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

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

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

The Standard Model (SM) Higgs potential

double-Higgs production

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triple-Higgs production

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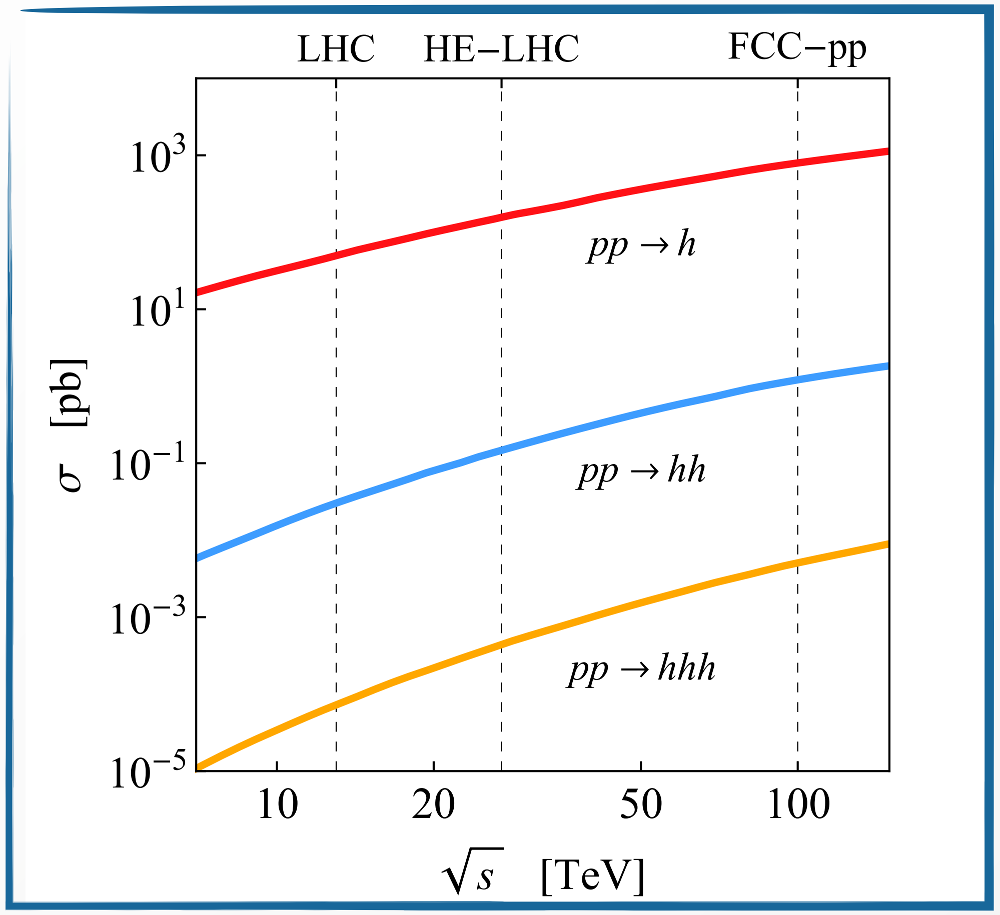
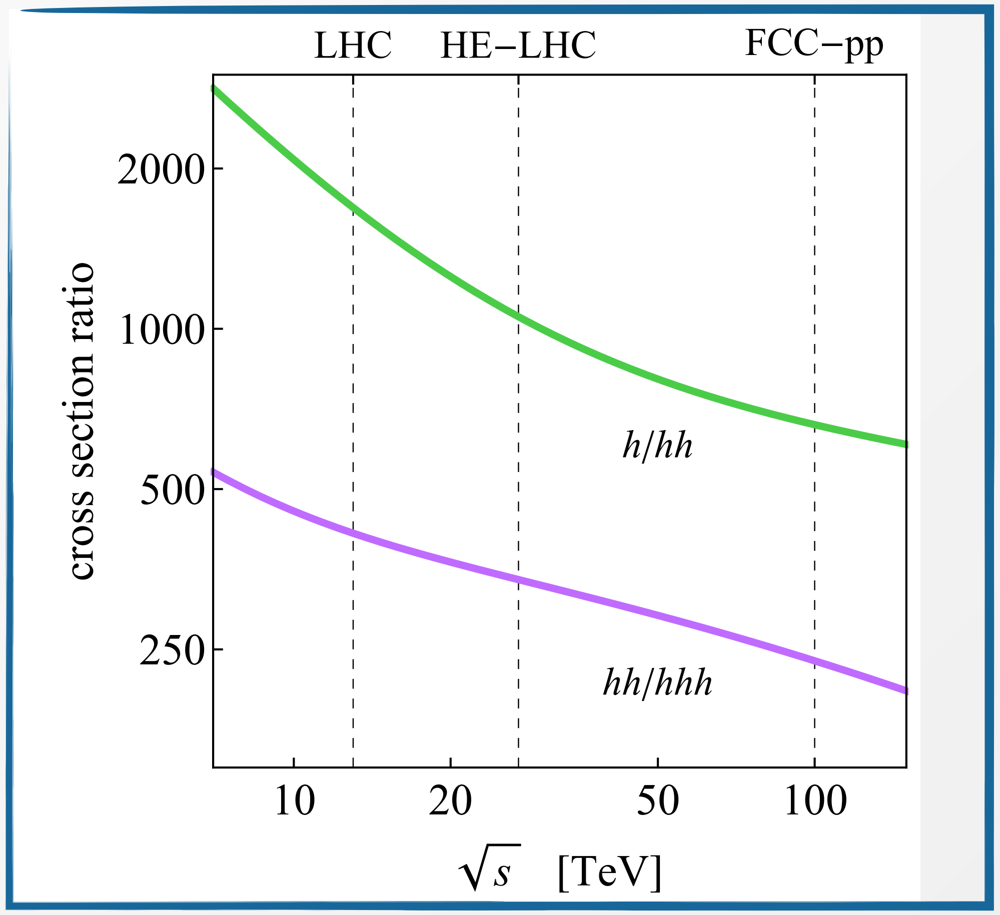
Higgs production at hadron colliders





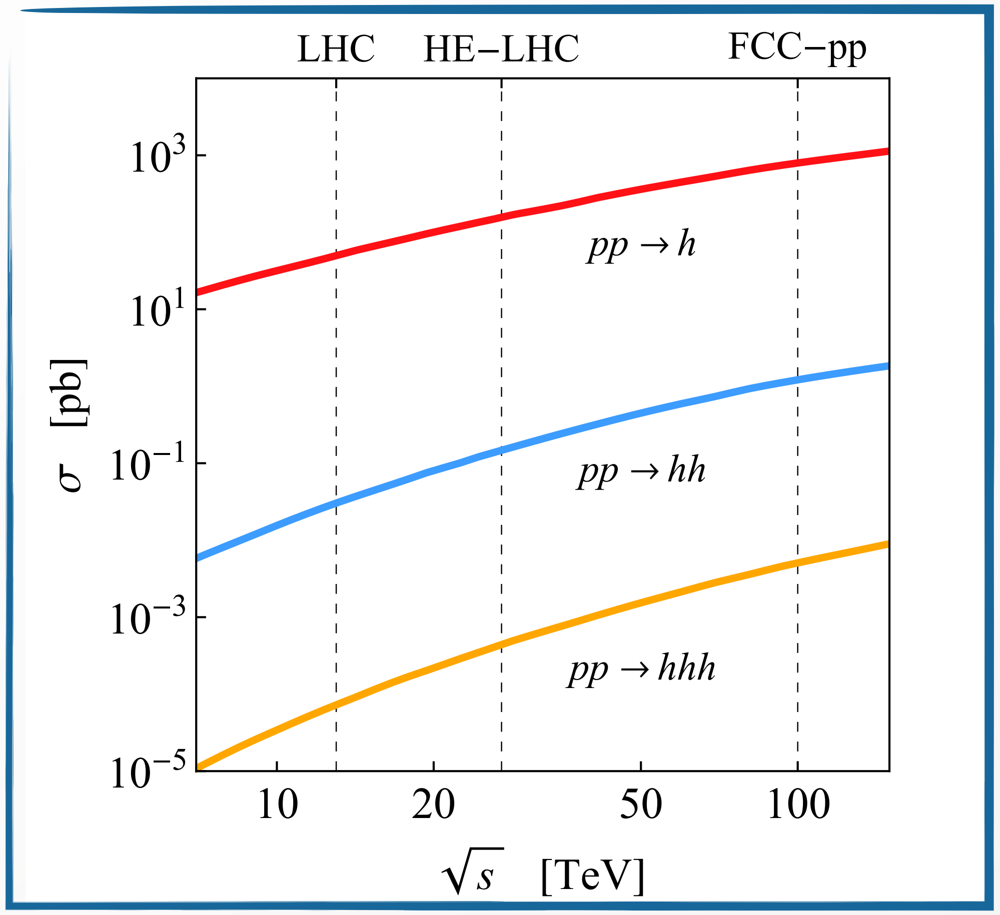
Multi-higgs production rate are small in the SM

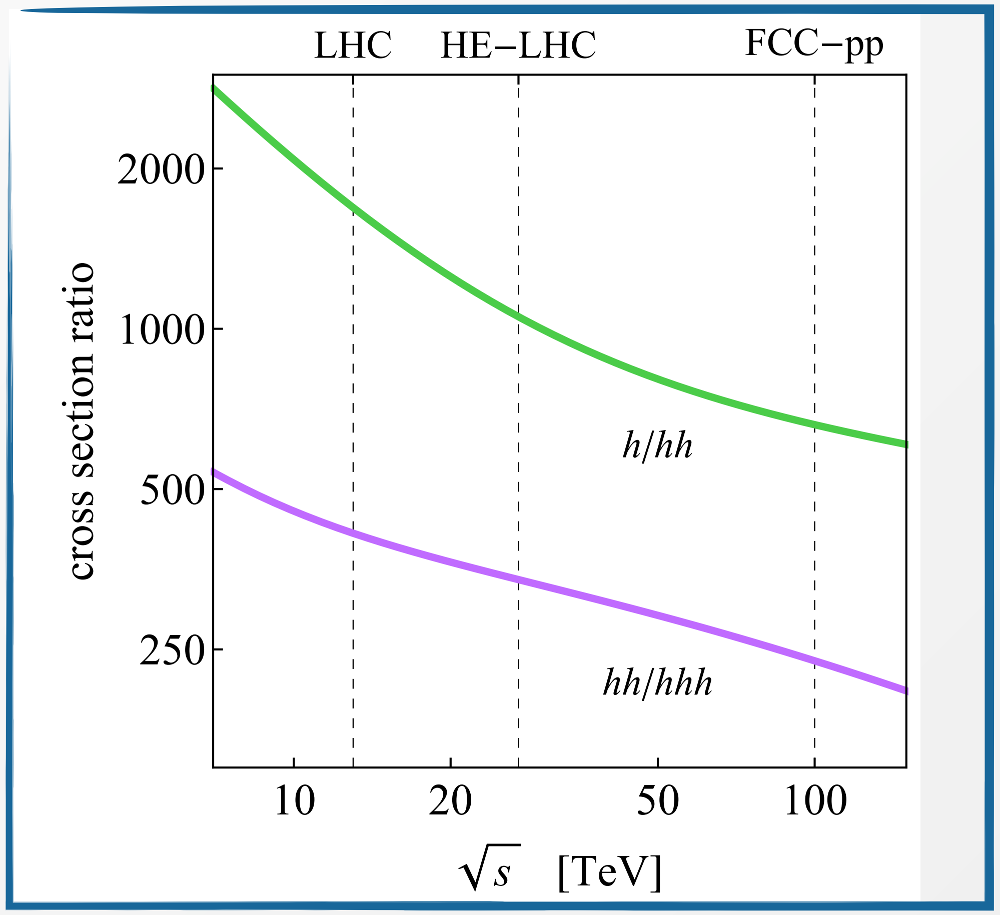
LHC: $O(1)$ determinations of the cubic Higgs self-coupling

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

SM effective field theory (EFT)

$$V \supset \kappa_3 \lambda v h^3 + \kappa_4 \frac{\lambda}{4} h^4$$

$\kappa_3, \kappa_4 \neq 1$ if physics beyond SM is present

Consider operators of dimension 6 and 8 in the SMEFT

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

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

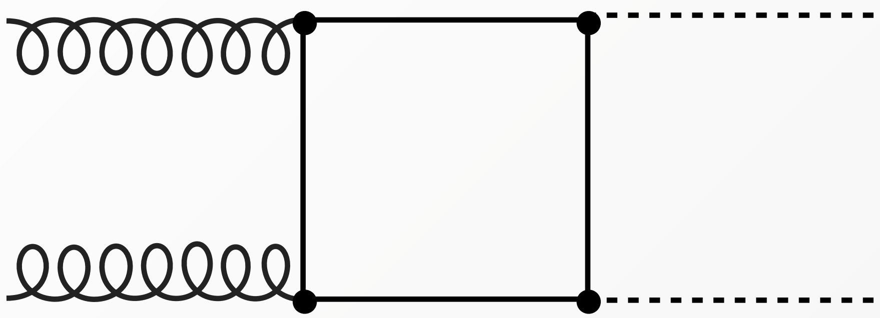
No assumption about the actual size of $\bar{c}_6$ and $\bar{c}_8$: cubic and quartic Higgs self-couplings can deviate independently from the SM predictions

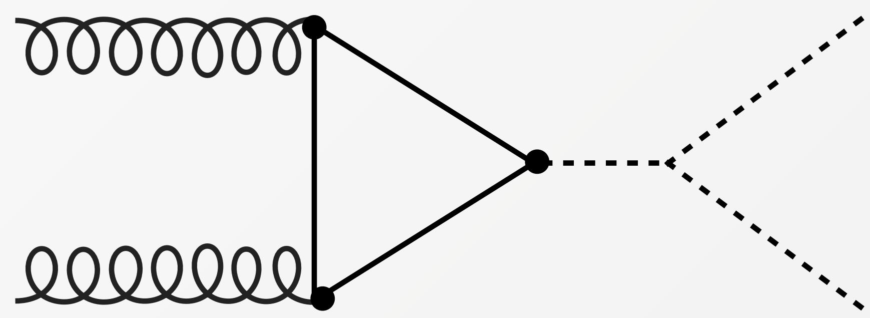
If O_6 is the only numerically relevant operator, strong correlation

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

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





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

[Glover, der Bij 1988]

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

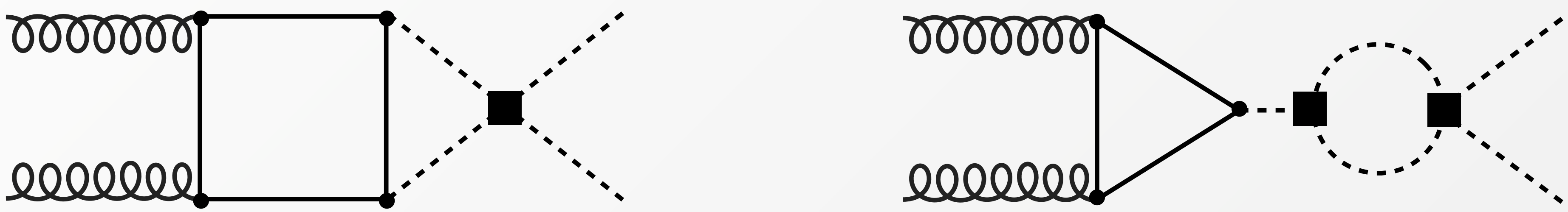
$$\sigma_{\rm LO} = \sigma_0 \int dt(|\mathcal{F}_1|^2 + |\mathcal{F}_2|^2)$$

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

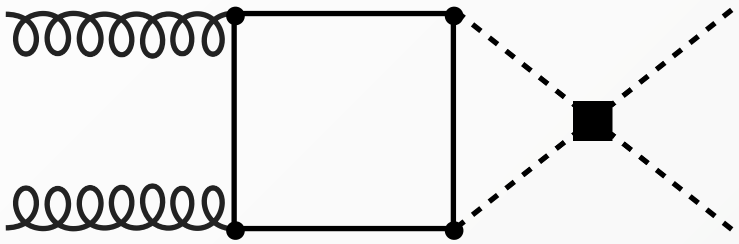
We calculate the relevant EW two-loop amplitudes and we combine them with the exact $\mathcal{O}(\alpha_s^2)$ matrix elements

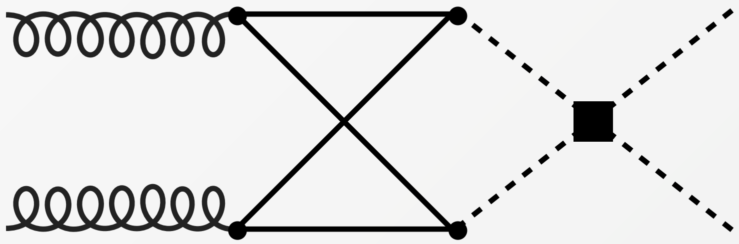


Total cross-section and differential distributions for double-Higgs production at NLO QCD, including arbitrary modifications of the cubic and quartic self-couplings

Final combination using constraints of the Higgs self-coupling in *hhh* production at HE-LHC and FCC-pp to study synergy and complementarity of the two approaches

Two-loop form factor (1)





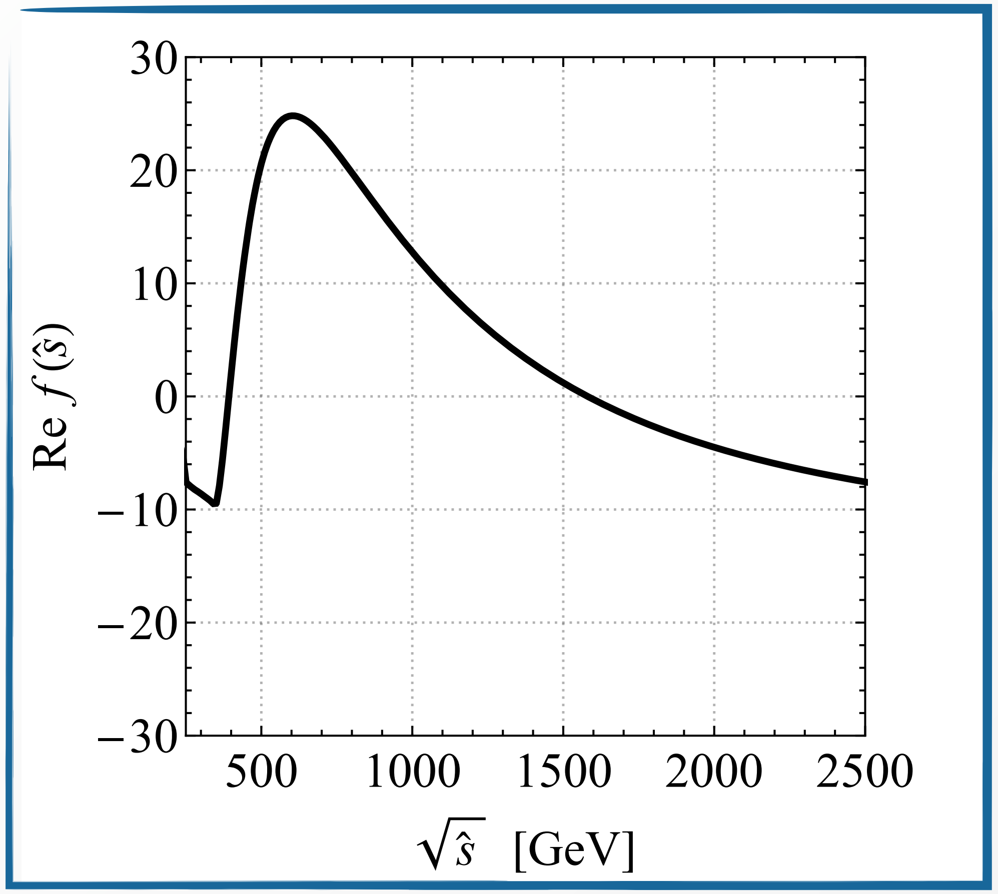
$$\Delta\mathcal{F}_1^{\kappa_4} = \frac{\alpha_s}{4\pi}\frac{\lambda\,\kappa_4}{(4\pi)^2}\; y_t^2\, f(\hat{s}) \qquad \Delta\mathcal{F}_2^{\kappa_4} = 0$$

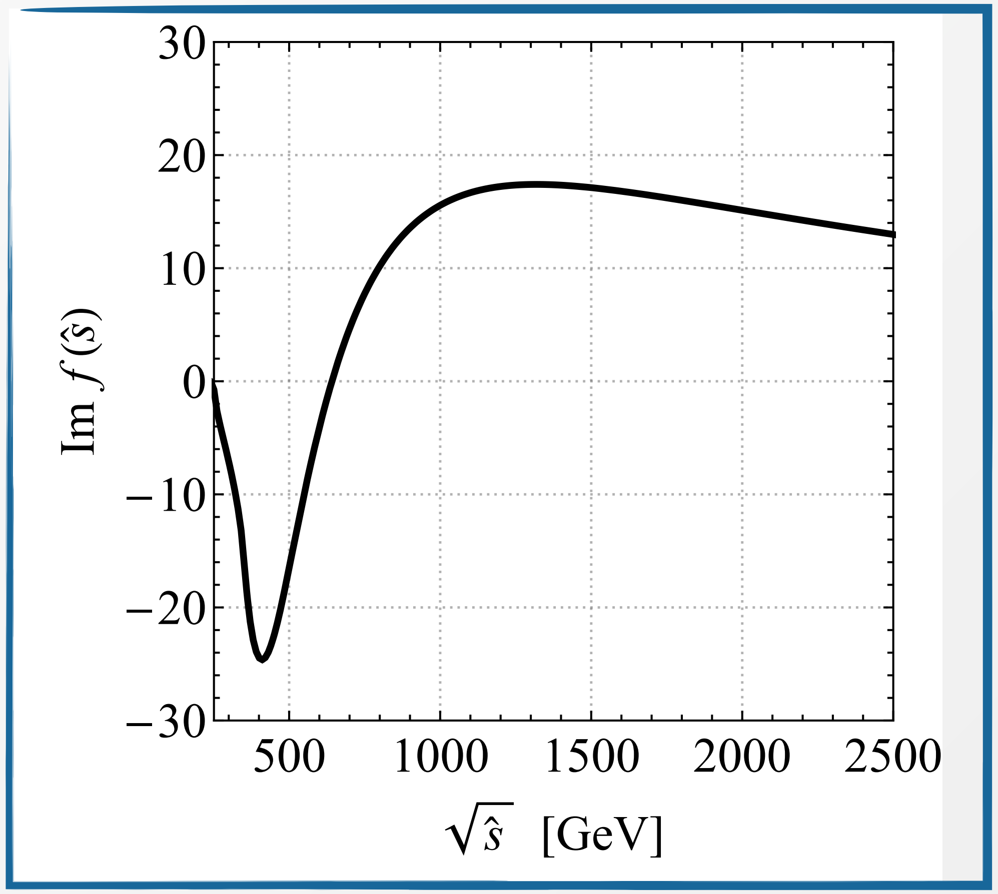
Two-loop integrals evaluated numerically using pySecDec package [1204.4152,1502.06595,1703.09692]

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

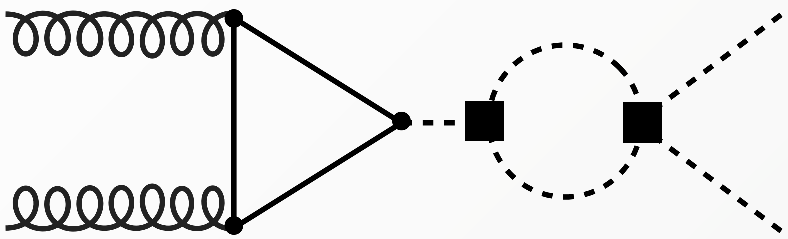
Two-loop form factor (1)

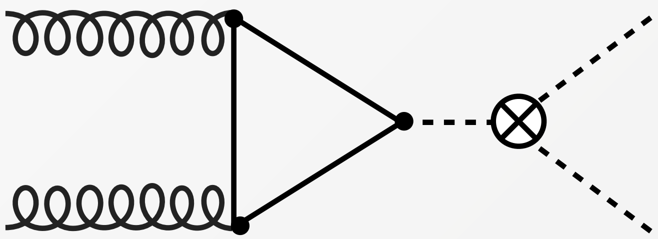




- Correction depends only on $\hat{s}$
- Correction to the spin-2 form factor is zero

Two-loop form factor (2)





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

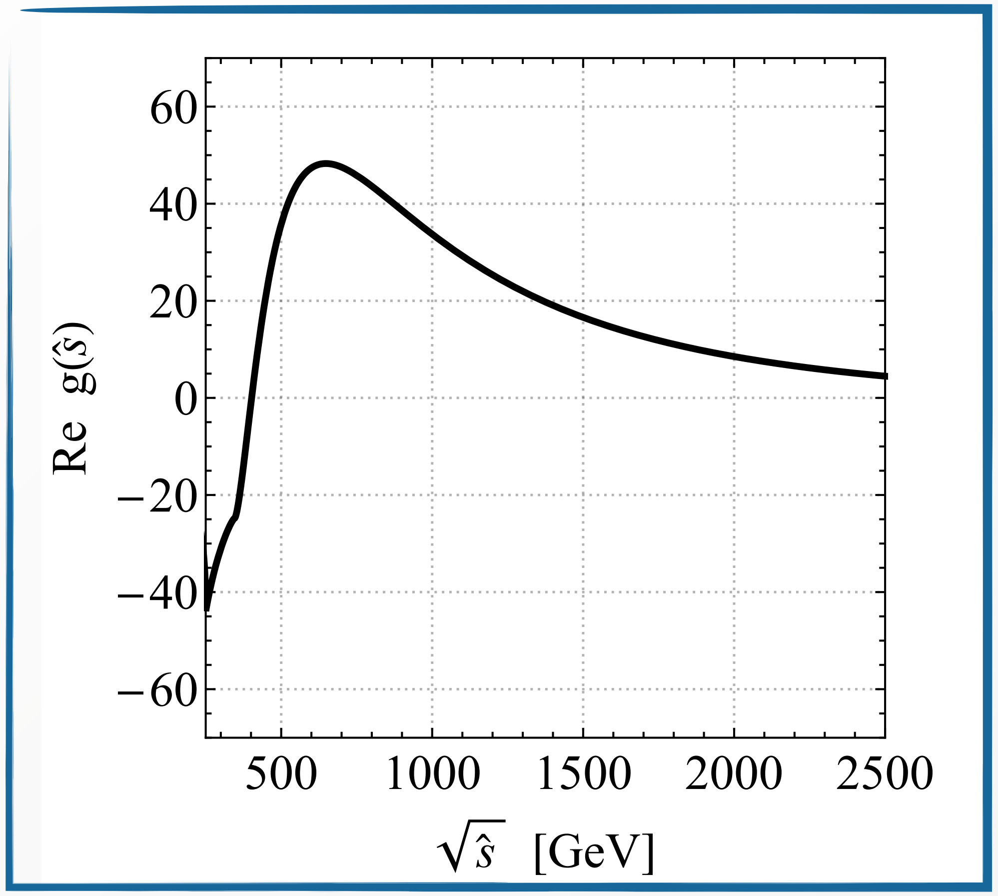
Function *g(s)* can be calculated analytically

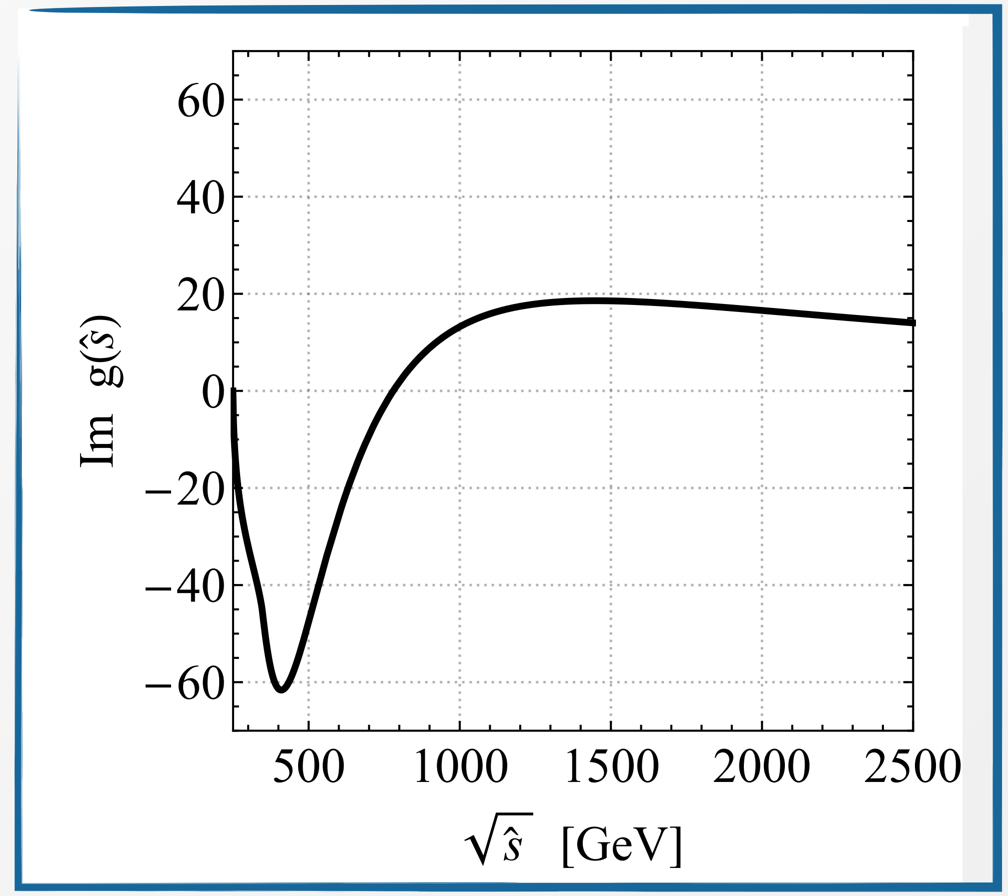
h^3 renormalised at vanishing external momenta (see **[1803.04359]**): the counterterm is chosen such that at zero-momentum transfer the one-loop diagrams plus the counterterm is equal to the h^3 coupling at tree level

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]

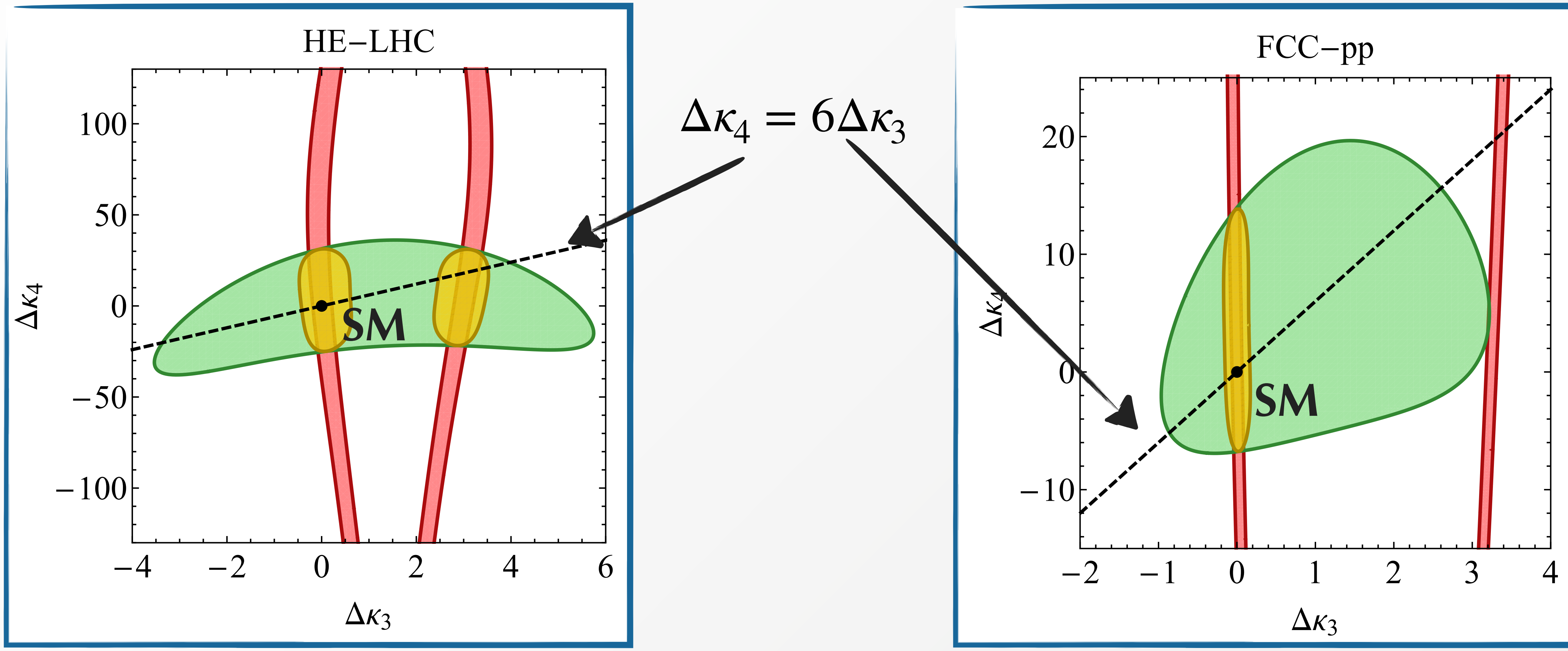
$b\bar{b}b\bar{b}\gamma\gamma$ final state:

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)

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

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

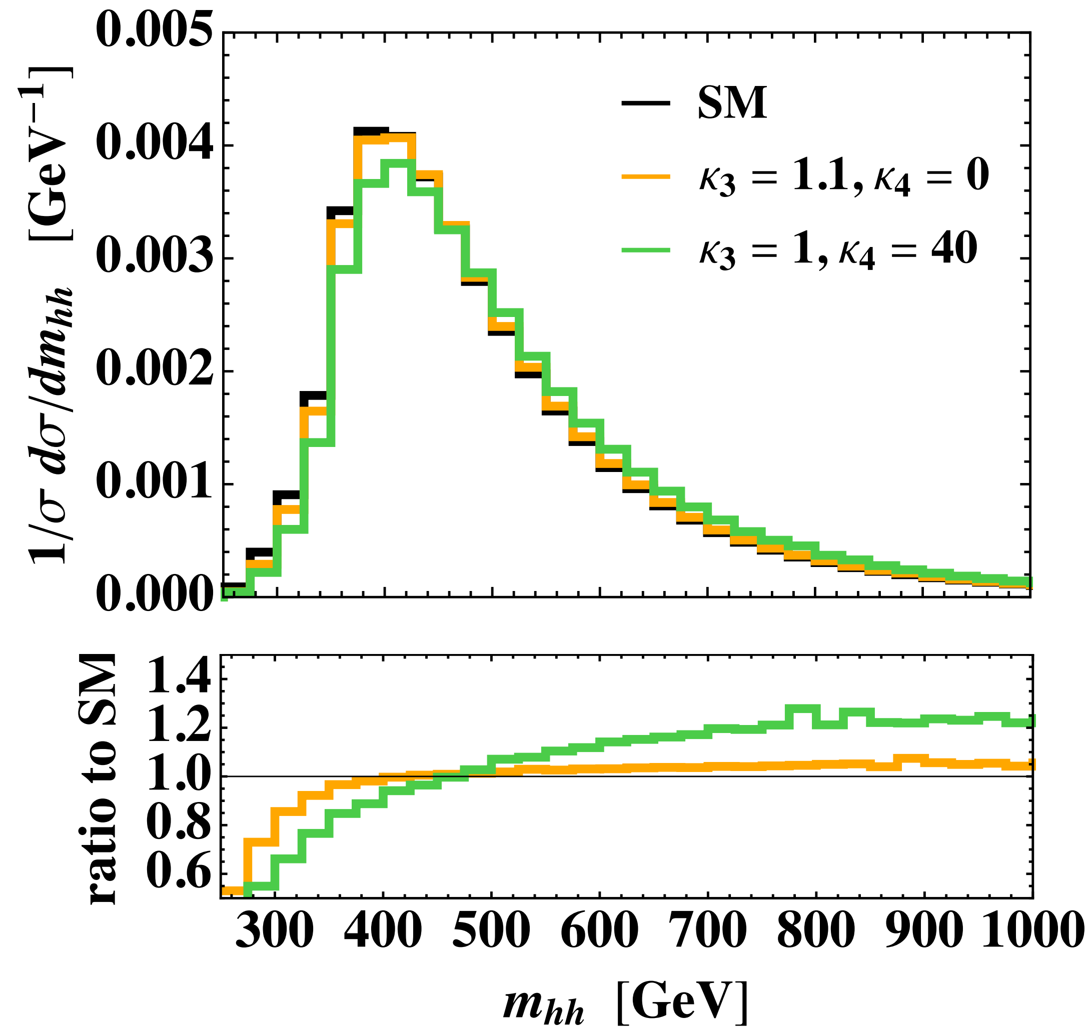
in agreement with [1606.09408]

large modifications due to O_6 only or both O_6, O_8

large modifications due to both O_6, O_8

Differential distributions in double-Higgs production

Precise measurement of differential distributions may resolve ambiguities or flat directions

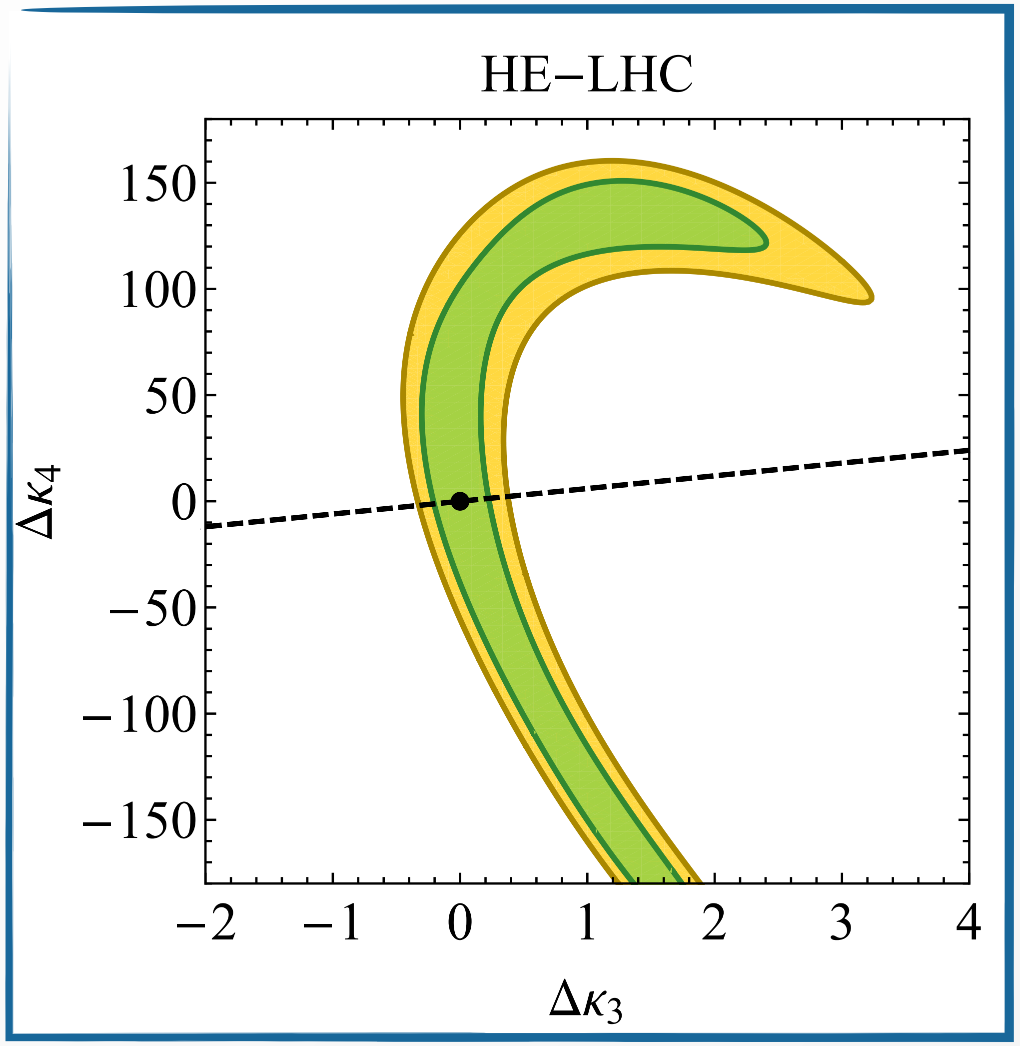


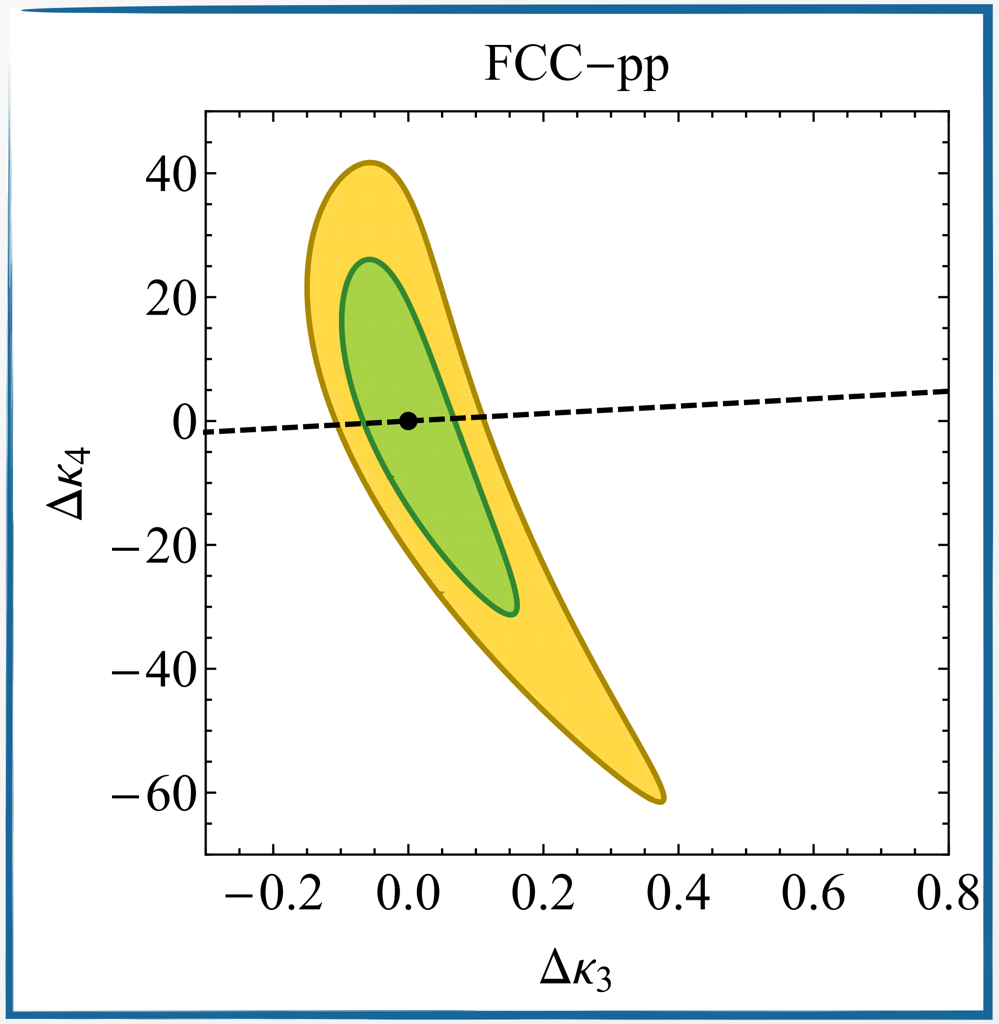
$$\left.\begin{array}{l}\kappa_3 = 1.1, \quad \kappa_4 = 0 \\ \\ \kappa_3 = 1, \quad \kappa_4 = 40\end{array}\right\}$$ double-Higgs production rate decreases by ~10%

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

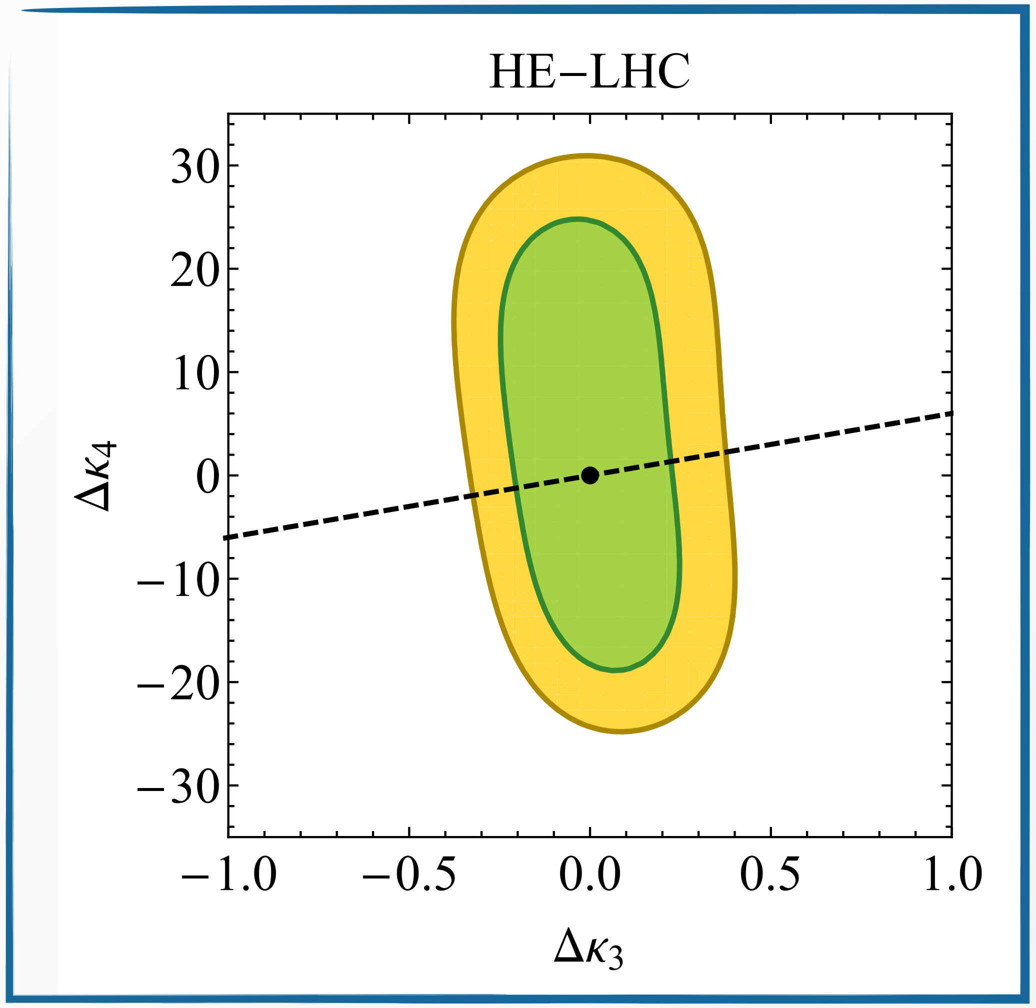
Bounds weaker than triple-Higgs production measurements

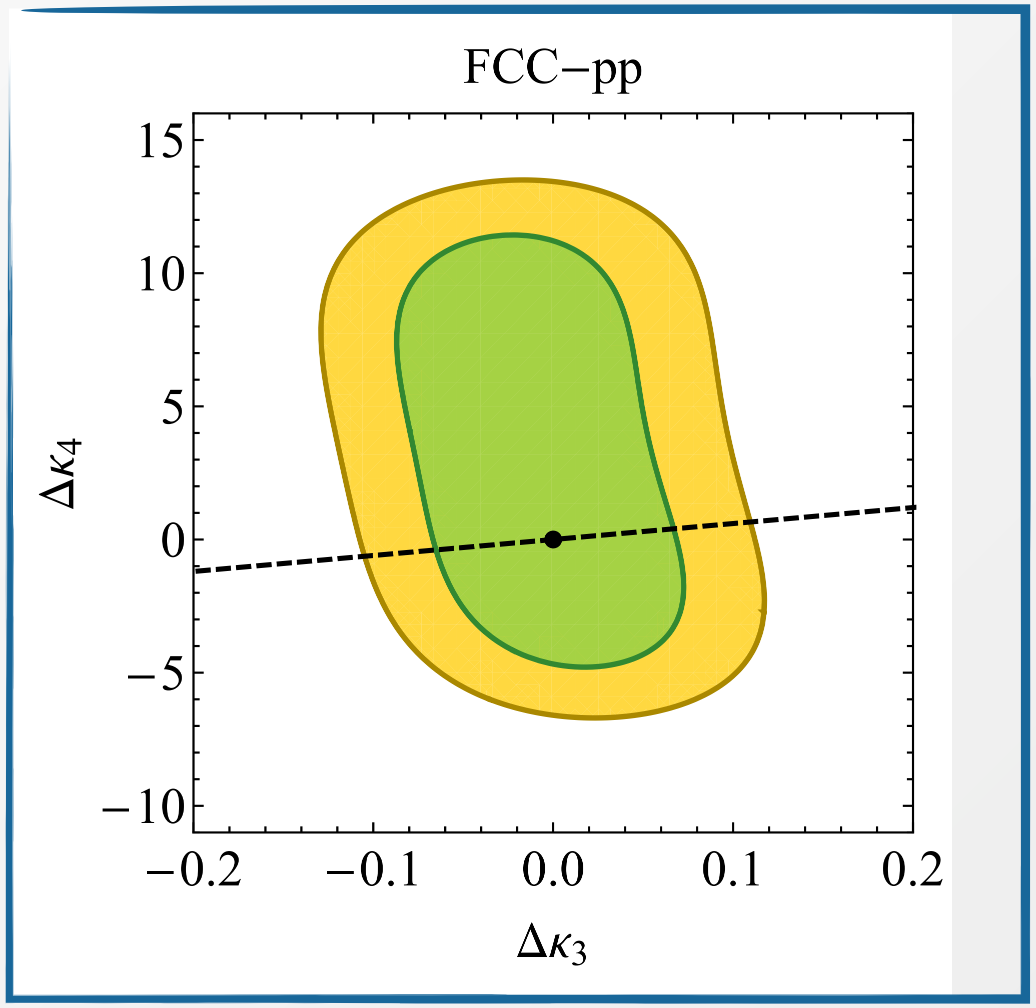
$\kappa_4 \in [-21, 29]$

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

Global fit

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





	HE-LHC		FCC-pp
$\kappa_3 = 1$	$\kappa_4 \in [-20,29]$	$\kappa_3 = 1$	$\kappa_4 \in [-5,13]$
Profiling over κ_3	$\kappa_4 \in [-17,25]$	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)