REINVENT

The quartic Higgs self-coupling at future hadron colliders

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Based on 1810.04665 with W. Bizon and U. Haisch + ongoing work

The Standard Model (SM) Higgs potential

$$V_{\rm SM} = \frac{m_h^2}{2} h^2 + \lambda_{\rm SM} v h^3 + \frac{\gamma_{\rm SM}}{4} h^4 \qquad\qquad \lambda_{\rm SM} = \gamma_{\rm SM} = \frac{m_H^2}{2v^2} \sim 0.13$$

$v \simeq 246\,\text{GeV}$	discovery of the W and Z bosons
$m_H \simeq 125\,\text{GeV}$	discovery of the Higgs boson at the LHC
$\lambda_{\rm SM}, \gamma_{\rm SM}$	essentially untested

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double-Higgs production

triple-Higgs production

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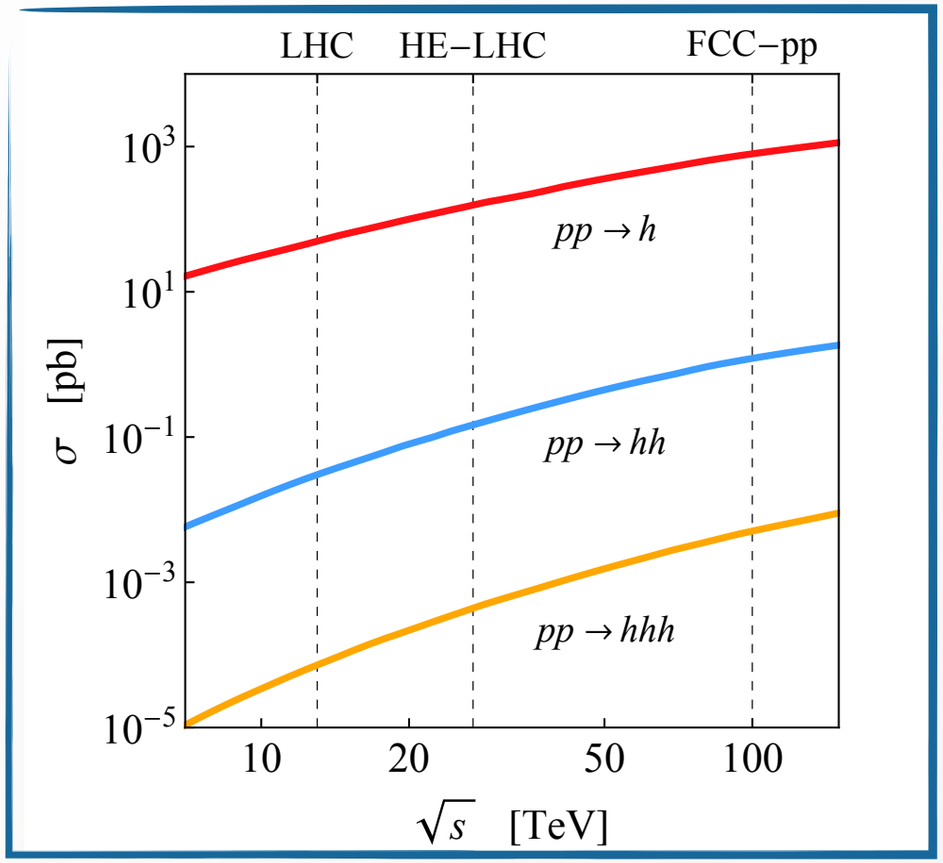
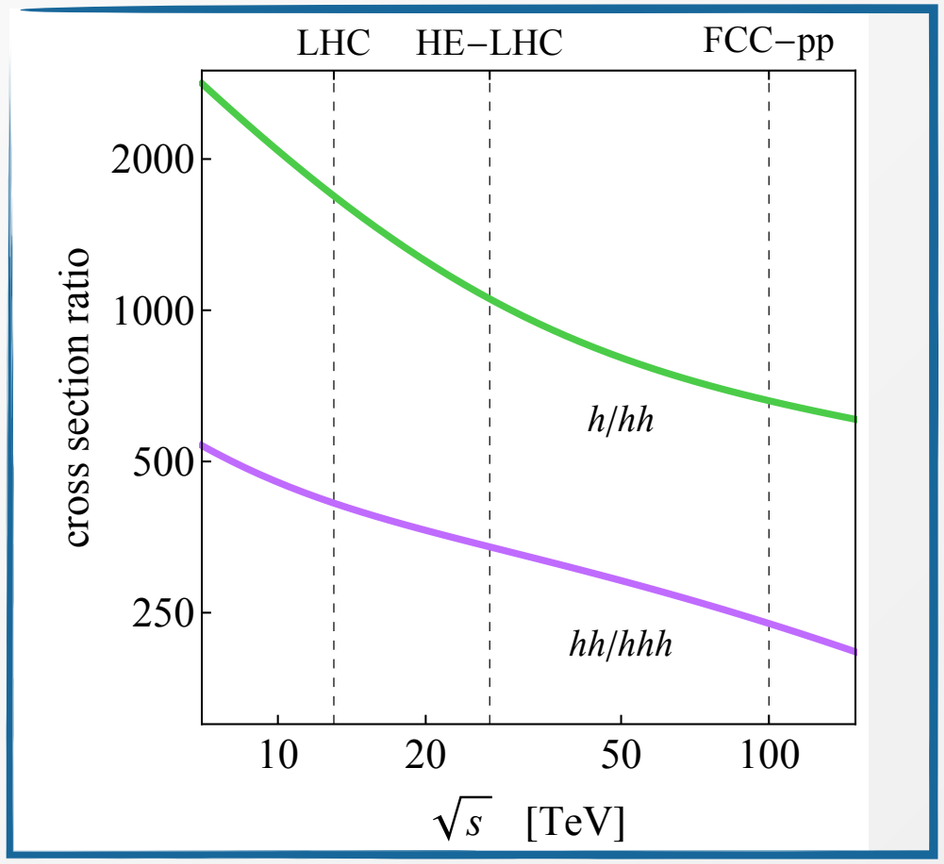
Higgs production at hadron colliders





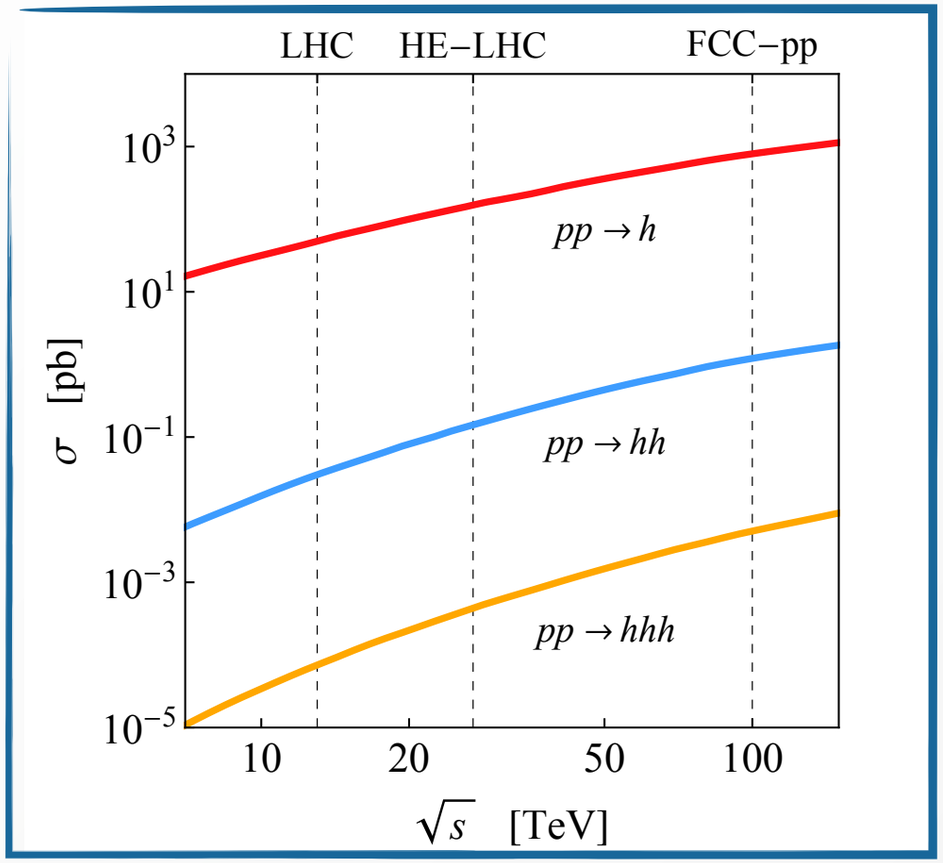
Multi-higgs production rate are small in the SM

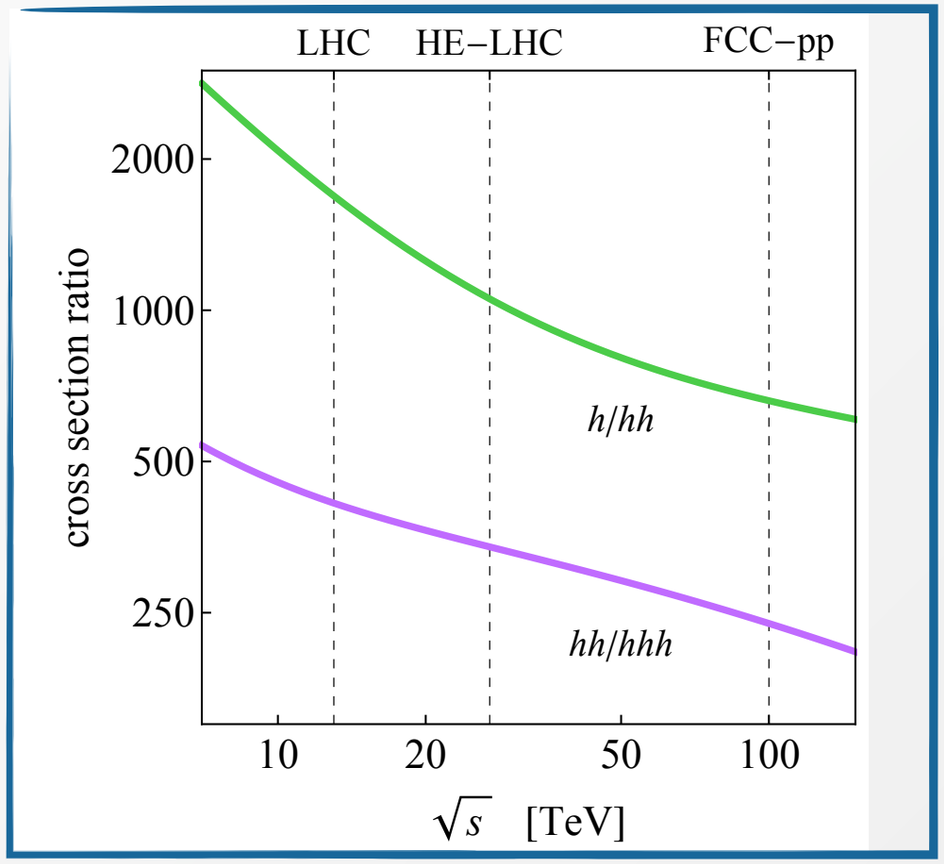
LHC: $O(1)$ determinations of the cubic Higgs self-coupling

HE-LHC: prospects of extracting the cubic Higgs self-coupling with $O(20\%)$

FCC-pp: weak bounds on the quartic self-coupling by measuring *hhh* production

Higgs production at hadron colliders





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Indirect constraints on the quartic Higgs self-coupling from double-Higgs production measurements

Idea already explored in the literature to constrain the trilinear coupling

Talk by Davide Pagani

Milan Theory Meeting 2018, Milan, 20 December 2018

SM effective field theory (EFT)

$$V \supset \kappa_3 \lambda v h^3 + \kappa_4 \frac{\lambda}{4} h^4 \qquad \kappa_3, \kappa_4 \neq 1 \quad \text{if physics beyond SM is present}$$

Consider operators of dimension 6 and 8 in the SMEFT

$$\mathscr{L}_{\text{SMEFT}} \supset \mathcal{O}_6 + \mathcal{O}_8 = -\frac{\bar{c}_6}{v^2} \left|H\right|^6 - \frac{\bar{c}_8}{v^4} \left|H\right|^8$$

$$\kappa_3 = 1 + \Delta\kappa_3 = 1 + \bar{c}_6 + 2\bar{c}_8 \qquad \kappa_4 = 1 + \Delta\kappa_4 = 1 + 6\bar{c}_6 + 16\bar{c}_8$$

No assumption about the actual size of $\bar{c}_6$ and $\bar{c}_8$: cubic and quartic Higgs self-couplings can deviate independently from the SM predictions

If O_6 is the only numerically relevant operator, strong correlation

$$\Delta\kappa_4 = 6\Delta\kappa_3$$

n.b. even if κ_3, κ_4 are treated as free parameters, processes such as $gg \to h$ or loop corrections to $e^+e^- \to hhZ$ can still be calculated consistently as long as the SMEFT is used to perform the computations

Anatomy of double-Higgs production

$$\mathscr{A}(gg \to hh) = \delta^{a_1 a_2} \epsilon_1^{\mu}(p_1) \epsilon_2^{\nu}(p_2) \left(\sum_{m=1}^{2} T_{m\mu\nu} \mathscr{F}_m \right)$$

[Glover, der Bij 1988]

$$T_{1\,\mu\nu} = \eta_{\mu\nu} - \frac{p_{1\,\nu} p_{2\,\mu}}{p_1 \cdot p_2} \qquad T_{2\,\mu\nu} = \eta_{\mu\nu} + \frac{1}{p_T^2 \left(p_1 \cdot p_2\right)} \Big(m_h^2 p_{1\,\nu} p_{2\,\mu} - 2\left(p_1 \cdot p_3\right) p_{2\,\mu} p_{3\,\nu}$$

$$-2\left(p_2 \cdot p_3\right) p_{1\,\nu} p_{3\,\mu} + 2\left(p_1 \cdot p_2\right) p_{3\,\mu} p_{3\,\nu} \Big)$$

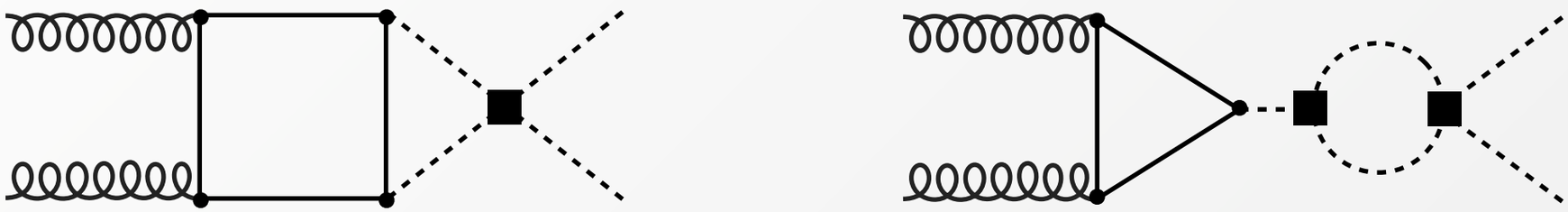
$$\sigma_{\mathrm{LO}} = \sigma_0 \int dt \left(|\mathscr{F}_1|^2 + |\mathscr{F}_2|^2 \right)$$

Double-Higgs production now know at NLO QCD with mass dependence
[1604.06447,1608.04798,1703.09252] [1811.05692]

NNLO QCD with mass dependence at NLO QCD
[1803.02463]

The quartic Higgs self-coupling in double-Higgs production

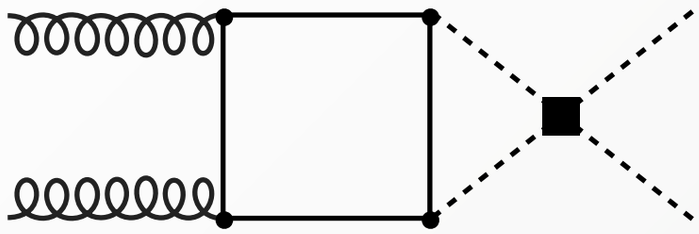
We calculate the relevant EW two-loop amplitudes and we combine them with the exact $\mathcal{O}(\alpha_s^2)$ matrix elements

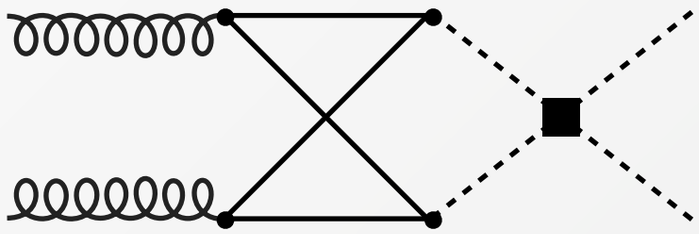


Total cross-section and differential distributions for double-Higgs production at NLO QCD, including arbitrary modifications of the cubic and quartic self-couplings

Final combination with constraints on the trilinear and the cubic self-couplings at HE-LHC and FCC-pp to study synergy and complementarity of the two approaches

Two-loop form factor (1)





$$\Delta\mathscr{F}_1^{\kappa_4} = \frac{\alpha_s}{4\pi}\frac{\lambda\,\kappa_4}{(4\pi)^2}\,y_t^2\,f(\hat{s}) \qquad \Delta\mathscr{F}_2^{\kappa_4} = 0$$

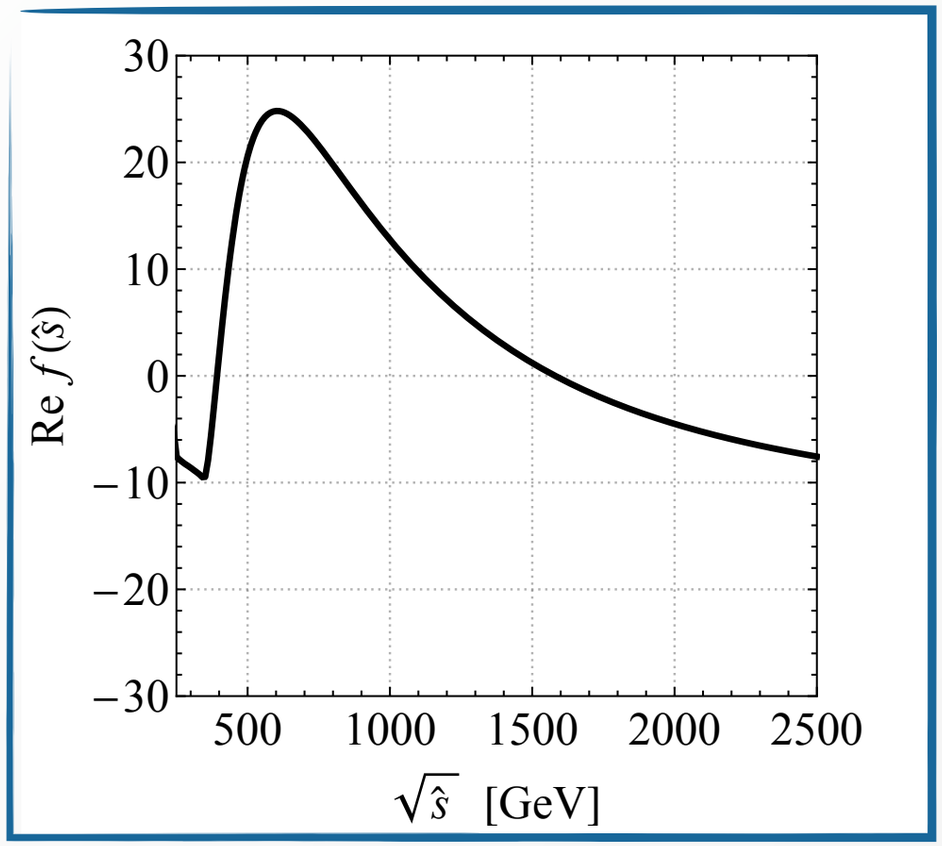
Two-loop integrals evaluated numerically using pySecDec package

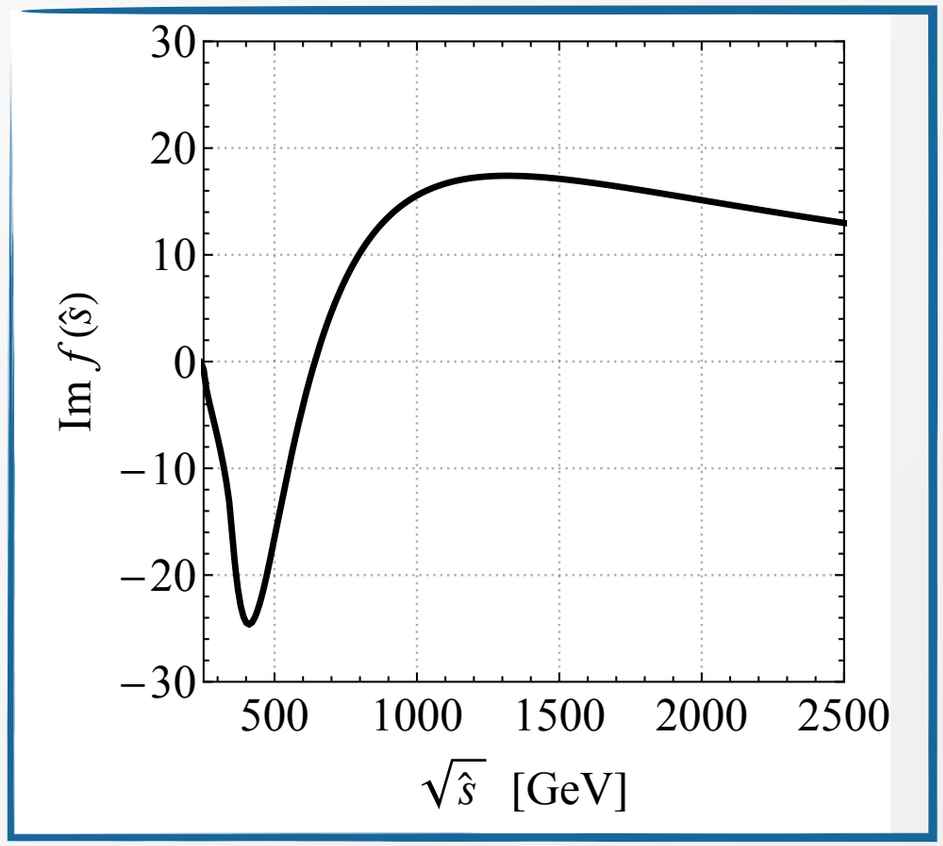
[1204.4152,1502.06595,1703.09692]

Checks

- For all calculated phase-space points, double and single $1/\epsilon$ poles cancel at the per-myriad accuracy
- Numerical check vs. (analytical) systematic expansion of the two-loop form factors in the large m_t limit

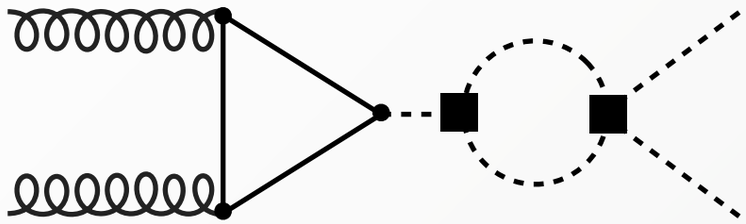
Two-loop form factor (1)

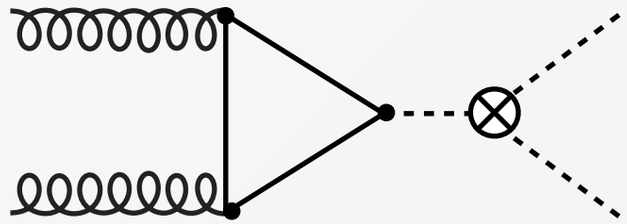




- Correction depends only on $\hat{s}$
- Correction to the spin-2 form factor is zero

Two-loop form factor (2)





$$\Delta\mathscr{F}_1^{\kappa_3\kappa_4} = \frac{\alpha_s}{4\pi}\,\lambda\,\kappa_3\,\frac{\lambda\,\kappa_4}{(4\pi)^2}\,g(\hat{s}) \qquad \Delta\mathscr{F}_2^{\kappa_3\kappa_4} = 0$$

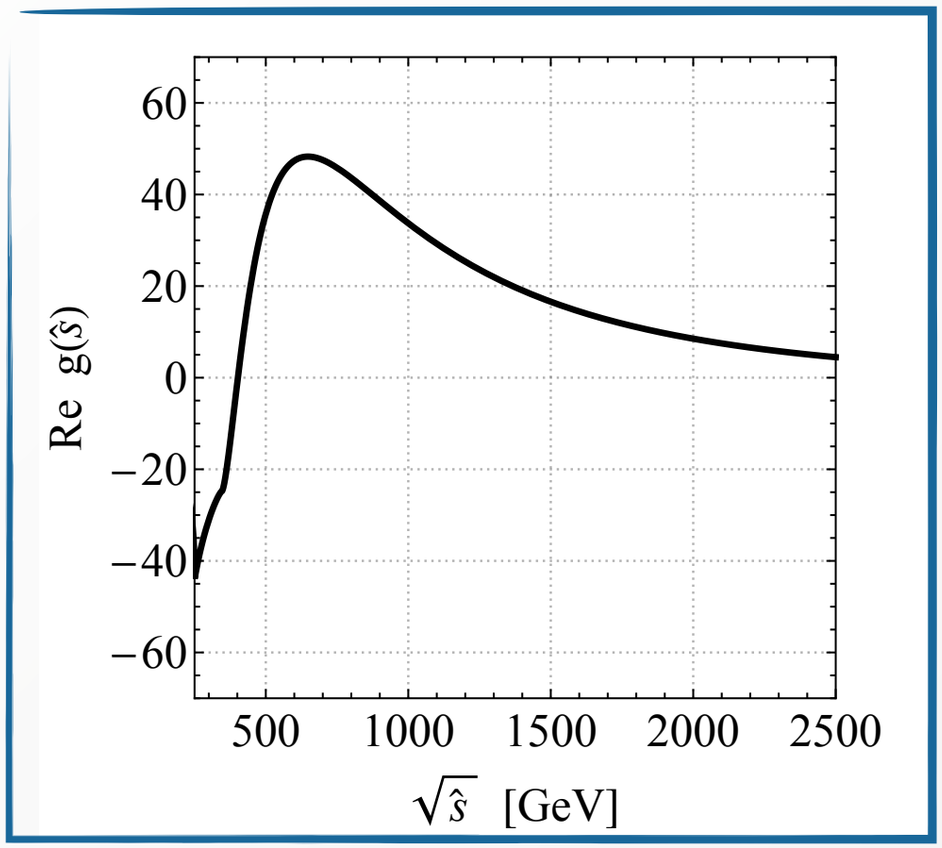
Function $g(s)$ can be calculated analytically

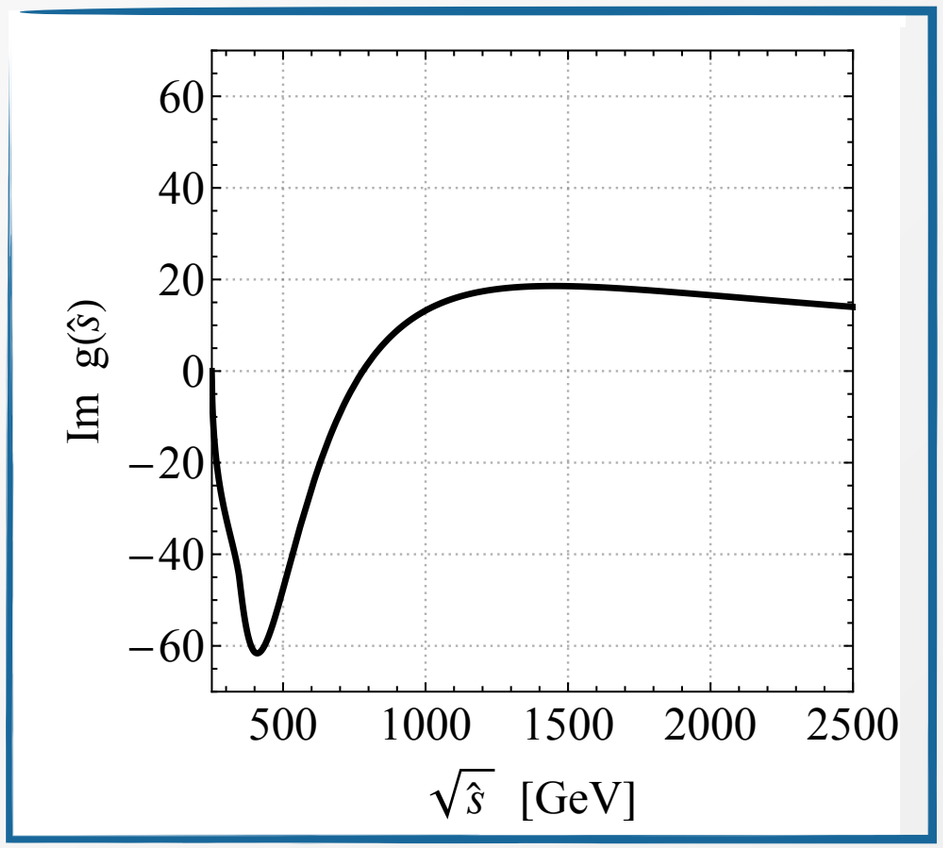
h^3 renormalised at vanishing external momenta (see **[1803.04359]**): the counterterm is chosen such that at zero-momentum transfer the one-loop diagrams plus the counterterm is equal to the h^3 coupling at tree level

Work ongoing to understand the connections with renormalization in the k framework to the one with SMEFT operators

Two-loop form factor (2)

[1802.07616,1803.04359]





- Non-trivial s-dependence, with pronounced extrema at $2m_t$ and $2(m_t+m_h)$

Results for double- and triple-Higgs production

Double-Higgs production: numerical results obtained using a customized version of POWHEG-BOX of the NLO QCD calculation **[1604.06447,1608.04798,1703.09252]**

$b\bar{b}\gamma\gamma$ final state:

estimated total uncertainty (th+exp)

15% (HE-LHC, 15 ab^{-1}), 5% (FCC-pp, 30 ab^{-1})

Triple-Higgs production: numerical results obtained using MadGraph5_amc@NLO; NLO QCD corrections obtained applying an overall normalization **[1408.6542]**

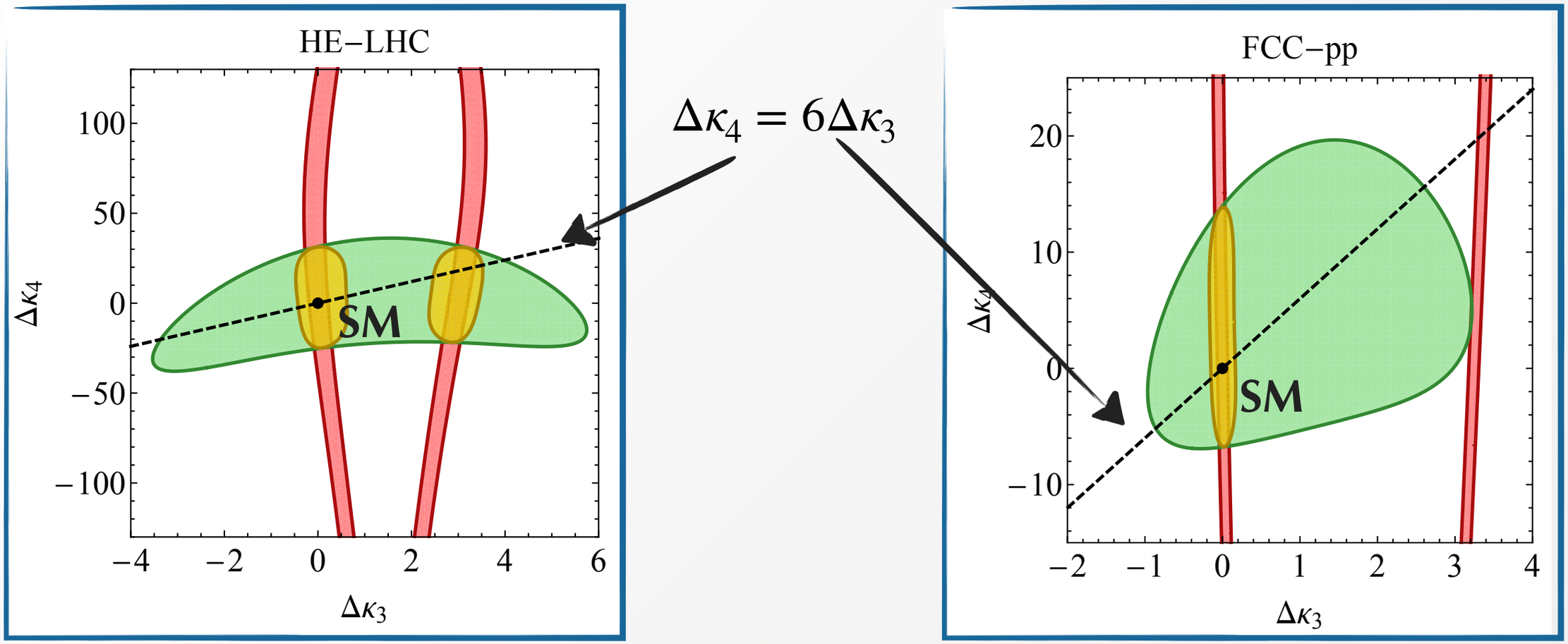
$b\bar{b}b\bar{b}\gamma\gamma$ final state:

simulations of relevant backgrounds ($b\bar{b}b\bar{b}\gamma\gamma, hhb\bar{b}$) within selection cuts **[1508.06524][1606.09408]**

HE-LHC, 15 ab^{-1}: exclusion of triple-Higgs production cross-section 11 x (SM value)

FCC-pp, 30 ab^{-1}: exclusion of triple-Higgs production cross-section 2 x (SM value)

Inclusive double- and triple-Higgs production



Red and green areas: limits from measurements of **double-Higgs** and **triple-Higgs** production

Yellow region $\Delta\chi^2 = 5.99$ (95% CL for a gaussian distribution)

$\kappa_4 \in [-21,29]$

large modifications due to O_6 only or both O_6, O_8

$\kappa_4 \in [-5,14]$

large modifications due to both O_6, O_8

in agreement with [1606.09408]

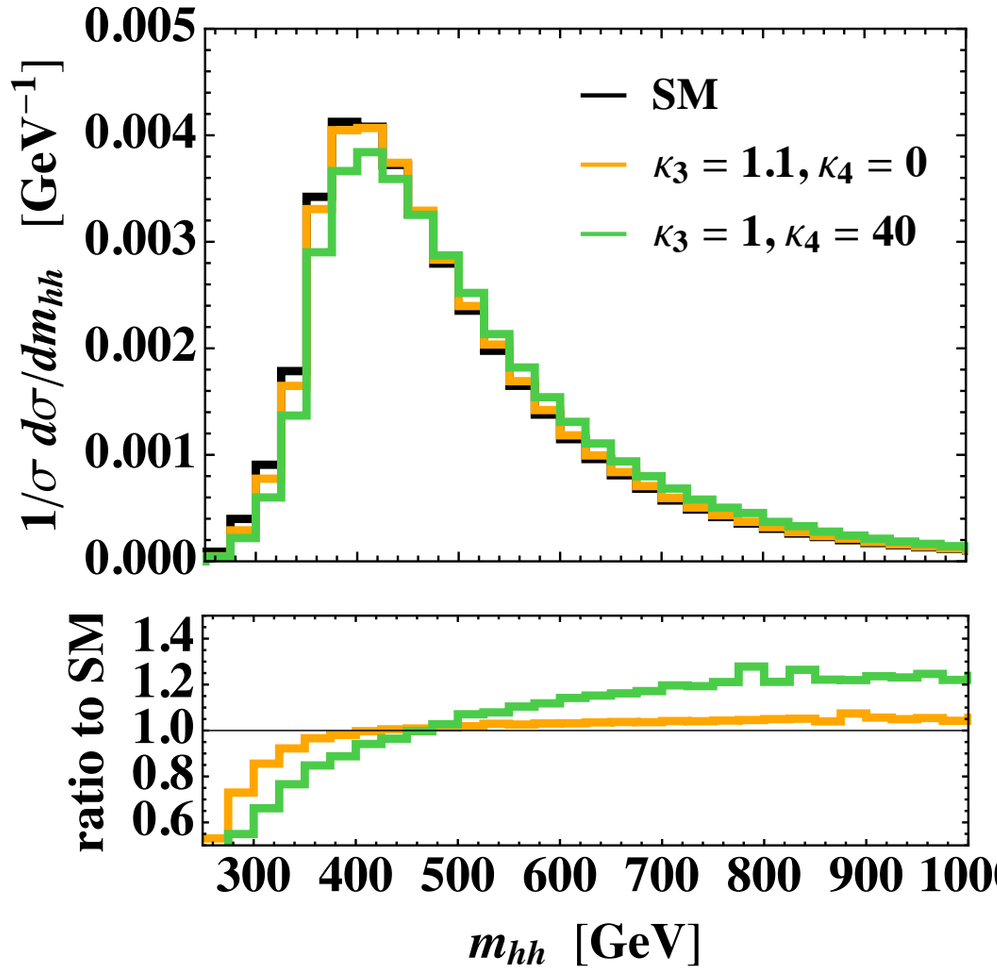
Differential distributions in double-Higgs production

Precise measurement of differential distributions may resolve ambiguities or flat directions

$\kappa_3 = 1.1, \quad \kappa_4 = 0$

$\kappa_3 = 1, \quad \kappa_4 = 40$

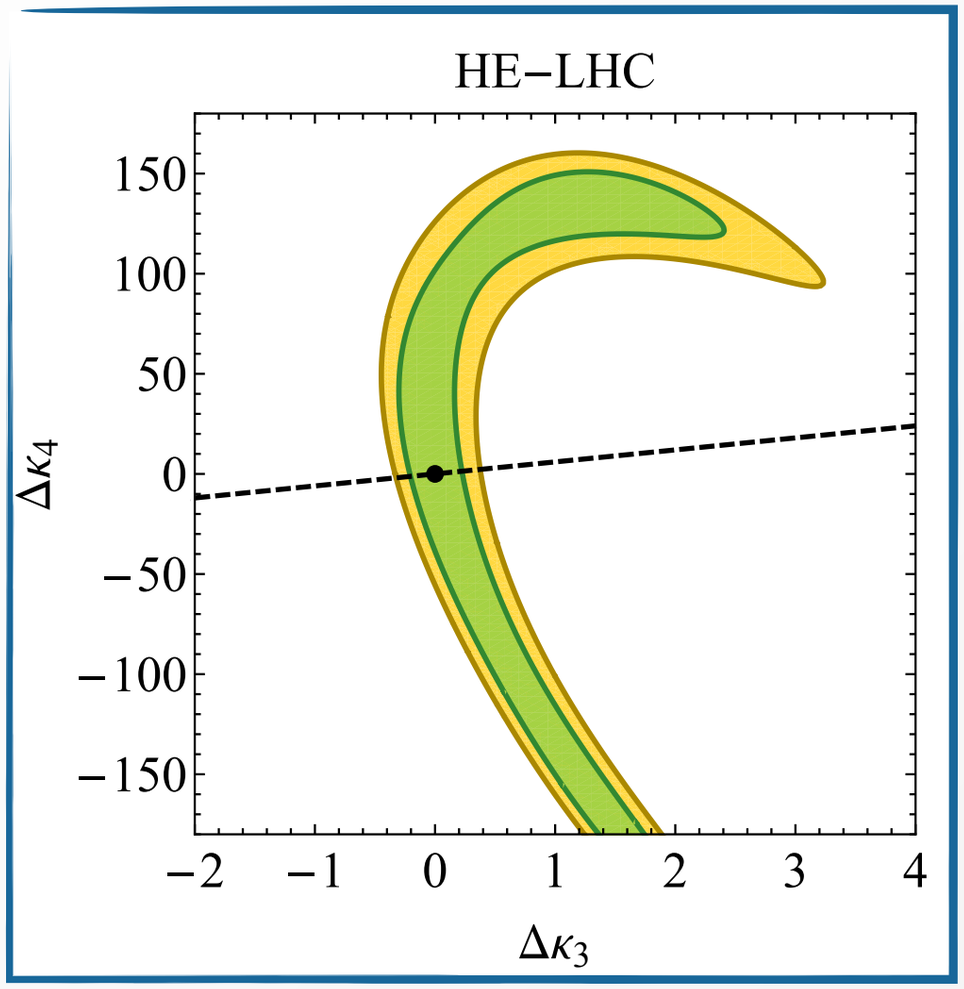
} double-Higgs production rate decreases by ~10%

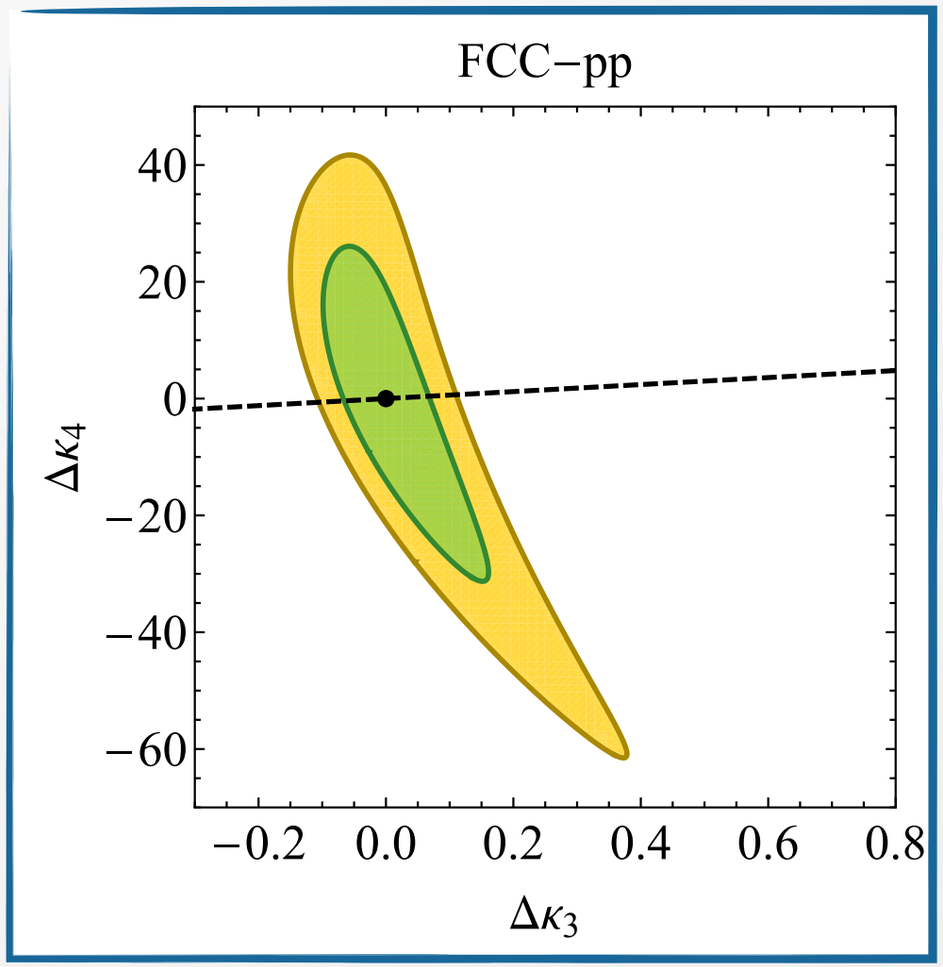


Shape analysis performed with `POWHEG-BOX+Pythia8` to include parton shower effects

No background estimate, CL curves mimic more sophisticated analysis which include simulation of all relevant backgrounds [1802.04319]

Differential distribution fit





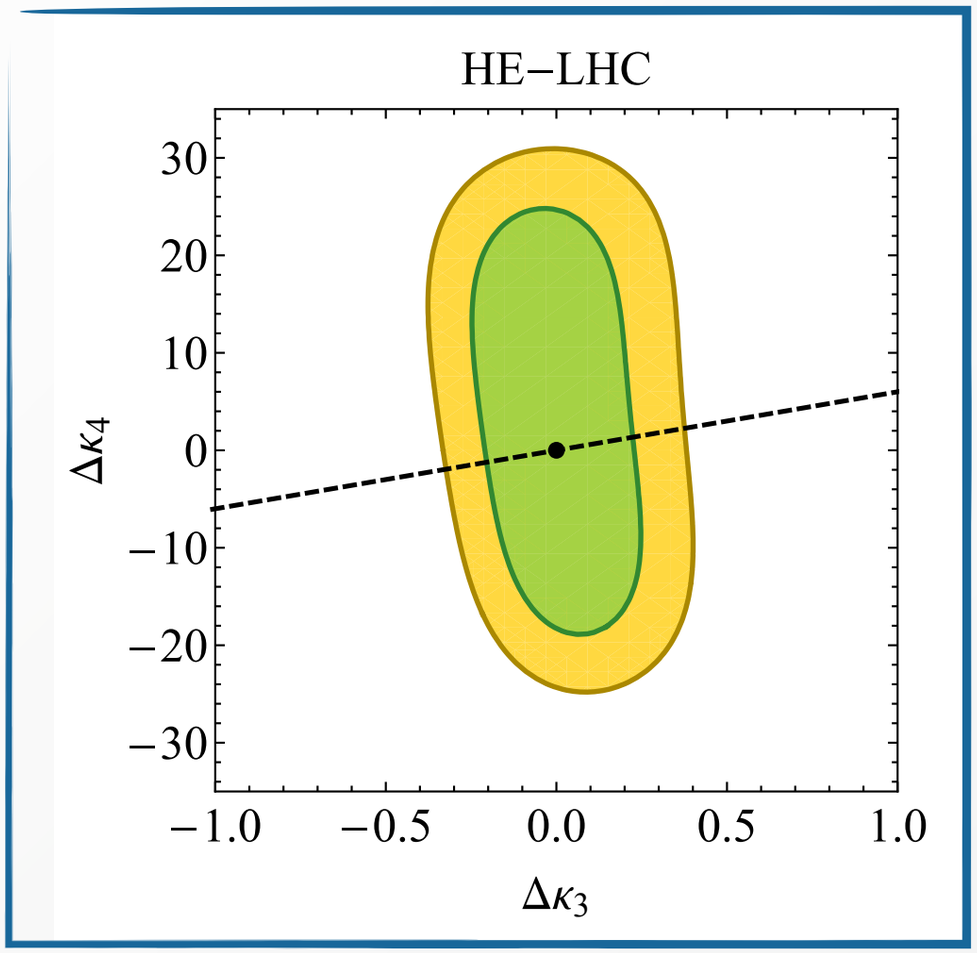
Degeneracy observed in the triple-Higgs production case now absent

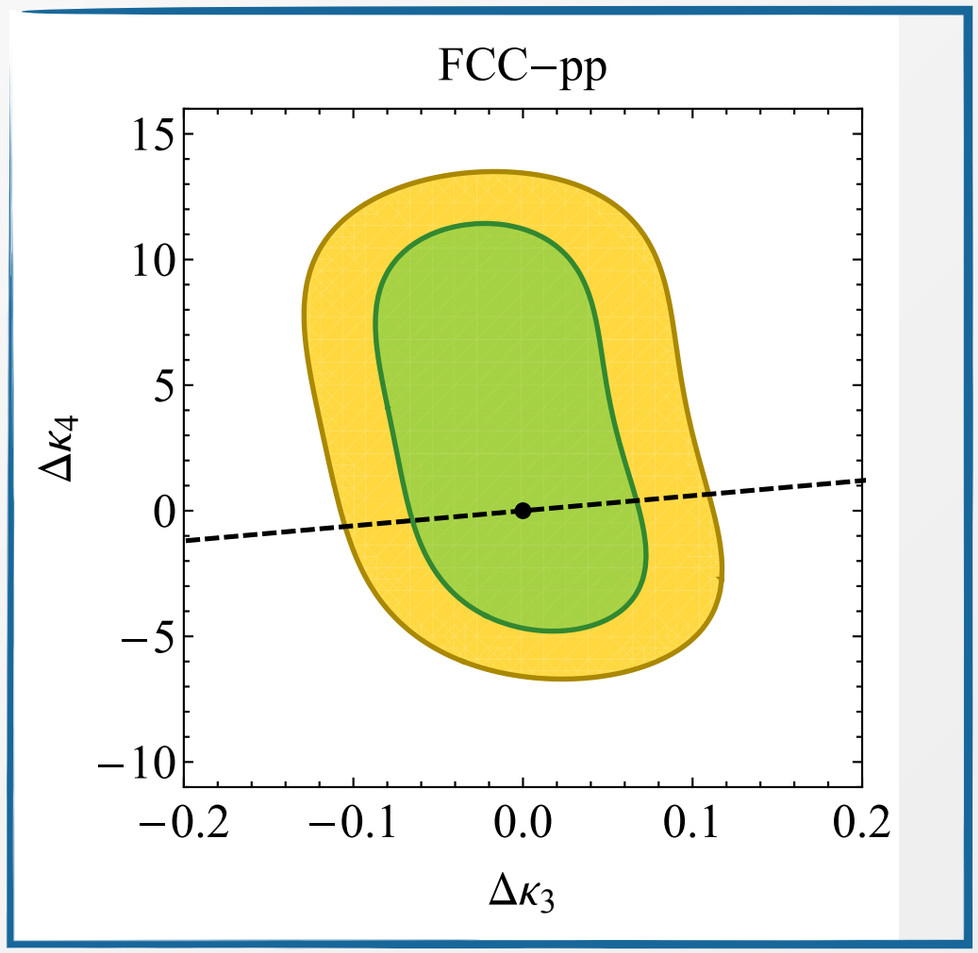
Bounds weaker than triple-Higgs production measurements

$\kappa_4 \in [-21,29]$ $\kappa_4 \in [-27,25]$

Global fit

Combined constraints using *hh* differential distributions and inclusive *hhh* production





$\kappa_3 = 1$ $\kappa_4 \in [-20,29]$

Profiling over κ_3 $\kappa_4 \in [-17,25]$

$\kappa_3 = 1$ $\kappa_4 \in [-5,13]$

Profiling over κ_3 $\kappa_4 \in [-4,12]$

Recapitulation

- We studied indirect constraints on the quartic Higgs self-coupling in double-Higgs production measurement at future colliders
- Differential measurements in $pp \to hh$ channel alone expected to lead to somewhat weaker determinations of quartic Higgs self-coupling than inclusive $pp \to hhh$ production
- Combined measurements of differential distributions in double-Higgs production and inclusive triple-Higgs production: $\kappa_4 \in [-17,25]$(HE-LHC), $\kappa_4 \in [-4,12]$(FCC-pp)
- Results can be compared to hypothetical constraints from HE e^+e^- machines: ILC-500 ($\kappa_4 \in [-11,13]$, ILC-3000 ($\kappa_4 \in [-5,7]$, finding comparable potential for FCC-pp and ILC-3000 **[1802.07616][1803.04359]**
- Phenomenological results in agreement with **[1811.12366]** (see talk by Davide)