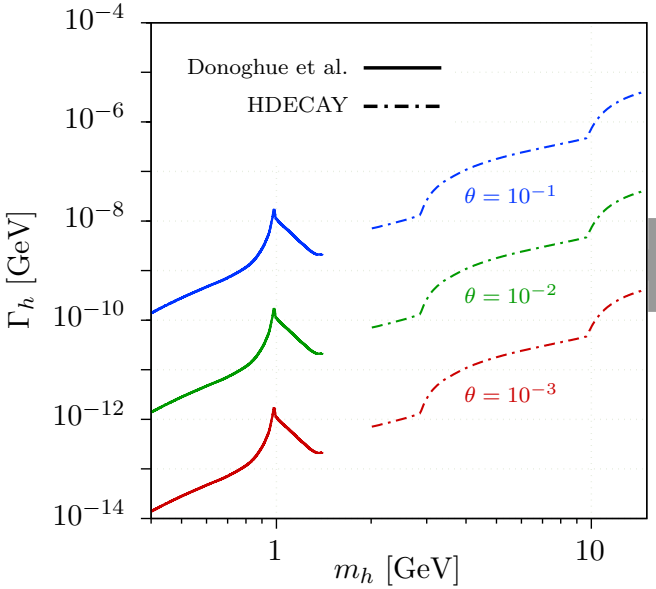
Decay length in lab frame

$$L_{\text{lab}} = \frac{E_h}{m_h \Gamma_h} + \mathcal{O}\left(\frac{m_h^2}{E_h^2}\right)$$

$$E_h \simeq \frac{m_H}{3}$$



Decay widths and decay lengths



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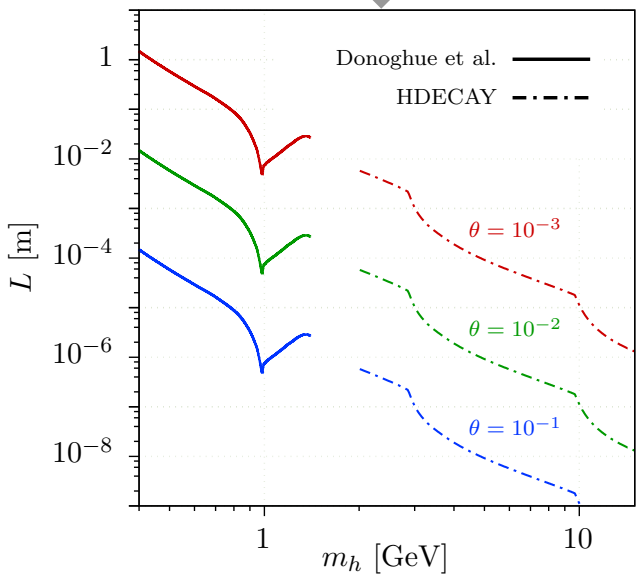

- **Displaced vertices** for small θ
- Generic case for small masses
- Needs to be taken into account during analyses