One-loop scalar leptoquark effects in Higgs pair production via gluon fusion

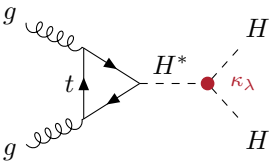
Marcelo Toscano Jiménez

Advisor: Dr. Gilberto Tavares Velasco

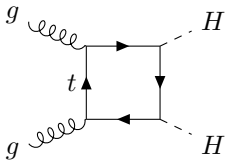
Facultad de Ciencias Físico Matemáticas
Benemérita Universidad Autónoma de Puebla

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Higgs pair production: a window on the trilinear coupling



(a) triangle: trilinear coupling (κ_λ)



(b) box: independent of κ_λ

- Loop-induced already at leading order; triangle and box interfere destructively [1,2] $\Rightarrow$ small rate (≈ 17 fb at 14 TeV, LO).
- $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$. Today (ATLAS+CMS, Run 2) [3]: $-0.71 < \kappa_\lambda < 6.1$ at 95 % CL. Projected uncertainty (68 % CL): $-26\,\%/+29\,\%$ at the HL-LHC [4], 3.4–7.8 % at the FCC-hh [5].
- New **coloured** particles enter at the **same loop order** as the top quark.

Questions of this talk

1. How large are the one-loop effects of a coloured scalar in $gg \to HH$?
2. How do they compare with correcting only the HHH vertex?

Scalar leptoquark S_1 with a Higgs portal

Model: $S_1 \sim (\bar{3}, 1, 1/3)$

$$\mathcal{L} \supset |D_\mu S_1|^2 - \mu_{S_1}^2 |S_1|^2 - \lambda_{S_1} |H|^2 |S_1|^2 + \left[y_{ij}^{LL} \overline{Q_i^c}\, i\sigma_2 L_j + y_{ij}^{RR} \overline{u_{R\,i}^c}\, e_{R\,j} \right] S_1 + \text{h.c.}$$ [6]

$$M_{S_1}^2 = \mu_{S_1}^2 + \tfrac{1}{2}\lambda_{S_1} v^2$$

$$HS_1S_1^* : \; -i\lambda_{S_1} v, \qquad HHS_1S_1^* : \; -i\lambda_{S_1}$$

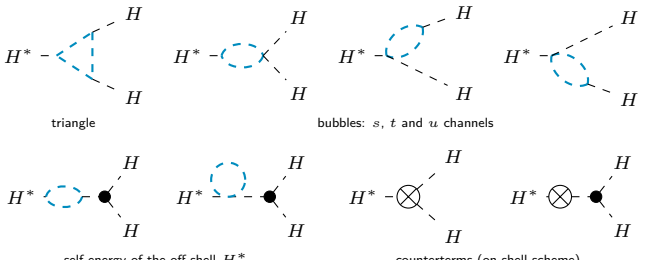
Gluon couplings fixed by QCD.

Benchmark

$M_{S_1} = 1$ TeV, $\quad \lambda_{S_1} = 1$

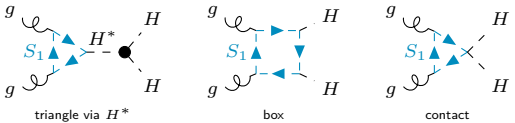
Previous $gg \to HH$ studies with scalar leptoquarks: [7,8]

(A) One-loop HHH vertex with S_1



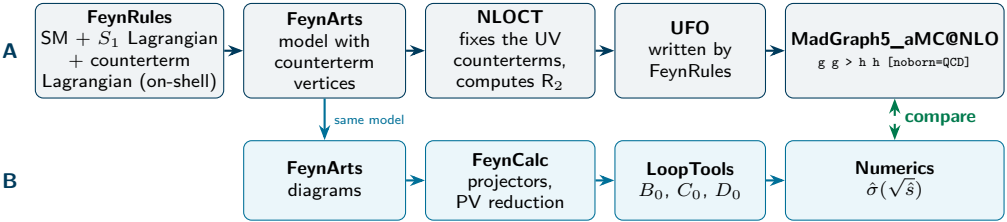
Tadpoles cancel against δt. Inserted in the top triangle it is **two loops**: computed separately, only for comparison.

(B) S_1 loops attached to the gluons



one loop, same order as the SM: **these give our results**

Two independent one-loop calculations



A: automated

A complete NLO UFO of S_1 (full Yukawa sector + Higgs portal), usable in MadGraph for any S_1 process, not only $gg \to HH$.

B: explicit

The same amplitude written out in FeynCalc and split by class of diagrams, so each contribution can be followed separately.

FeynRules [9], FeynArts [10], NLOCT [11], MadGraph5_aMC@NLO [12], FeynCalc [13], LoopTools [14].

Cross-checks: same diagrams, same numbers

Same diagrams

✓ $30 = 16$ SM $+ 14$ S_1

in both chains

Same cross section at fixed $\sqrt{\hat{s}}$

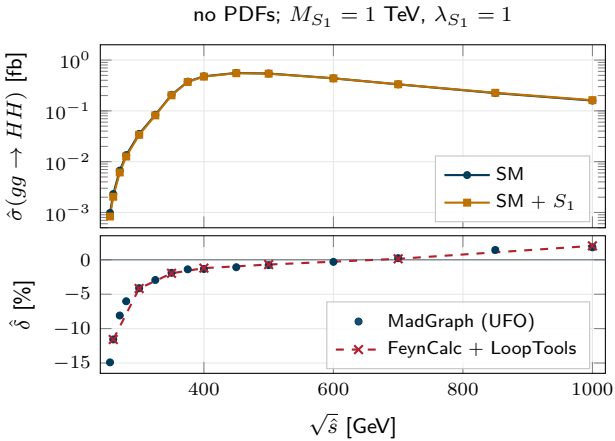
Relative change $\hat{\delta} = \hat{\sigma}_{\mathrm{SM+S_1}}/\hat{\sigma}_{\mathrm{SM}} - 1$:

$\sqrt{\hat{s}}$	MadGraph (A)	FeynCalc + LoopTools (B)
260 GeV	$-11.57 \pm 0.10\,\%$	$-11.58\,\%$
500 GeV	$-0.77 \pm 0.08\,\%$	$-0.69\,\%$
1 TeV	$+1.82 \pm 0.33\,\%$	$+2.03\,\%$

Consequence

Each class of diagrams is finite and gauge invariant on its own, so its contribution can be isolated (slide 7).

Partonic cross section: FeynCalc vs. MadGraph



$\hat{\delta} \equiv \hat{\sigma}_{\mathrm{SM+S_1}}/\hat{\sigma}_{\mathrm{SM}} - 1$ at fixed $\sqrt{\hat{s}}$

Setup

One loop: SM + all S_1 loops attached to the gluons (no vertex correction).

- MadGraph without PDFs: 15 energies from 255 GeV to 1 TeV, with $\lambda_{S_1} = 0$ and 1.
- FeynCalc + LoopTools: 7 energies, angular integration with Gauss–Legendre.

Result

- The two calculations **agree** at all 7 energies ($\chi^2 = 4.7$, $|\mathrm{pull}| \leq 1.4$).
- $\hat{\delta}$ goes from about $-15\,\%$ near threshold to $+2\,\%$ at 1 TeV.
- Sign change near $\sqrt{\hat{s}} \approx 650$ GeV.

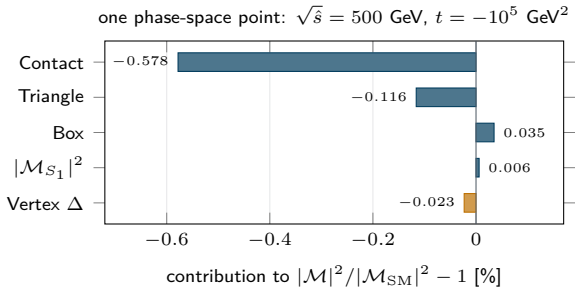
Anatomy of the effect

Effect on $\hat{\sigma}$, integrated over the angle (FeynCalc + LoopTools)

$\sqrt{\hat{s}}$ [GeV]	$\hat{\delta}_{S_1}$ (one loop)	$\hat{\delta}_{\triangle}$ (vertex)	$\lvert\hat{\delta}_{\triangle}/\hat{\delta}_{S_1}\rvert$
260	$-11.58\,\%$	$-1.05\,\%$	0.09
300	$-4.17\,\%$	$-0.30\,\%$	0.07
350	$-1.96\,\%$	$-0.12\,\%$	0.06
400	$-1.21\,\%$	$-0.066\,\%$	0.05
500	$-0.69\,\%$	$-0.024\,\%$	0.03
700	$+0.14\,\%$	$+0.019\,\%$	(near sign change)
1000	$+2.03\,\%$	$+0.056\,\%$	0.03

The corrected vertex is not enough

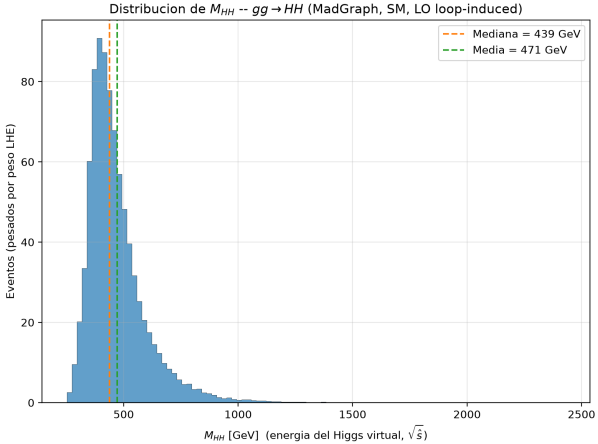
Away from the sign change, the one-loop HHH vertex alone gives only **3–9 %** of the effect. The S_1 loops attached to the gluons dominate.



How the pieces combine

Each bar is the interference of one class of diagrams with the SM. The contact diagram ($HHS_1S_1^*$) dominates; the triangle ($= C_{\triangle} \times$ contact, $C_{\triangle} = \lambda_{HHH} v/(\hat{s} - m_H^2) = 0.20$) adds to it, and the box cancels a small part ($-0.06\times$ contact). The orange bar (vertex Δ) is the separate two-loop piece, shown only for comparison.

From partonic to hadronic: 14 TeV



SM $gg \to HH$ events from MadGraph (LO), $M_{HH} = \sqrt{\hat{s}}$.

- SM events cluster at $M_{HH} \approx 400$–500 GeV (median 439 GeV), where $\hat{\delta}$ is between $-1.3\,\%$ and $-0.8\,\%$.
- The largest effects (near threshold) sit where there are few events $\Rightarrow$ the M_{HH} distribution is the natural observable.

Hadronic, 14 TeV, LO (MadGraph)

$\sigma_{\rm SM} = 17.32 \pm 0.02$ fb, $\sigma_{\rm SM+S_1} = 17.14 \pm 0.01$ fb

$\Rightarrow \ \delta_{hh} = \mathbf{-1.04 \pm 0.16}\,\%$

One loop, $M_{S_1} = 1$ TeV, $\lambda_{S_1} = 1$ (this work)

Negative for $\lambda_{S_1} > 0$ and opposite in sign to single-Higgs production, as found by Gabriel et al. [7] for the same type of model.

Outlook

	UFO chain	HHH vertex	$gg \to HH$ amplitude	$\hat{\sigma}$: FeynCalc vs. MadGraph
Leptoquark $S_1 \sim (\bar{3}, 1, 1/3)$	✓	✓	✓	✓
Manohar–Wise octet $S \sim (8, 2)_{1/2}$	✓	**next**	–	–
4321 model (Ω_1, Ω_3 portals)	–	–	–	–

New models

- **Manohar–Wise** [15]: large colour factor and several states ($S^{\pm}$, S_R, S_I) with different couplings to the Higgs.
- **4321** [16]: implemented from its scalar potential; no $gg \to HH$ study found in the literature.

Next steps

- $gg \to H$ from the same form factors: correlate δ_h and δ_{hh} for each model (for S_1 they have opposite signs).
- The same class-by-class anatomy for Manohar–Wise and 4321, where several states can cancel each other.

Summary

- The full one-loop S_1 contribution to $gg \to HH$ was computed in **two independent ways**: an automated FeynRules–NLOCT–UFO model in MadGraph and an explicit FeynCalc amplitude. They agree within the Monte Carlo uncertainties.
- Partonic effect: about $-15\,\%$ near threshold, $+2\,\%$ at 1 TeV; hadronic effect at 14 TeV: $-1.0\,\%$ ($M_{S_1} = 1$ TeV, $\lambda_{S_1} = 1$).
- The one-loop corrected HHH vertex alone gives only 3–9 % of the effect; the S_1 loops attached to the gluons, mainly the contact topology, dominate.
- The validated pipeline is now being applied to the Manohar–Wise octet and the 4321 model.

Thank you!

Backup: the $gg \to HH$ amplitude

Two tensor structures, spin 0 (A_1) and spin 2 (A_2), with the colour factor δ^{ab} outside [2]:

$$\mathcal{M}\Big(g^a_\mu(p_1)\, g^b_\nu(p_2) \to H(p_3)H(p_4)\Big) = \delta^{ab}\, \epsilon_1^\mu \epsilon_2^\nu \Big[F_1\, A_{1,\mu\nu} + F_2\, A_{2,\mu\nu}\Big]$$

$$A_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1\cdot p_2}, \qquad p_T^2 = \frac{2(p_1\cdot p_3)(p_2\cdot p_3)}{p_1\cdot p_2} - p_3^2$$

$$A_2^{\mu\nu} = g^{\mu\nu} + \frac{p_3^2\, p_1^\nu p_2^\mu - 2(p_3\cdot p_2)\, p_1^\nu p_3^\mu - 2(p_3\cdot p_1)\, p_3^\nu p_2^\mu + 2(p_1\cdot p_2)\, p_3^\mu p_3^\nu}{p_T^2\,(p_1\cdot p_2)}$$

Projectors in D dimensions ($A_1\cdot A_1 = A_2\cdot A_2 = D-2$, $A_1\cdot A_2 = D-4$), $F_i = P_i^{\mu\nu}\mathcal{M}_{\mu\nu}$:

$$P_1 = \tfrac{1}{4}\Big[\tfrac{D-2}{D-3}A_1 - \tfrac{D-4}{D-3}A_2\Big], \qquad P_2 = \tfrac{1}{4}\Big[-\tfrac{D-4}{D-3}A_1 + \tfrac{D-2}{D-3}A_2\Big]$$

Form factors by class of diagrams:

$$F_1 = F_1^{\mathrm{SM},\triangle} + F_1^{\mathrm{SM},\square} + F_1^{S_1,\triangle} + F_1^{S_1,\square} + F_1^{S_1,c}, \qquad F_2 = F_2^{\mathrm{SM},\square} + F_2^{S_1,\square}$$

$$F_1^{S_1,\triangle} = C_\triangle\, F_1^{S_1,c}, \qquad C_\triangle = \frac{\lambda_{HHH}\, v}{\hat{s} - m_H^2 + i\, m_H \Gamma_H}, \qquad \lambda_{HHH} = \frac{3m_H^2}{v}$$

Corrected vertex (approach A): $F_1^{\mathrm{SM},\triangle} \to \Big[1 + \Delta(\hat{s})\Big] F_1^{\mathrm{SM},\triangle}$. Each F_i is a combination of B_0, C_0, D_0 (FeynCalc), evaluated numerically with LoopTools.

Backup: partonic cross section in chain B

Sum over colours and polarizations, average over the initial state $(1/256)$:

$$\overline{|\mathcal{M}|^2} = \frac{8 \cdot 2}{256}\left(|F_1|^2 + |F_2|^2\right) = \frac{|F_1|^2 + |F_2|^2}{16}$$

Two-body phase space, factor $\frac{1}{2}$ for identical Higgs bosons, $\beta = \sqrt{1 - 4m_H^2/\hat{s}}$:

$$\hat{\sigma}(\hat{s}) = \frac{1}{2}\int_{-1}^{1} d\cos\theta\, \frac{\beta}{32\pi\hat{s}}\,\overline{|\mathcal{M}|^2} = \frac{\beta}{1024\,\pi\,\hat{s}}\int_{-1}^{1} d\cos\theta\,\left(|F_1|^2 + |F_2|^2\right), \qquad \hat{t} = m_H^2 - \frac{\hat{s}}{2}\left(1 - \beta\cos\theta\right)$$

What chain B evaluates

$$\hat{\delta}(\sqrt{\hat{s}}) = \frac{\displaystyle\int_{-1}^{1} d\cos\theta\,\left(|F_1|^2 + |F_2|^2\right)}{\displaystyle\int_{-1}^{1} d\cos\theta\,\left(|F_1^{\mathrm{SM}}|^2 + |F_2^{\mathrm{SM}}|^2\right)} - 1$$

g_s^2, the factor $\frac{1}{2}$ and the overall normalization cancel in the ratio. Integral over $\cos\theta$ with 24-point Gauss–Legendre quadrature. Inputs: $m_H = 125$, $m_t = 173$, $m_b = 4.7$, $v = 246.22$ GeV, $y_q = \sqrt{2}\,m_q/v$; $M_{S_1} = 1$ TeV, $\lambda_{S_1} = 1$.

Backup: all the checks

A: automated chain (MadGraph)

- ✓ **Standard Model limit** ($\lambda_{S_1} = 0$, 14 TeV, LO): 17.32 ± 0.02 fb, against 17.31 ± 0.01 fb from MadGraph's own loop model: **0.06 %**.
- ✓ **Counterterms**: with the counterterms of the model itself, the one-loop HHH vertex is UV finite (on-shell scheme).

Same diagrams in both chains

- ✓ 30 diagrams: 16 SM (top and bottom loops) + 14 with S_1.

B: explicit amplitude (FeynCalc)

Split by class of diagrams: SM triangle and box; S_1 triangle, box and contact. Each class is checked on its own:

- ✓ **UV finite**: no infinity survives, as it must for a process with no tree-level contribution.
- ✓ **Gauge invariant**: replacing a gluon polarization by its momentum gives zero (Ward identity).
- ✓ **Spin structure**: triangles and contact give no spin-2 part, since the gluons couple to a single scalar.
- ✓ **Numerics**: the result does not change with the UV regulator of LoopTools ($< 10^{-15}$).

Consequence

Each class is a gauge-invariant, finite piece of the amplitude, so its contribution can be isolated (slide 7). The cross sections of both chains agree at every energy (slide 6).

Backup: partonic comparison in numbers

$\sqrt{\hat{s}}$ [GeV]	MadGraph $\hat{\delta}$ [%]	FeynCalc $\hat{\delta}$ [%]	pull
260	-11.57 ± 0.10	-11.58	0.1
300	-4.12 ± 0.13	-4.17	0.4
350	-1.89 ± 0.07	-1.96	0.9
400	-1.34 ± 0.09	-1.21	-1.4
500	-0.77 ± 0.08	-0.69	-1.0
700	$+0.24 \pm 0.19$	$+0.14$	0.5
1000	$+1.82 \pm 0.33$	$+2.03$	-0.6

MadGraph 3.7.0, `lpp1 = lpp2 = 0`, 10^4 events per run; $m_H = 125$, $m_t = 173$, $m_b = 4.7$, $v = 246.22$ GeV; $M_{S_1} = 1$ TeV, $\lambda_{S_1} = 1$.

Backup: the one-loop corrected HHH vertex

Relative correction to the tree-level vertex $-3i\,m_H^2/v$ (internal masses M_{S_1}, $\lambda \equiv \lambda_{S_1}$):

$$\Delta(\hat{s}) = -\frac{\lambda^3 N_c v^4}{24\pi^2 m_H^2}\, C_0(m_H^2, m_H^2, \hat{s}) + \frac{\lambda^2 N_c v^2}{48\pi^2 m_H^2}\left[B_0(m_H^2) - B_0(\hat{s})\right] - \frac{\lambda^2 N_c v^2}{32\pi^2}\,\mathrm{DB}_0(m_H^2)$$

On-shell renormalization

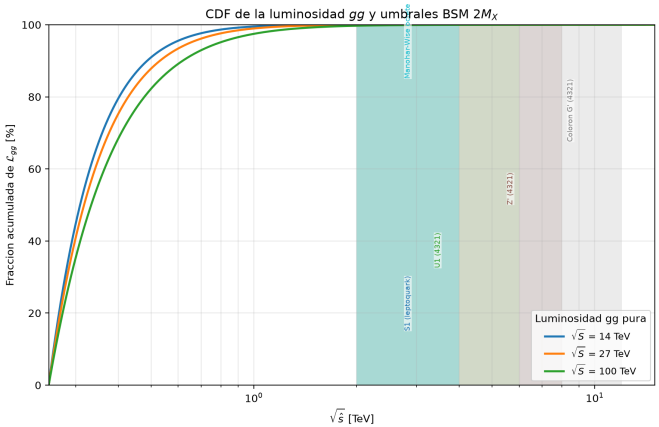
$\hat{T} = 0 \Rightarrow \delta t = -T; \quad \mathrm{Re}\,\hat{\Sigma}(m_H^2) = 0 \Rightarrow \delta m_H^2;$

$\mathrm{Re}\,\hat{\Sigma}'(m_H^2) = 0 \Rightarrow \delta Z_H = -\dfrac{\lambda^2 N_c v^2}{16\pi^2}\,\mathrm{DB}_0(m_H^2)$

Checks

Loops + counterterms from the model itself: the UV pole cancels. $\Delta(500\ \text{GeV}) = 4.4 \times 10^{-4}$ for $M_{S_1} = 1$ TeV, $\lambda = 1$.

Backup: gg luminosity and the thresholds $2M_X$



- Cumulative fraction of the gg luminosity at 14, 27 and 100 TeV.
- Bands: thresholds $2M_X$ for S_1, the Manohar–Wise octet and the 4321 states.
- Even at 100 TeV almost all of the luminosity lies below the thresholds: the new states are probed in the decoupling regime.

Backup: four failures in the automated chain

Symptom	Cause	Fix
`WriteCT` ends without errors but the `.nlo` file is empty (0 insertions)	The model has tadpole vertices; the generic file `Lorentz` was used	Call `WriteCT` with the generic file `"LorentzTadpole"`
Unresolved `FCGV`, `FASUNT`, `FAGS` in the `.nlo` and the UFO	The FeynArts model had been patched by FeynCalc (`FAPatch`); NLOCT does not recognise the renamed symbols	Generate the model in a clean FeynArts; patch only a copy for FeynCalc
`WriteFeynArtsOutput` never ends; spurious vertices violating charge	Wolfram 15 protects `Commutator` and `MatrixSymbol`, which FeynRules redefines	`Unprotect[Commutator, MatrixSymbol]` before loading FeynRules
The UFO does not load in MadGraph (Python 3)	`complex > float` comparisons, loose colour traces `SumOver`, antiparticle named `S1m13*`	Real internal parameters with `re(...)`; `SumOver -> 3`; rename to `S1m13~`

The first three failures were silent: each step finished "successfully". Every one is now caught by a check that takes seconds.

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