Constraints on the quartic Higgs self-coupling from double-Higgs production

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Based on 2402.03463 with Z. Gillis, B. Moser and P. Windischhofer and 1810.04665 with W. Bizon and U. Haisch

The Standard Model (SM) Higgs potential

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

$v \simeq 246\,\text{GeV}$	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

The Standard Model (SM) Higgs potential

double-Higgs production

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

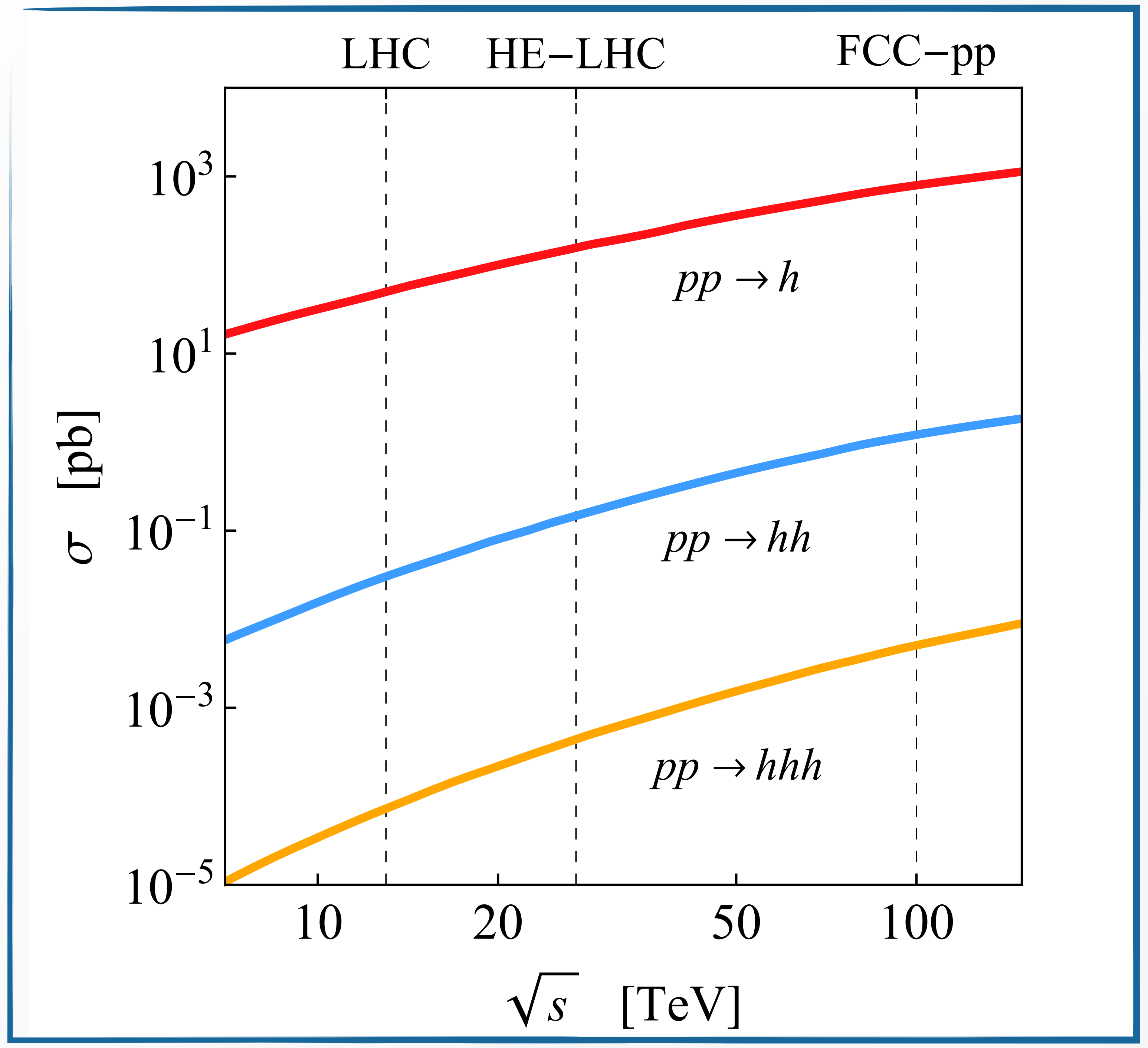
triple-Higgs production

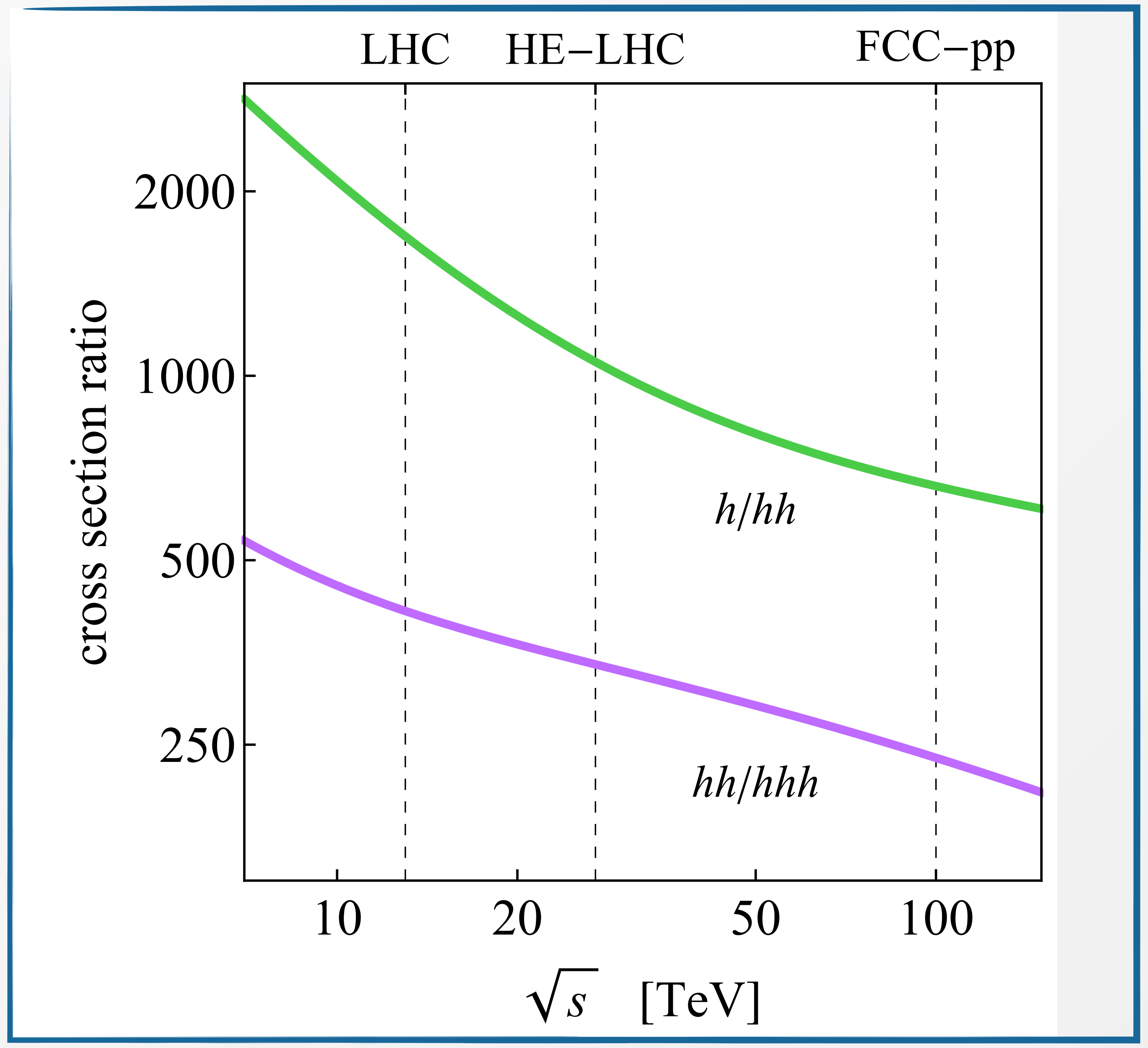
$v \simeq 246\,\text{GeV}$ — discovery of the *W* and *Z* bosons

$m_H \simeq 125\,\text{GeV}$ — discovery of the Higgs boson at the LHC

$\lambda_{SM}, \gamma_{SM}$ — essentially untested

Higgs production at hadron colliders





Multi-higgs production rate are **small in the SM**

HL-LHC: expected 4σ significance for double-Higgs production with 3000 fb^{-1}

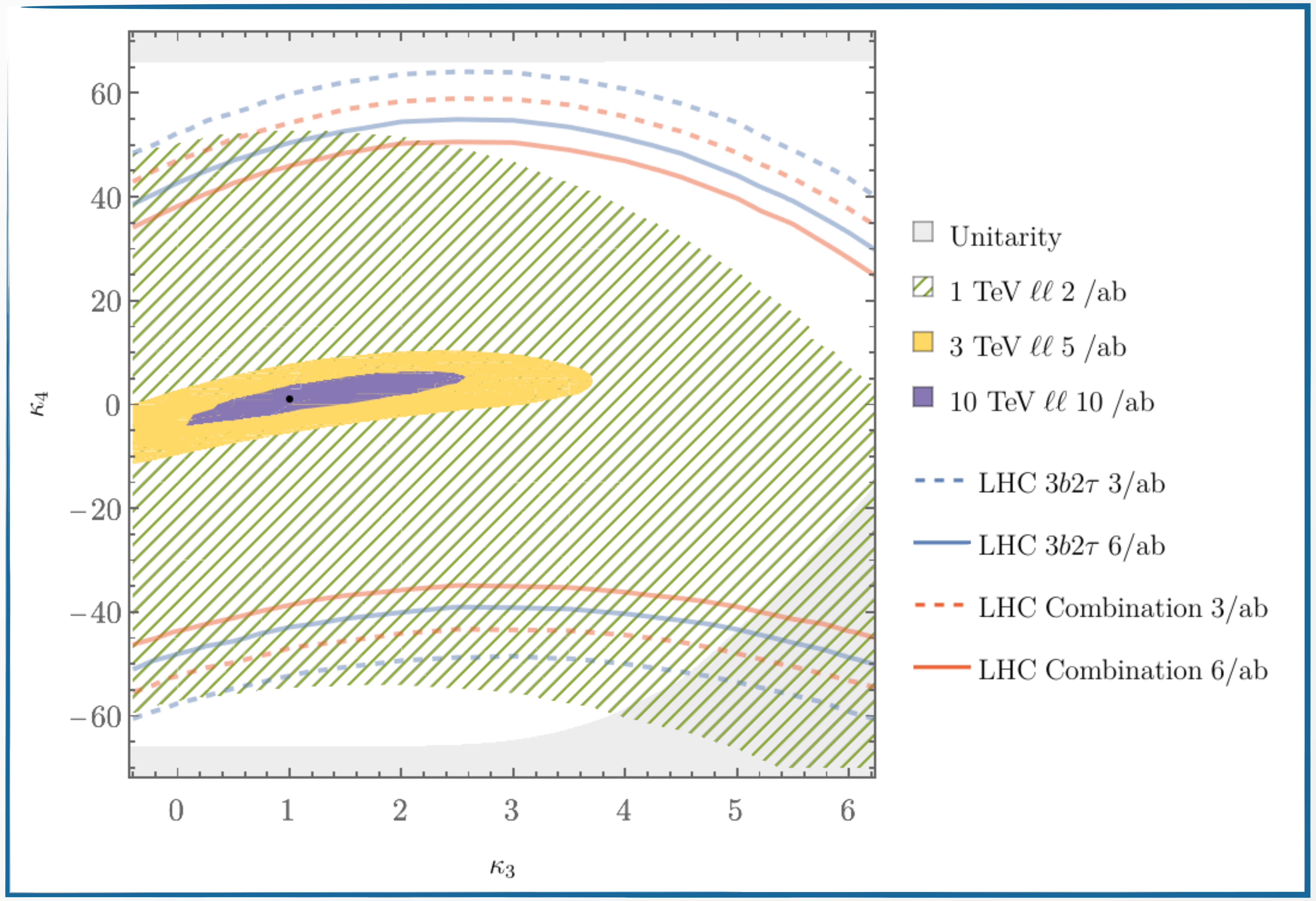
HE-LHC: prospects of extracting the cubic Higgs self-coupling with $O(20\%)$

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

Any hope to constrain the quartic Higgs self-coupling at HL-LHC?

Accessing the quartic Higgs self-coupling at hadron colliders

2312.04646 focuses on *hhh* production. Graph Neural Network are used to maximise the statistical yield focusing on $6b$ and $4b2\tau$ channels



Bounds found to be competitive with a 1 TeV lepton collider such as ILC

Accessing the quartic Higgs self-coupling at hadron colliders

Complementary approach: constraining the Higgs quartic self-coupling indirectly from double Higgs productions

Idea explored first to access indirectly the **Higgs trilinear self-coupling** via **differential distributions** in single Higgs production

Subsequently exploited for bounding the Higgs quartic self-coupling looking at **double Higgs production** (1810.04665, 1811.12366, the latter also includes a first sensitivity study at HL-LHC)

Our work/this talk: exploratory studies at HL-LHC based on the calculation of 1810.04665, release of **public Monte Carlo event generator** at NLO QCD

SM effective field theory (EFT) and κ framework

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

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

Consider operators of dimension 6 and 8 in the **SMEFT**

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

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

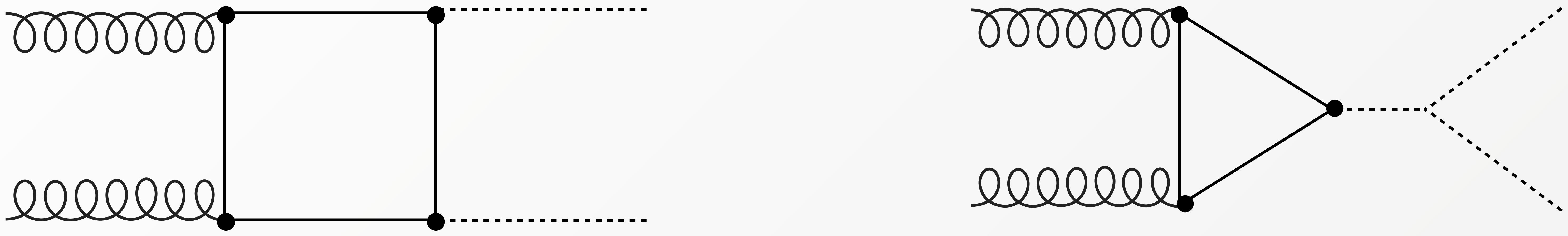
No assumption about the actual size of $\bar{c}_6$ and $\bar{c}_8$: cubic and quartic Higgs self-couplings can **deviate independently** from the SM predictions

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 be calculated consistently if 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]

$$T_{1\,\mu\nu} = \eta_{\mu\nu} - \frac{p_{1\,\nu}p_{2\,\mu}}{p_1 \cdot p_2}$$

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

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

Double-Higgs production known at NLO QCD with full top mass dependence

[1604.06447,1608.04798,1703.09252,1811.05692]

NNLO QCD with mass dependence at NLO QCD

[1803.02463]

Complete NLO EW corrections recently calculated

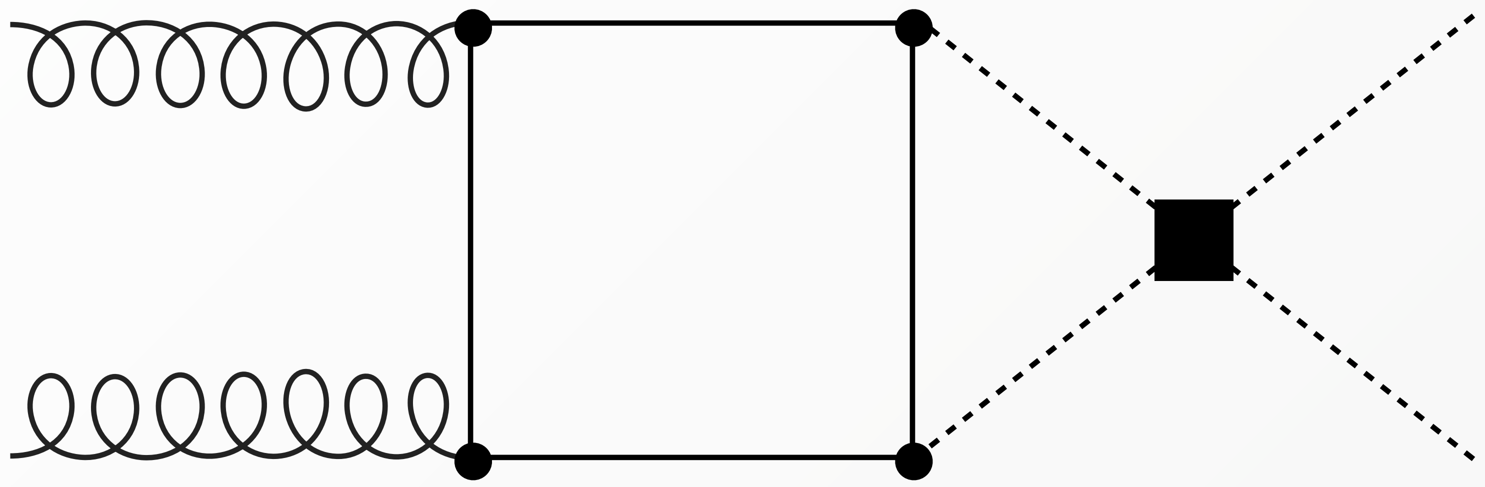
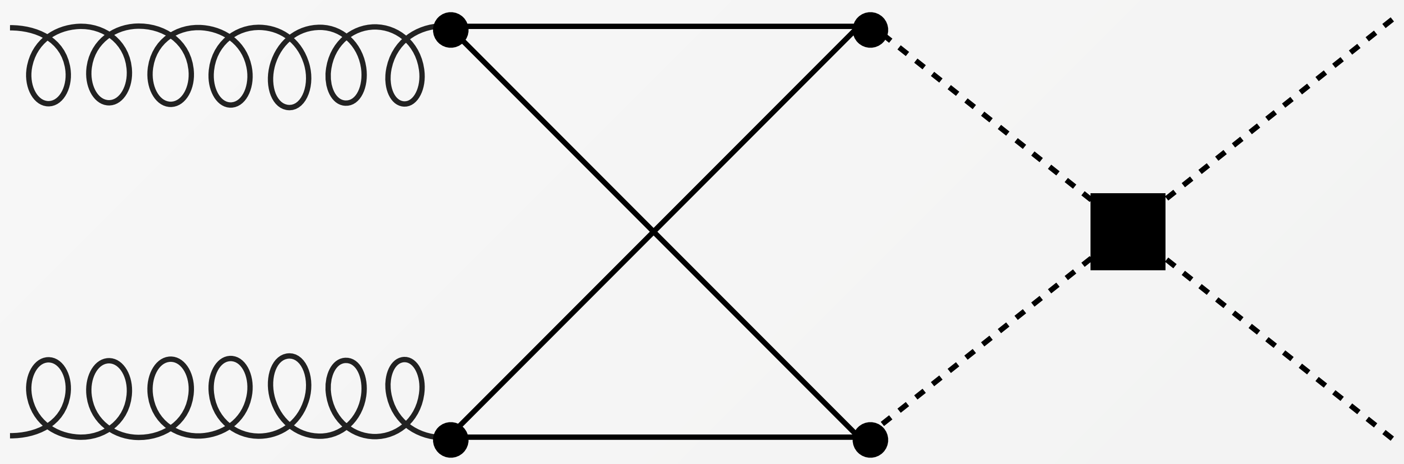
[2311.16963]

The quartic Higgs self-coupling in double-Higgs production

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

Allows us to calculate total cross-section and differential distributions for double-Higgs production at NLO QCD, including **arbitrary modifications** of κ_3 and κ_4

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

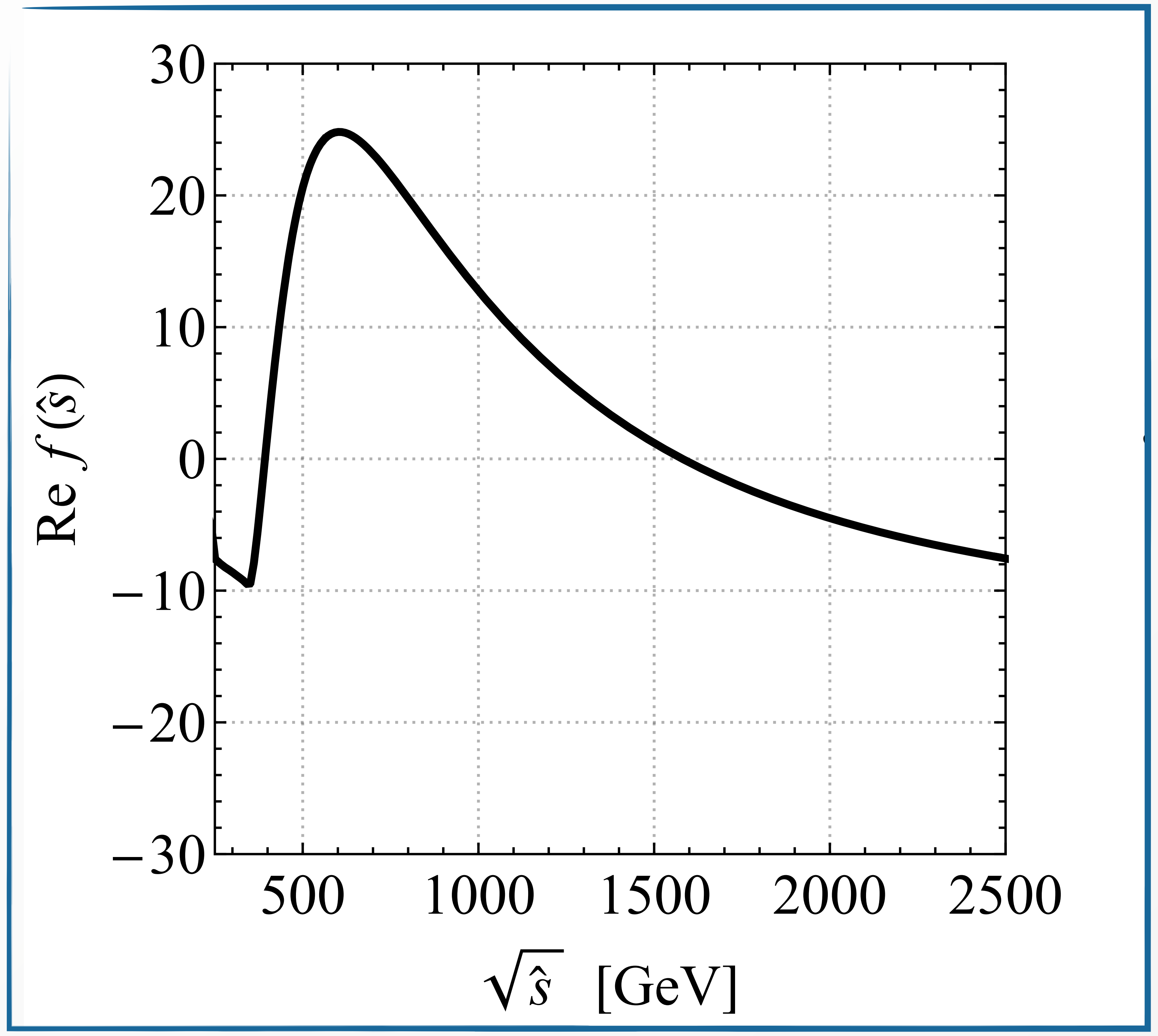
[1204.4152,1502.06595,1703.09692]

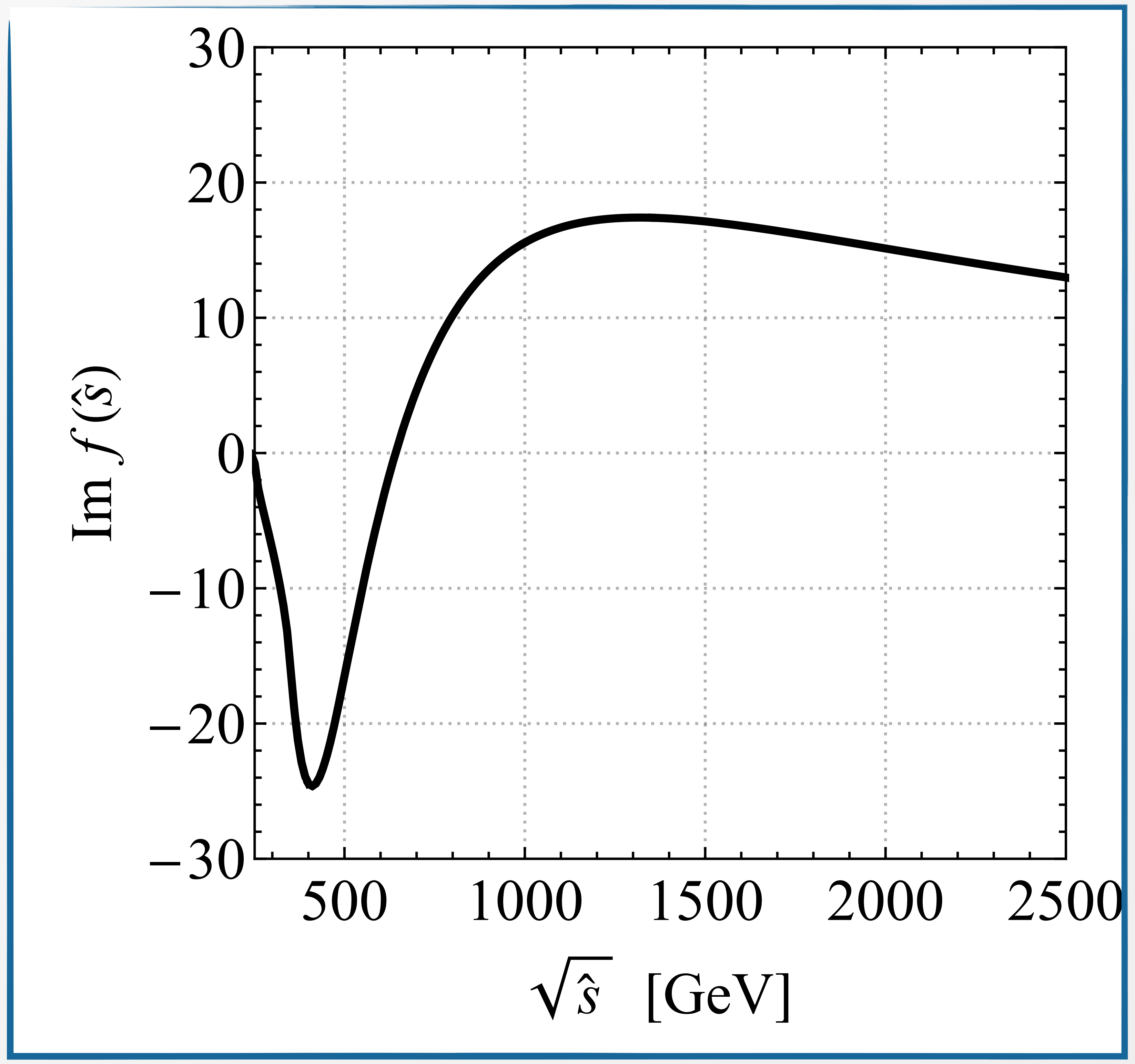
No renormalisation needed

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

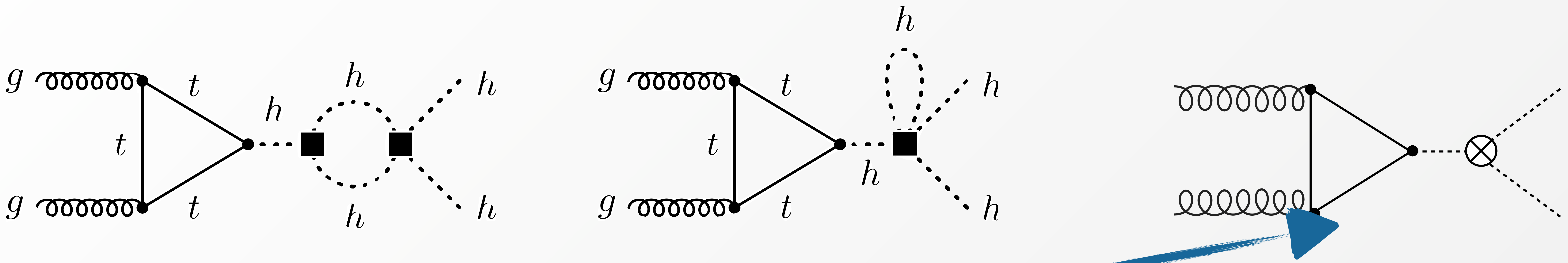
Two-loop form factor (1)





- Correction depends only on $\hat{s}$
- Correction to the spin-2 form factor is zero
- Impact expected on kinematics for double-Higgs production due to the pronounced maxima and minima

Two-loop form factor (2)

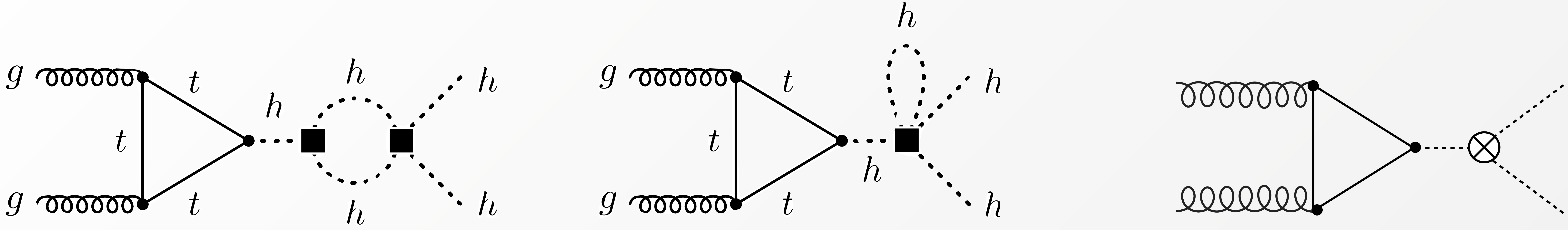


One-loop counterterms contribution associated to Higgs tadpole, wave function, mass and corrections to operator renormalisation needed for **gauge invariance**

T_h, Z_h, m_h renormalised in the on-shell scheme, α renormalised in the G_μ scheme

Operator renormalisation performed in the $\overline{MS}$ scheme

Two-loop form factor (2)



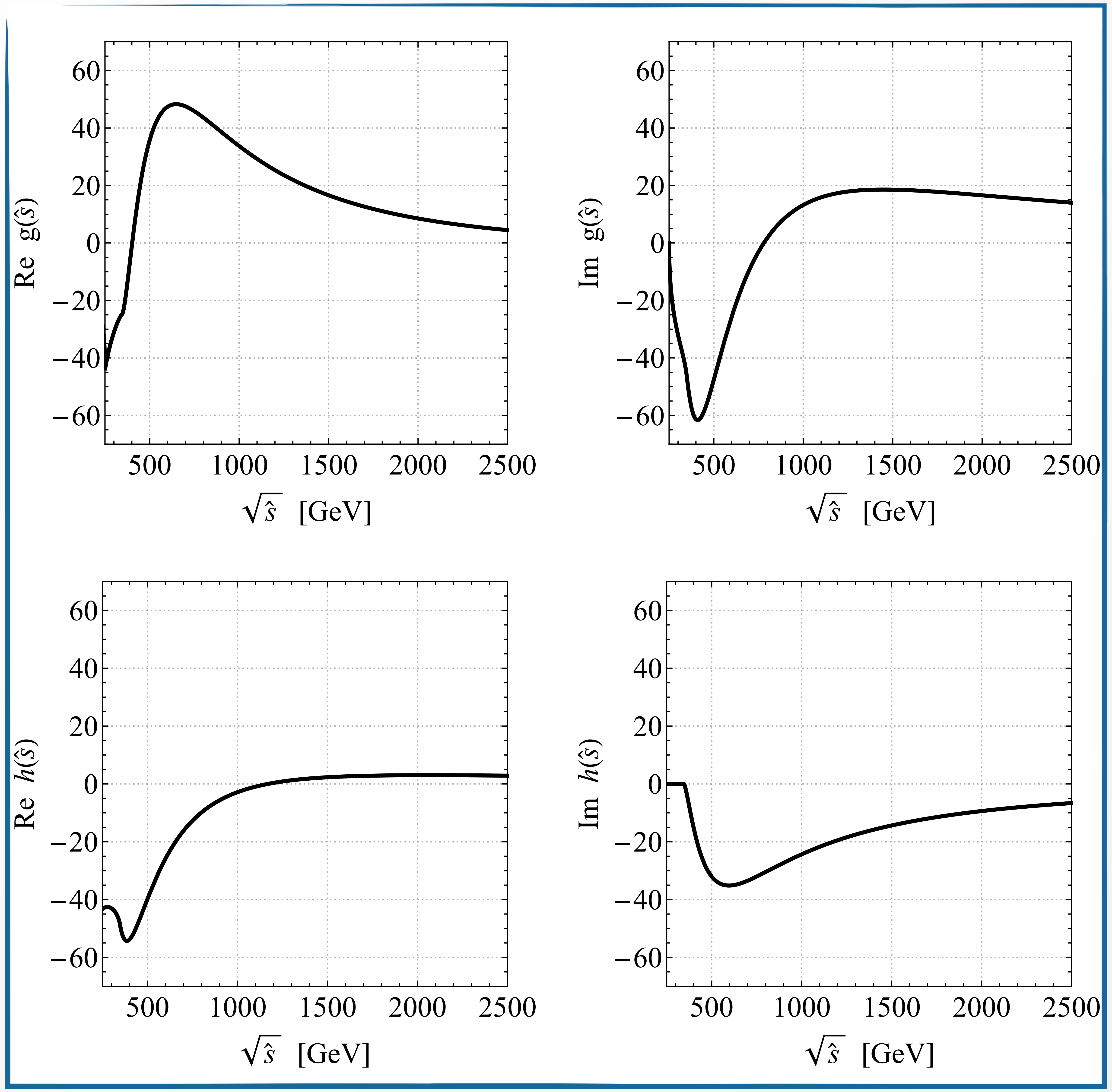
$$\Delta\mathcal{F}_1^{\kappa_3\kappa_4} = \frac{\alpha_s}{4\pi}\,\lambda\,\kappa_3\,\frac{\lambda\,\kappa_4}{(4\pi)^2}\,g(\hat{s}) \qquad \Delta\mathcal{F}_2^{\kappa_3\kappa_4} = 0$$

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

Functions $\hat{g}(\hat{s}), \hat{h}(\hat{s})$ can be **calculated analytically**

Second contribution is **model-dependent**. Here we consider a quintic self-interaction of the form $V \supset \kappa_5/v h^5, \kappa_5 = \lambda(3\bar{c}_6 + 14\bar{c}_8)/4$, and we neglect contributions from higher-dimensional operators of dimension 10 and above

Two-loop form factor (2)



- Non-trivial $\hat{s}$-dependence, with pronounced extrema at $2m_t$ and $2(m_t + m_H)$
- Impact expected on kinematics for double-Higgs production

Results at LHC and HL-LHC

Formulae implemented in the latest version of the **ggHH** code within the POWHEG-BOX framework (including bug-fix of the 2-loop QCD virtual) [1604.06447,1608.04798,1703.09252,1903.08137]

Results available at **NLO QCD in the full theory,** using (hardcoded) value of $m_t = 173\,\text{GeV}$

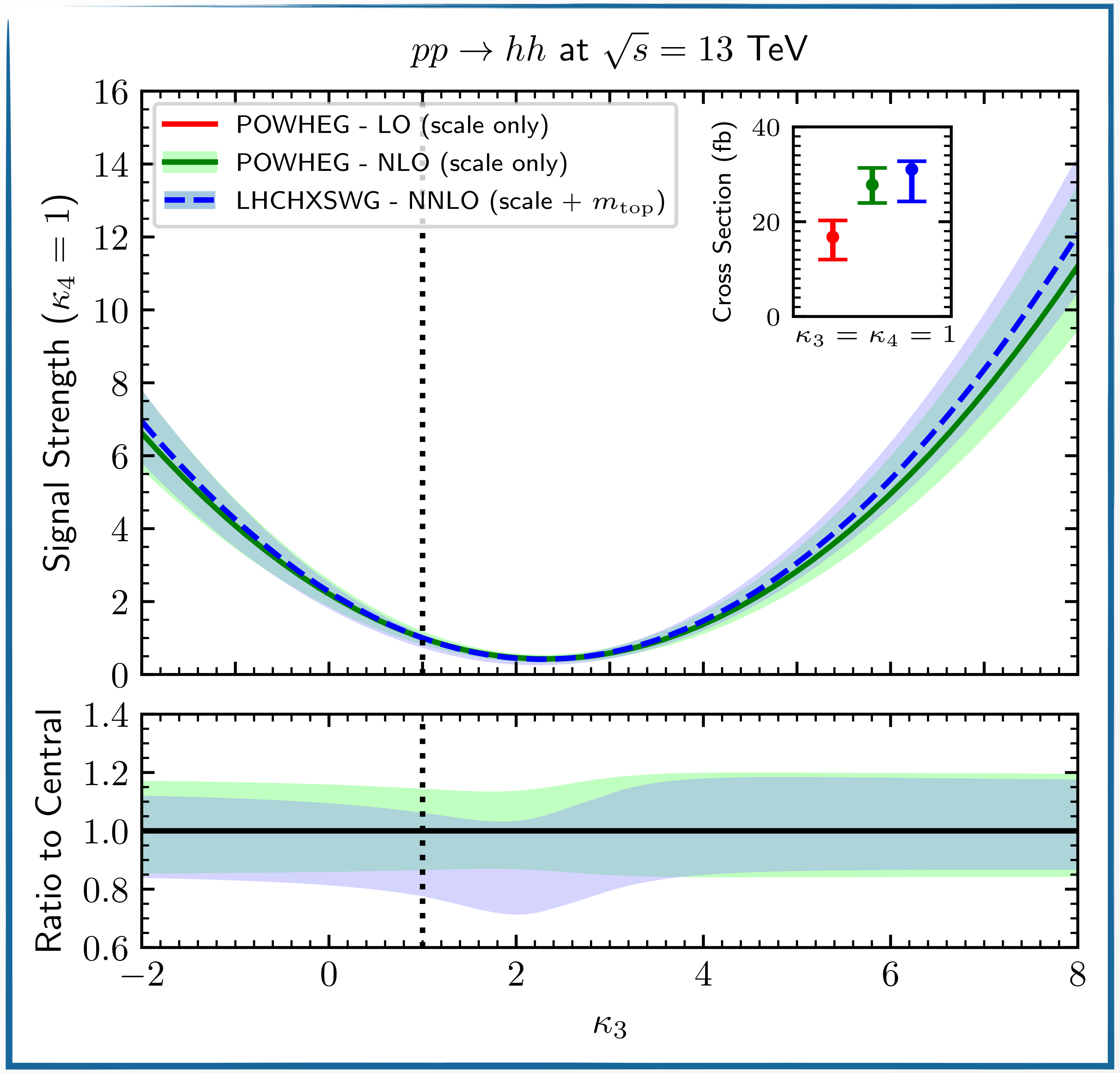
We use PDF4LHC15 NLO PDFs and set central factorisation and renormalisation scales to $\mu_F = \mu_R = m_{HH}/2$

Scale uncertainties calculated using **7-scale variation envelope**; effectively, upper and lower values determined by fully correlated $\mu_F = \mu_R = m_{HH}$ and $\mu_F = \mu_R = m_{HH}/4$ variations

Experimental systematic uncertainties not considered

We provide **signal strengths** as a function of κ_3, κ_4 for 13, 13.6, 14 TeV c.o.m. energies

Results at LHC and HL-LHC: κ_3 dependence



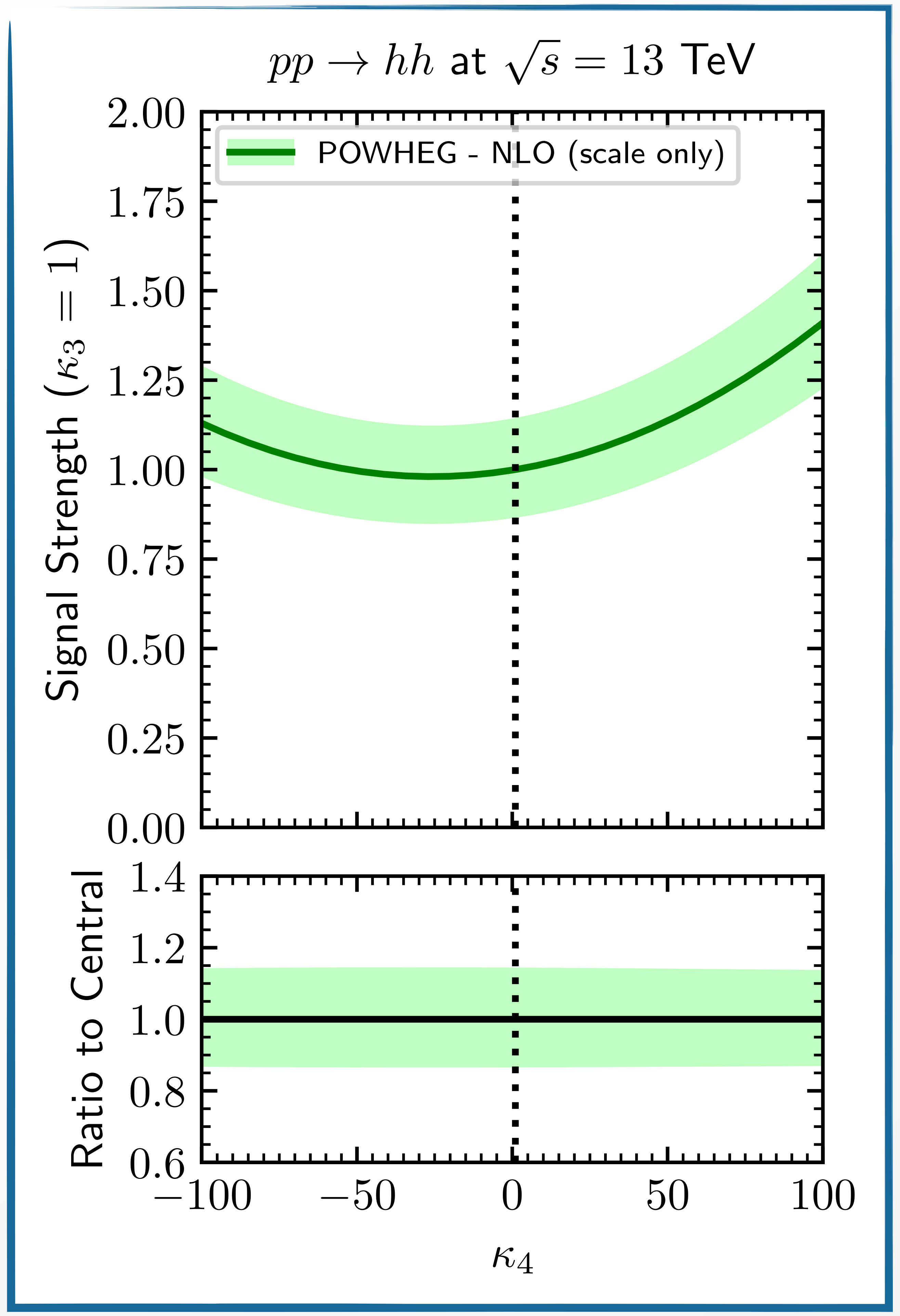
κ_3 dependence for $\kappa_4 = 1$ very close to the results of 1903.08137

SM cross section at NLO QCD close to the FT_{approx} NNLO one

Scale uncertainties at the **15% level**, of the **same size of the FT_{approx} NNLO** ones, which also include top mass and renormalisation scheme uncertainties

Signal strength **essentially overlaps with the FT_{approx} NNLO results** currently recommended by the HXSWG

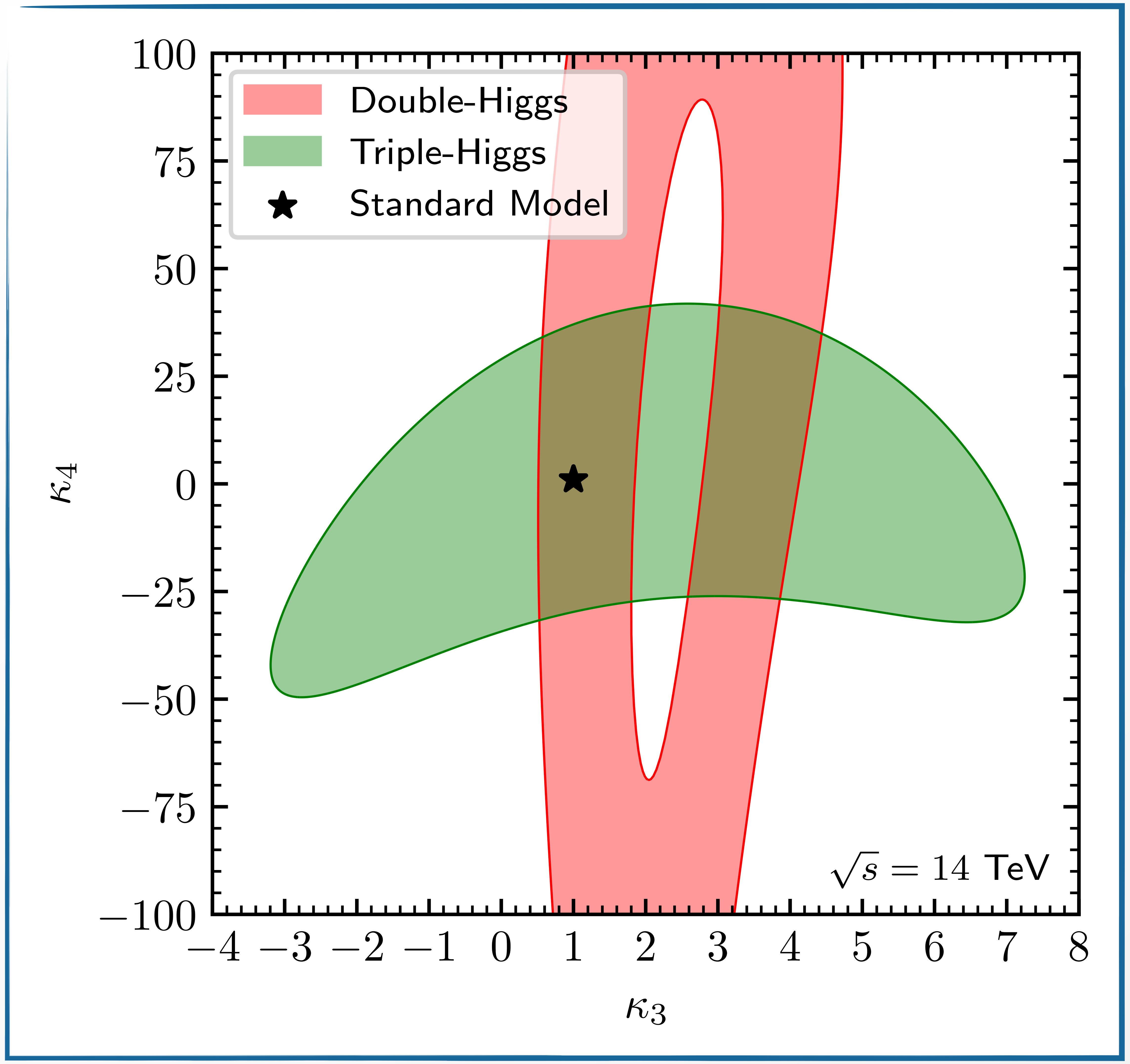
Results at LHC and HL-LHC: κ_4 dependence



Signal strength depends rather weakly on the value of κ_4 as expected (**indirect probe**)

More pronounced dependence expected by looking **at differential distributions.** Thanks to **publicly available code**, experiments can now directly pursue this possibility

Results at LHC and HL-LHC: constraints in the $\kappa_3 - \kappa_4$ plane

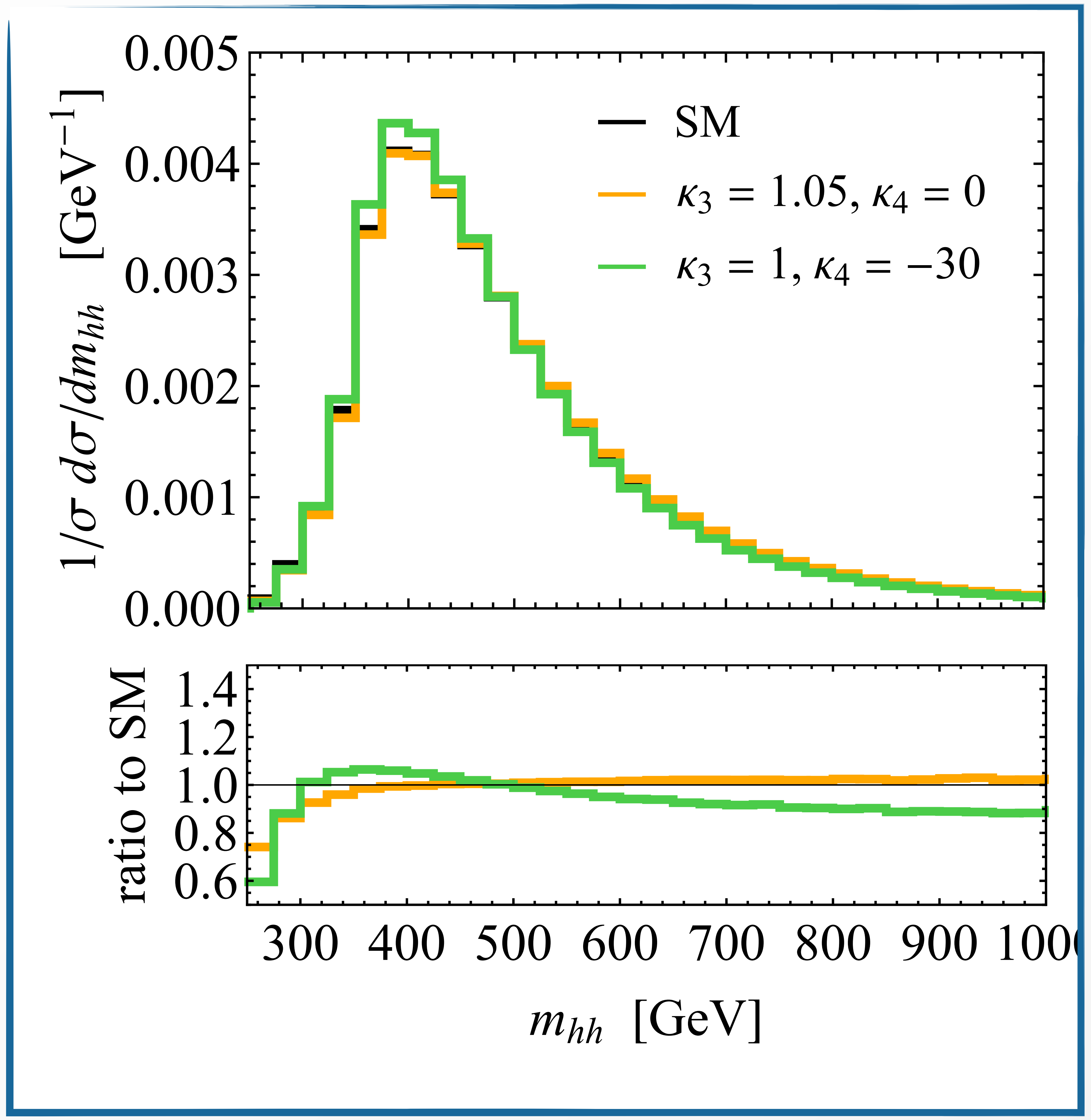


We draw hypothetical constraints in the $\kappa_3 - \kappa_4$ plane, assuming 50% uncertainty on μ_{HH} and $\mathcal{O}(20)$ bound on μ_{HHH}

Complementary constraints on the $\kappa_3 - \kappa_4$ plane

Precise measurement of differential distributions may resolve ambiguities or flat directions

Information from differential distributions: results at HE-LHC

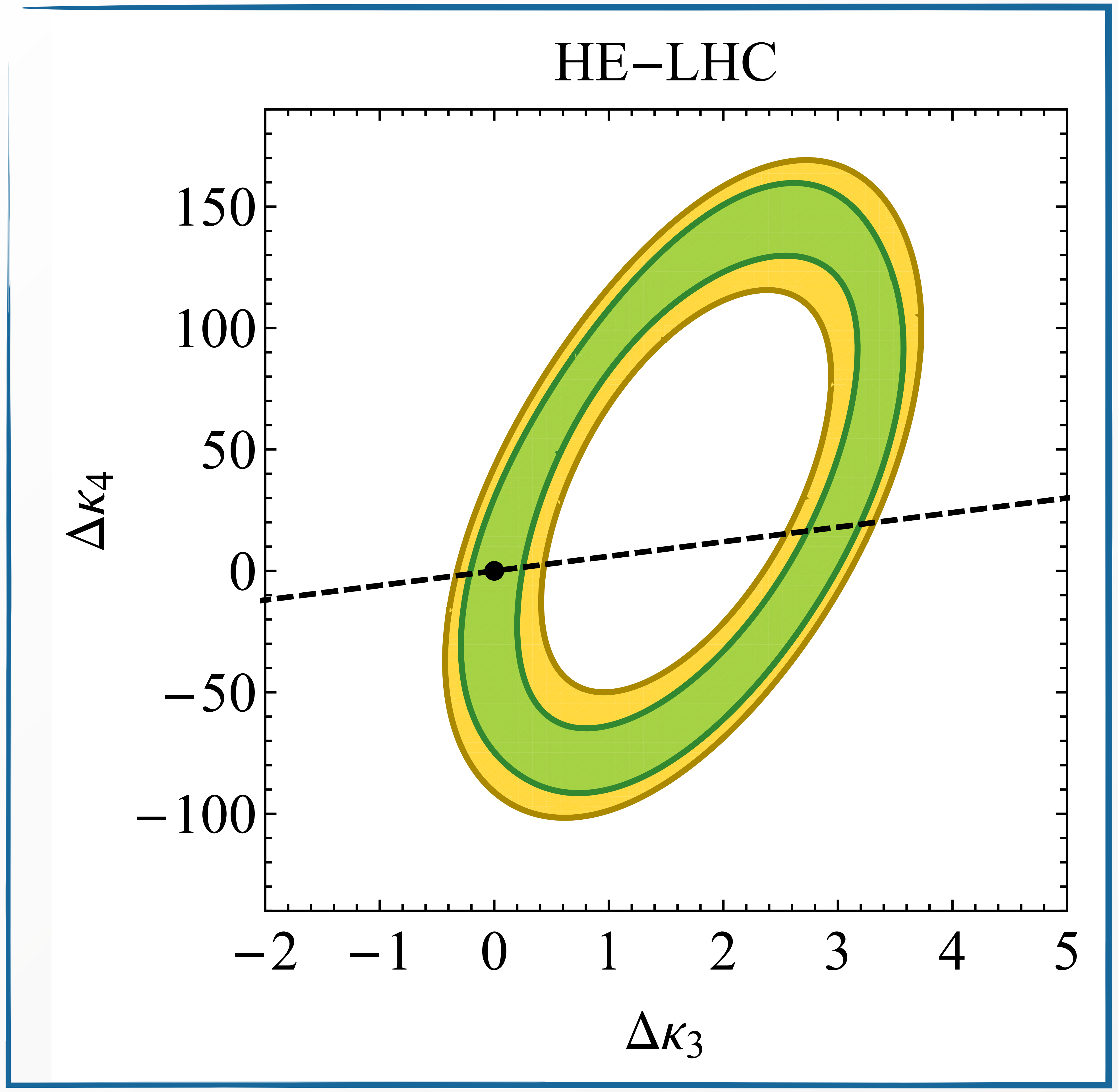


Shape analysis was performed in 1810.04665 with POWHEG-BOX+Pythia8 to include parton shower effects in the $b\bar{b}\gamma\gamma$ **final state**

70% b-tagging efficiency assumed, 15% (0.3%) mis-tagging rate for charm (light flavours)

Green and yellow κ_3, κ_4 choices yield undistinguishable total cross-sections

Information from differential distributions: results at HE-LHC

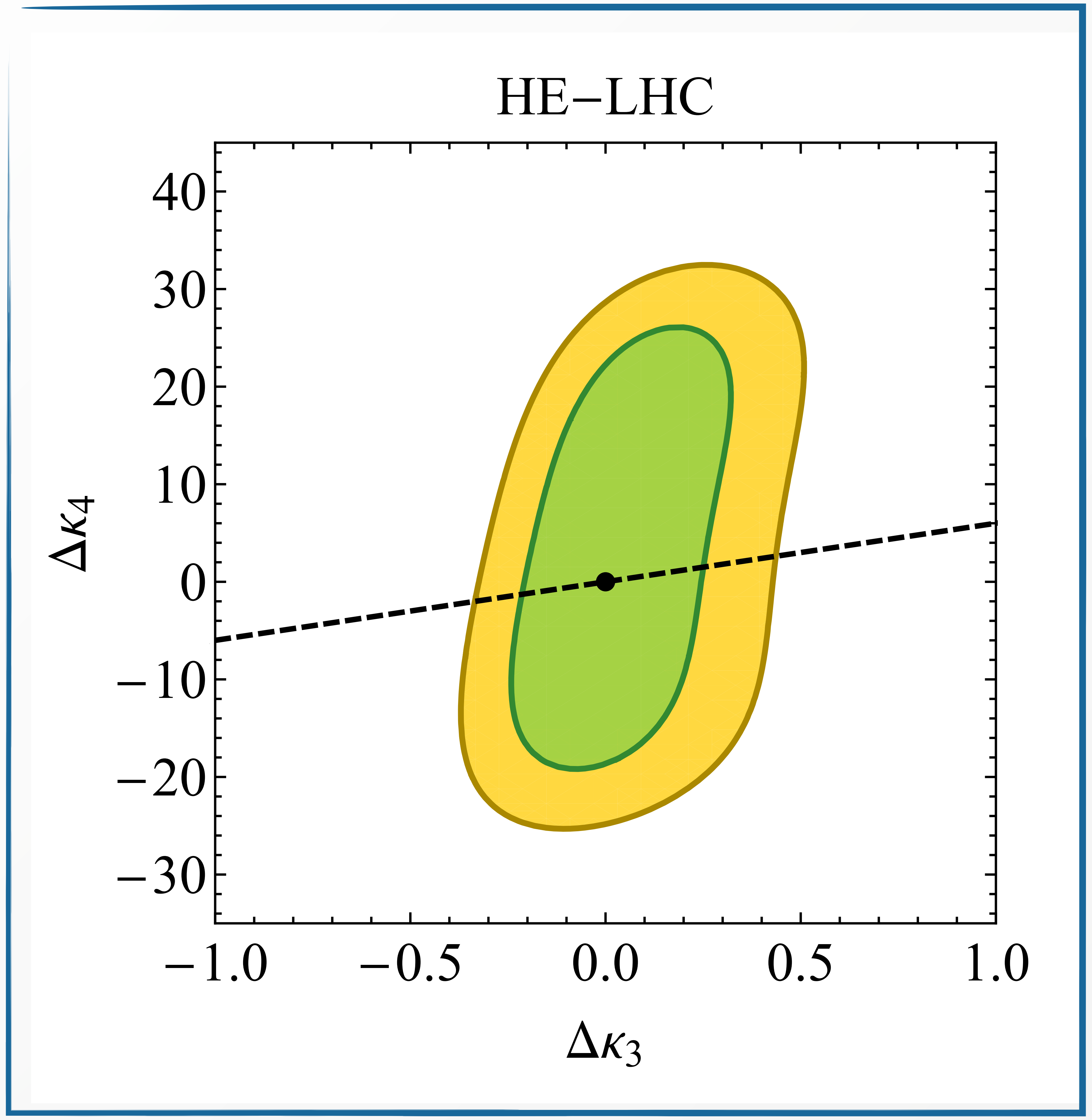


No background estimate, but CL curves mimic more sophisticated analysis which **includes simulation of all relevant backgrounds** [1802.04319]

Optimistic $< \mathcal{O}(5)\,\%$ theoretical and experimental uncertainty estimates at HE-LHC

Differential measurements in $pp \to hh$ channel alone expected to lead to somewhat weaker determinations of κ_4 than inclusive $pp \to hhh$ production

Information from differential distributions: combined results at HE-LHC



Best sensitivity obtained by performing a **global fit** (*hhh* inclusive, *hh* inclusive + fiducial)

$\kappa_3 = 1$ $\kappa_4 \in [-21,27]$

Profiling over κ_3 $\kappa_4 \in [-17,26]$

Improvement over inclusive measurement alone

Recapitulation

- We studied **indirect constraints** on the quartic Higgs self-coupling in double-Higgs production measurement

- **Best sensitivity** to κ_3 and κ_4 obtained exploiting synergy and complementarity of **indirect constraints** in inclusive and differential *hh* production and **direct constraints** from inclusive *hhh* production

- Release of **public Monte Carlo event generator** in the POWHEG-BOX framework which allows to arbitrarily vary κ_3 and κ_4

- We would like our implementation to be used by LHC experiments in conducting **detailed sensitivity studies,** and would appreciate a discussion on what is needed to have this be incorporated into the **WG recommendations**